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Propuesta de integración de demanda activa en el sistema de distribución: variables, escenarios y estudio de caso.

Proposal for integrating active demand in the distribution system: variables, scenarios, and case study.

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Resumen

En este artículo se propone la integración de demanda activa en el sistema de distribución mediante el uso de técnicas metaheurísticas. Se emplea la metodología de dinámica de sistemas, que permite identificar variables relevantes para la participación de la demanda. El enfoque sistémico utilizado ayuda a caracterizar tanto variables endógenas como exógenas, lo que resulta crucial para evaluar las fortalezas y debilidades del proceso de integración de la demanda activa. Además, se considera el tiempo de transición en la evolución del sistema. El trabajo propone un desarrollo por etapas, definiendo escenarios diversos e integrándolos con la ciencia de datos para crear hojas de ruta adaptadas a diferentes sistemas de distribución y a condiciones específicas. Se presenta un estudio de caso clásico que evalúa el impacto de esta transición y determina la política de regulación necesaria para lograr una integración efectiva de la demanda activa.

Palabras clave: demanda activa; dinámica de sistemas; recursos energéticos distribuidos; sistema de distribución; técnicas metaheurísticas.

Abstract

This article proposes the integration of active demand into the distribution system with metaheuristic techniques. The system dynamics methodology is employed to identify relevant variables for demand participation. The systemic approach used helps characterize both endogenous and exogenous variables, which is crucial for evaluating the strengths and weaknesses of the active demand integration process. Additionally, consider the transition time in the system's evolution. The paper proposes a phased development, defining diverse scenarios and integrating them with data science to create tailored roadmaps for distribution systems and specific conditions. A classic case study presented, evaluating the impact of this transition and determining the necessary regulatory policy to achieve effective integration of active demand.

Keywords: active demand; dynamical systems; distribution system; distributed energy resources; metaheuristic techniques.

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1. Introduction

The rapid transformation of the distribution system requires adopting technologies that administer, manage, and evolve flexibility, decentralization, and resilience, currently null or in low proportion, to integrate variables within the distribution system and evaluate the impact of their adoption and participation.

Among the variables are the addition of non-conventional sources of variable renewable energy, data science, and the emergence of enabling technological infrastructures that manage decisions in the planning and execution of energy roadmaps—these present essential challenges within the integration, resulting in a distribution system transformation [1].

The transition to a resilient, environmentally friendly, autonomous, and intelligent distribution system driven by decentralization, decarbonization, and digitalization, the 3 Ds [2]–[5]. According to the definition given by the [6], [7] monitoring of active demand, it is associated with an opening, a "*democratization*" of electricity. Some authors consider the terms energy and electricity interchangeably. The concept of democratization for this work applied to the electrical distribution system. According to the democratization of energy, it is a context of expansion, liberation, and transfer of powers that leads to the decentralization of the service and that, socially, consumers have a greater participation in the decisions of the system [8], [9].

The current distribution system faces significant challenges that require attention and practical solutions. First, there is a need to massify renewable energy sources in the system. As energy demand increases, it is crucial to massively integrate sustainable sources into the electricity distribution system, which requires appropriate investments and policies. In addition, the current system relies heavily on a centralized infrastructure for its control and operation. This dependence can limit the flexibility and adaptability of the system to changes in demand and power generation. It is necessary to explore solutions that allow greater decentralization and use of distributed resources. Another critical challenge is the lack of a multi-track consumption tracking system. Measuring and understanding energy consumption in real-time at different levels and connection points is essential for efficient and optimized management.

Addressing these challenges requires a comprehensive and collaborative vision, where technological innovation, adequate regulation, and all actors' participation promote. Moving towards a more resilient, efficient, and sustainable distribution system that can meet future energy challenges is essential. There is an urgent need for an innovative alternative known as a transactive system. According to [9] an approach that promotes the participation of users who consume energy generates and shares it with the grid. In this system, prosumers, those users who produce their energy, can exchange it with other participants in the network directly and transparently. The above creates a collaborative environment where distributed energy resources are maximized and encourages small-scale renewable generation.

The insertion of prosumer users, those who generate their energy and inject it into the system, is practically null or in meager participation in many cases. It is essential to encourage the participation of these users in the distribution system, facilitating their integration and establishing appropriate incentives.[1]

The transactive system represents a promising alternative to evolve the current electricity distribution system, as it allows greater integration of renewable energy and more efficient demand management. In addition, it encourages the participation and empowerment of users in energy decision-making. It offers a transformative perspective for the future of electricity distribution, promoting the transition towards a more sustainable, equitable, and flexible model. Its adoption and continuous development can contribute significantly to the construction of a more resilient energy system oriented to the well-being of society.

The document is structured as follows: Section 2 presents the relationship between active demand, 3D, and differences in classical cutting systems. Section 3 shows vital elements in integrating active demand with the support of metaheuristic techniques (MH) employing a causal diagram with a system dynamics approach that relates concepts and actions. Section 4 shows the proposed scenarios for evaluating the integration of active demand with distribution systems, the degree of interaction between concepts, and their characterization. Section 5 shows the case study of the classic type with distinctive elements of transactive interaction, such as the insertion of MH techniques—and finally, the corresponding conclusions and references.

2. The relationship between demand, 3D's, and classic distribution systems.

The concept of demand [10] is fully established when there is a quantification of the user's consumption and an electrical system that monitors energy distribution. Keep in mind that at this stage, you still have a basic infrastructure in a single way that records simple data. In addition, the system is classic, with generation in some cases hydraulic or fossil fuels, but in its essence with the classic stages: generation, transmission, and distribution.

As Figure 1 shows, one of the challenges facing the distribution system is to have a rigid demand that does not have any monitoring beyond quantifying the consumption rate. The data and infrastructure used were primary in one direction, and the infrastructure was informational only. The electrical distribution system's evolution seeks to move from a classic, rigid, verticalized, and centralized approach to a more modern and adaptable one. The aforementioned is accomplished by applying dynamic, prospective, and metaheuristic methodologies.

These methodologies allow greater flexibility and anticipation capacity in the face of changes and challenges in the electricity sector. The objective is to move to a transactive distribution system in which the participation of all actors is fundamental [11]–[13].

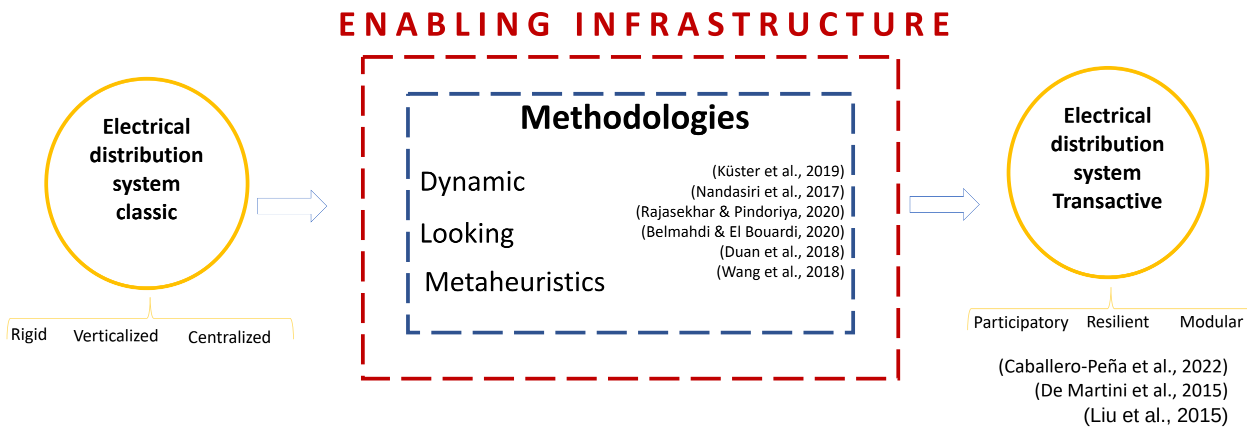

Figure 1. Change from a classical electrical system to a transactive system and conceptual relationship. Own source based on [14]

The new system characterizes itself as participatory, involving consumers and energy generators in decision-making and system management. In addition, it is resilient, able to adapt quickly to changing conditions and overcome obstacles. The transactive distribution system encourages a transactional approach involving exchanging energy and data between participants. Integrating user-to-user and user-to-network transactions allows for greater efficiency and optimization in electrical network management because it facilitates coordination and more direct and effective energy exchange [15]–[17].

When integrating elements such as variable loads and partially distributed generation, the concept of demand becomes more complex. Data is no longer simple but becomes multivariate, posing challenges to adapt to those changes. Although conventional generation still predominates, researchers are exploring hybrid energy solutions that enable greater end-user participation in demand [18], [19].

With the integration of distributed energy resources (DERS) and distributed generation, the concept of demand changes. By having a decentralized generation, it is necessary to have a way to measure in a single direction and several directions. Since the end-user has more participation in the demand, it is necessary to integrate data science elements for the planning and predicting consumption based on a generation that is becoming increasingly variable since it depends on natural resources such as the sun or wind. Demand response (RD) programs must evolve to active demand to reach a transactive system, decentralized, real-time, and highly dynamic demand. To achieve this synergy within the system, concepts such as prediction with data science, enabling infrastructure 4.0, Blockchain, and cloud computing must be integrated, necessary inputs to achieve a projection of digitization application over time.

3. Aspects to consider in integrating active demand supported by metaheuristic techniques.

Several challenges arise when transforming the distribution system in the future. The first challenge we need to address is to integrate datification and heuristic models that enable us to plan the integration of distributed generation in the short, medium, and long term. Machine Learning and Deep Learning applications stand out with predictors such as Neural Networks support vector machines, in addition to the hybrid combination of these predictors, which gives the models robust answers.

The authors [1], [20] show how this tool provides elements of prediction and support to install energy capacity of solutions that use the variable primary resource with high uncertainty. However, models that use data tend to have a concept [21]–[24] *drift* when training data changes, compromising their performance. The gradual shift in the conditions of active demand integration presents a challenge directly associated with this drift phenomenon. Demand transitions from a passive and static element to an active and dynamic one, exhibiting high nonlinearity. From a mathematical modeling perspective, it is advantageous to represent this transition heuristically.

The literature unanimously acknowledges that monitoring demand is essential to ensure the system's readiness to respond to unforeseen events with significant impacts. Requires contingency plans encompassing distributed generation and prediction through holistic models. The transactive distribution system supports monitoring active demand and establishing the figure of the prosumer within the transactive distribution system, thanks to the synergy of 3D: digitalization, decarbonization, and decentralization.

Digitalization plays a fundamental role in activating demand and allowing the emergence of prosumers within the transactive distribution system, implying that users not only consume energy but can also generate it and share it with the grid. Digitalization also enables the system's evolution toward this new form of interaction.

The relationship between the transactive distribution system and 3D is not unidirectional, as it involves decarbonization and decentralization. These aspects are crucial to the system's evolution and have internal variables, such as distributed generation, that allow the figure of the prosumer. However, this evolution does not happen immediately but requires assessing the delay needed to integrate the correct elements and analyze the impact through roadmaps and prospective analyses.

The delay time in the transition to a transactive system significantly affects the degree of conversion. This transition cannot happen immediately, as we must carefully assess the impacts from multiple perspectives: economic, social, environmental, and technological. A robust infrastructure enabling secure and reliable transactions is crucial to ensuring the integrity and efficiency of the transactive system [25], [26]. In addition, evolution involves the management of large volumes of data to transform both the user and the system.

Assessing the transition's pace and extent of implementation should consider country-specific conditions, as rapid digitalization and evolution can potentially disrupt both the market and distribution system. These changes also affect human activities, such as taking readings, maintenance actions, and related services, and then the proposed methodology based on system dynamics is presented.

3.1 Proposed Methodology and expected results when applying it.

In this work, a methodology based on system dynamics is employed. The use of system dynamics offers essential strengths in the field of the electrical distribution system. This methodology makes it possible to accurately identify existing problems and generate a detailed analysis of solution hypotheses. One of the main advantages of system dynamics is its ability to evaluate the proposed solutions in specific scenarios of integration of variables in the electrical distribution system. Enriching these scenarios with differentiating data is fundamental to obtaining a comprehensive and accurate understanding of the potential solutions. In this section, we define the methodology using dynamic systems; however, we validate its applicability in a later scenario due to the interactions among endogenous variables, the 3D elements, and the outcomes of each scenario defined within the distribution system.

Furthermore, we employ metaheuristic techniques to analyze and validate the results obtained in each scenario. System dynamics stands out for its ability to address the complexity inherent in the electrical distribution system and its evolution. By considering multiple variables and interactions within the system, this methodology allows an understanding of cause-effect relationships and evaluating the impact of different variables on system performance. In addition, system dynamics provides a structured and visual way to model and simulate variable integration scenarios. It makes it easier to understand how different variables interact and how the system evolves, allowing informed decisions and potential challenges to be anticipated [11], [27].

Exogenous variables are defined as those outside the distribution system's evolution scope. Although these variables influence the transition within the ecosystem, they are of a mixed nature, such as costs, evolution time, and the social and environmental impacts of this evolution. Another variable type is endogenous. The enabling infrastructure, Blockchain, and data science provide a framework for integrating active demand. Furthermore, market regulation policies and dispatch policies also play a crucial role.

In addition to the strengths mentioned above, the system dynamics methodology is expected to facilitate the identification of exogenous and endogenous variables in the electrical distribution system. These variables play a crucial role in understanding and analyzing the proposed scenarios.

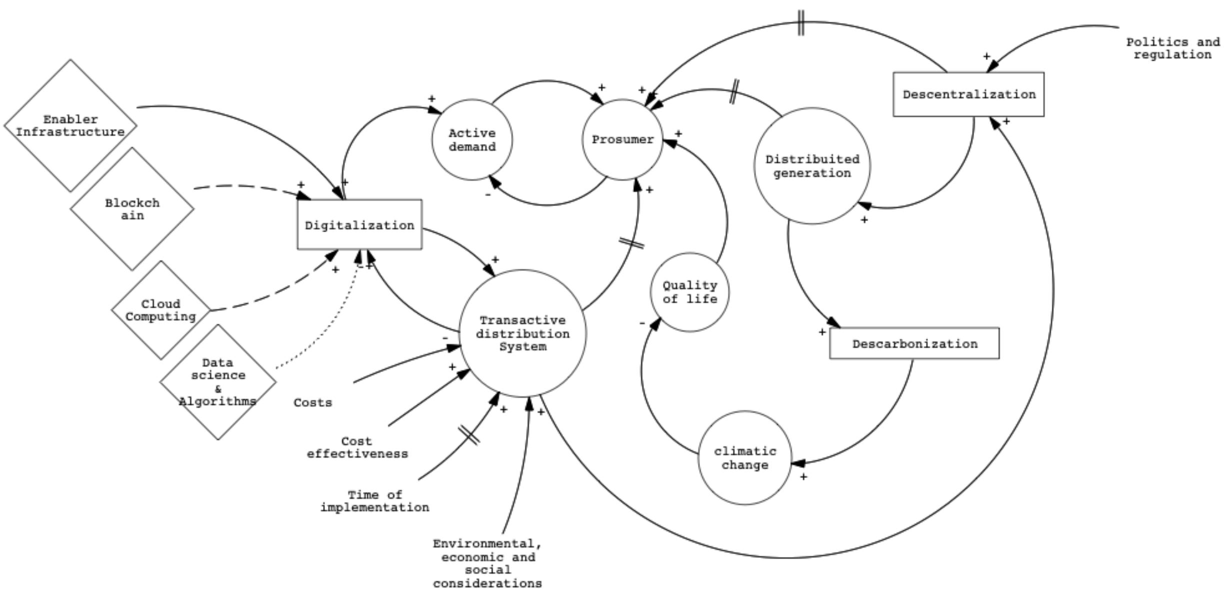

Figure 2. Causal diagram of 3D impact and integration considerations in the evolution to active user and transformation of the distribution system. Source: authors.

Figure 2 shows the causal diagram of 3D impact and integration considerations in the evolution to active user and transformation of the distribution system. The evaluation scenarios' input challenge axes are considered exogenous variables. By taking strengths from the widely addressed research of active demand within the distribution system, it evaluates the central axes of the challenge of integrating demand and its participation actively. [28], [29].

These axes are economic, social, environmental, technical, and regulatory [9]. The authors [30]–[32] agree that dynamic transformation impacts the axes mentioned above by moving from a hierarchical system to a dynamic system and mostly participatory with the end user. The prosumer and the transactive distribution system directly relate to decarbonization and decentralization. The first aspect is directly related to climate change and how the assessment scenarios should mark a roadmap that evaluates the environmental implications of the transition.

In decentralization, the technical-regulatory scenario must be evaluated, the latter being an exogenous variable to the transition. Distributed generation, as an element of the DERs, gives the distribution system flexibility and contributes to the de-verticalization of the system. Exogenous variables, such as external factors or environmental influences, are outside the system's control. On the other hand, endogenous variables are those that can be influenced and modified by actions and decisions made within the same system.

Identifying these exogenous and endogenous variables allows for establishing clear criteria regarding the relevance of their integration in the proposed scenarios, which means that those variables that have a more significant impact on the electricity distribution system and the achievement of the objectives set can be evaluated and prioritized. When considering these variables, their influence on aspects such as electricity demand, power generation, grid infrastructure, prices, and other relevant factors can be considered, providing a solid basis for informed and strategic decision-making in planning and managing the electrical distribution system.

System dynamics and metaheuristic techniques are integrated into a hybrid methodology, effectively evaluating the behavior of variables over time. System dynamics provides a structured and visual approach to modeling and simulating complex scenarios, while metaheuristic techniques offer powerful tools for analyzing and optimizing solutions to highly complex problems.

From an electrical integration standpoint, policies and regulations affect decentralization, as they are directly related to distributed generation and associated technical variables such as dispatch and self-generation power limits. While a relationship exists between distributed generation and Demand Management (DM) techniques, a bridge between these concepts and distribution systems is defined. When digitally transforming a distribution system, DM techniques must be employed to track demand and optimize end-user processes.

The criteria for constructing and defining the causal diagram stem from analyzing variables that impact the evolution of the distribution system. Firstly, it is crucial to consider the 3D as a direct set of influences on the distribution system, where each dimension is singled out for independent definition. For instance, decarbonization is defined through distributed generation, impacting quality of life and climate change.

The method to build the causal diagram involves differentiation and characterizing each variable that impacts each 3D.

Combining both methodologies makes capturing the dynamics and interactions between variables possible while using intelligent search techniques and heuristics to find optimal or near-optimal solutions in real-time. This hybrid methodology is instrumental in strategic decision-making and long-term planning, as it allows understanding and anticipating the impact of different variables over time, thus optimizing the results obtained. The proposed scenarios are shown below.

4. Proposed scenarios

The proposed scenarios aim to provide an evaluation sheet regarding the insertion of MH techniques and the evolution of the concept of the transactive system within the distribution system. To define the type of scenario, it is necessary to consider analyses that evaluate the employed metaheuristic models, the considerations in terms of quality, reliability, and security, and the integration index of Distributed Energy Resources (DERs). The following scenarios are defined:

-*Foundations scenario*
-*Management scenario*
-*Integration scenario*

Figure 3 displays the characteristics that define the proposed scenarios. We apply the framework of evaluation stages to the distribution system to define the scenarios. The system needs prior characterization to identify its components.

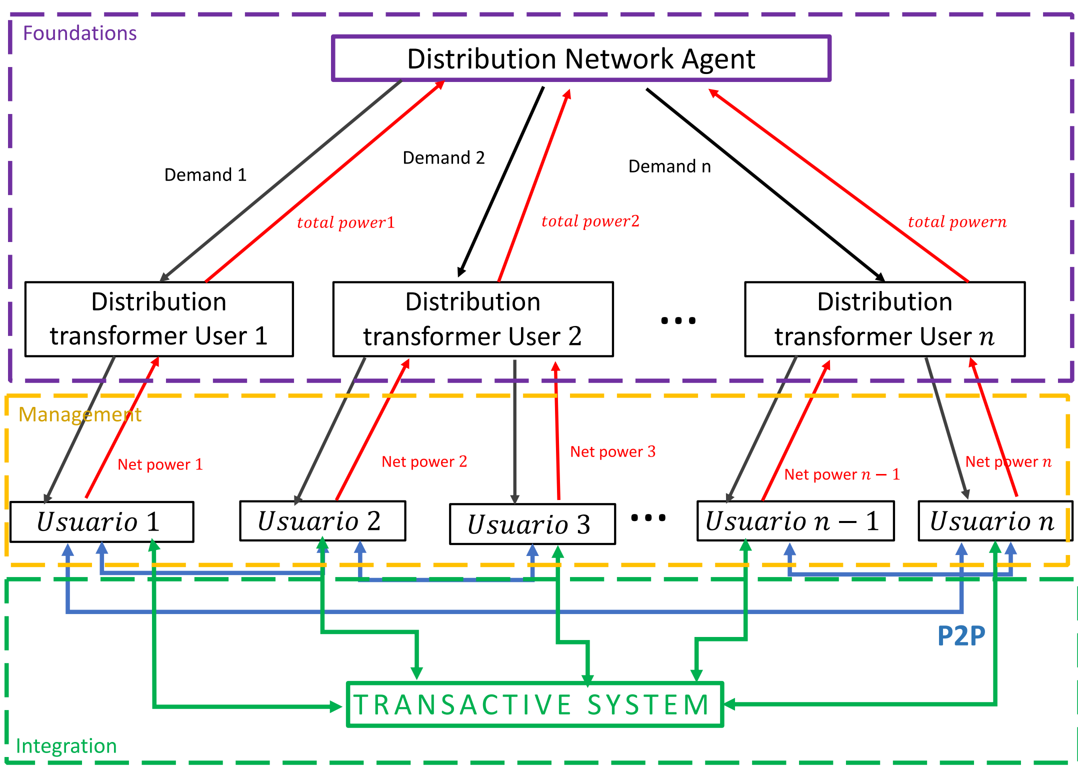

Figure 3. Proposed evaluation scenarios. Source: authors.

According to Figure 3, participants' characteristics must align with those of the agents within the distribution system. Consequently, we must define a computer agent for controlling and registering each participant. An agent is a computer system that relies on autonomous hardware or software, responds to changes, and interacts with other agents. In this initial stage, we must evaluate the metaheuristic techniques and the machine learning (ML) and deep learning (DL) models employed to define control and interaction. The network nodes for connecting clients to the network are preliminarily defined within the distribution system. In order to define scenarios, it is necessary to evaluate whether customers have an energy management system that would facilitate communication with other customers and a network synergy. This implementation of three scenarios aims to characterize and transform the network; according to the application of each scenario, it evolves faster to a transactive system, considering many customers with different behaviors, P2P transactions, P2C, and technical network limitations.

The first scenario, *foundations*, is dedicated to the balancing characteristics of the grid, maintaining restrictions on the flow of energy while minimizing its cost. The scenario must have some tools and assets, including recording power purchase transactions to the upstream grid, sending dynamic demand signals, or using your storage. The advantage of this scenario is that only energy injected into each network node is needed as input to develop the dynamics.

For the second scenario, *management*, it is necessary to know the details of each client's behavior to forecast the generation pattern (if any) and demand. A decentralized and dynamic distribution system is already in place for this scenario. In the previous scenario, there are several challenges to consider:

-Next day purchased energy or future transaction
-Status of the energy management system
-Status of the demand for the next 24 hours.

The objective of the second scenario is the modeling of customers, the relationship with the network, and the forecast quantification of the demand of each one. This scenario can be synthesized in an optimization-quantification-prediction stage to obtain the minimum cost of energy traded from and to the external grid. To do this, customers decide between buying electricity from the grid, using their generation on-site if available, or participating in P2P transactions to meet their energy demand.

In the third stage, *integration*, customers decide between buying electricity from the grid, using their generation if available, or engaging in P2P transactions to meet their energy demand. All decisions are made based on demand schedules and network preferences. The central problem revolves around optimizing each client to determine whether it is already prosumer that particular bidirectional dynamics between agents, eliminating the possibility of network restrictions and evaluation of currents in each node.

The main difference lies in the integration scenario, which establishes a peer-to-peer (P2P) communication network with real-time transactions. The explanation of stages involving optimization, quantification, and prediction in both the "management" and "integration" scenarios remains consistent. Clients are tasked with deciding whether to buy, produce, or sell energy. This fundamental principle applies to both scenarios.

Despite the apparent objective similarities, the integration scenario introduces a pivotal advancement in communication and interaction. Specifically, an operational P2P communication framework exists in the integration scenario where real-time energy transactions occur. This level of immediate interaction among participants transforms the dynamics of decision-making. Unlike the "management" scenario, the "integration" scenario leverages this P2P communication architecture to facilitate seamless and instant energy exchanges and transactions. This transformative aspect of real-time communication is the key factor that differentiates the two scenarios.

5. Case study.

For the case study, define a distribution system with various energy generation sources. They characterize the demand of this system in a manner that aims to achieve an economic dispatch of units for minimizing generation costs. This dispatch considers the necessity to satisfy demand, technical, geographical, and generator-specific constraints. These constraints stem from diverse generation sources, including solar, wind, hydropower, and fossil fuels.

In the context of an isolated distribution system operating as a microgrid, the focus centers on economic dispatch. This process aims to minimize costs stemming from various energy sources at play. Active participation in the demand and the contribution from small-scale self-generators are essential components.

According to the above, the initial problem is to find the power Ec. 1, which each generator must produce to meet, f_{tot} is the total dispatch function, and f_i Is each of the functions that describe the energy sources to be dispatched:

$$\min f_{tot}(p) = \sum_{1=1}^{6} f_i(p_i) \quad (1)$$

$$s.t. \sum_{i=1}^{6} p_i = P_d{}^{\circ} \quad (2)$$

$$P_{\min_i i} \leq p_i \leq P_{max} \; para \; i = 1, \ldots, 6 \quad (3)$$

Each of the shipped powers, the $p_1, p_2, \ldots, p_n$cost functions for the $i - esimo$ GD and the whole system, P_d is the total user demand, as shown by Eq 3. The maximum operating ranges allowed for each unit. P_{min} y P_{max}. The function that describes the energy cost of dispatch in $\$KWh$ is modeled according to the nature of each.

The parameters of each unit are shown in the following table:

GD	$P_{mini}(kWh)$	$P_{maxi}(kWh)$	Source Energy
GD_1	100	500	Solar
GD_2	82	362	Solar
GD_3	65	315	Wind
GD_4	50	271	Hydropower
GD_5	0	60	Wind
GD_6	20	260	Fossil Fuels

Table 1. Maximum and minimum powers. Source: Authors.

The case study analyzes the dispatch at a particular time of day, and the demand is fixed at a value. $P_d = 1150kWh$.

It is based on a scenario in which the electricity distribution network allows to disconnect normatively to carry out a generation dispatch by a self-generator. However, significant limitations are identified during the analysis, such as storing the different variable sources that the study defines. These limitations directly impact the effective hours of use of the system, which generates restrictions and difficulties in managing the energy generated.

Another aspect that stands out in this case study is that the distribution network is not interconnected. Implies that there is no constant and efficient flow of energy between different points of the network, which can affect the hosting capacity of the network and limit its efficiency.

Based on these findings, the need to improve the hosting capacity of the distribution network arises. It involves considering strategies and solutions to optimize the use of storage batteries, overcome identified limitations, and ensure a more stable and reliable power supply. This case study highlights the importance of analyzing and understanding the behavior of electricity demand in scenarios where the distribution network allows disconnection to make generation dispatches. In addition, it highlights the need to address the limitations associated with storage batteries and improve grid hosting capacity to ensure an efficient and sustainable energy supply.

The characteristics of this distribution system are still classic, with users that are passive-centralized and static demand. However, there are Distributed Generation components and power ranges to optimize demand. The case is analyzed by integrating hybrid MH techniques with optimization such as Particle Swarm Optimization and neural networks (PSO + NN). Figure 4 shows the results of the case study.

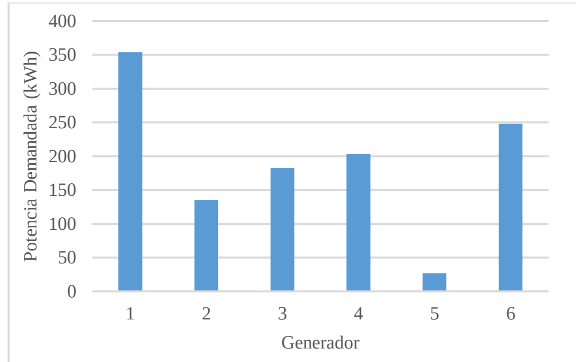

Figure 4. Power of the generator's dispatches. Source: authors.

The foundation scenario is preliminarily evaluated in this case study since there are still restrictions on the type of distribution system. It is still highly verticalized, and there is no total insertion of the prosumer figure within the system since there is no demand management, for example, in addition to monitoring. However, a digitization component represented in the MH model is integrated using hybrid MH techniques to find the optimal dispatch power.

Figure 5 shows the results of the hybrid algorithm PSO + NN. This algorithm is based on heuristics being necessary for the initialization of the system in a candidate population of solutions, which, according to the algorithm, will "move" to the most optimal solution. Each potential solution is called a particle, which has an initial speed and position associated with it.

The use of PSO+NN techniques is relevant in the case study due to the nonlinear nature of the energy sources that are part of the microgrid. Each source has a degree of uncertainty that weakens classical optimization models when finding a solution. Although the preliminary case study sheds light on how data science elements can be integrated into dispatch solutions when dealing with autonomous systems, variable nature sources, and energy dispatch subject to constraint functions.

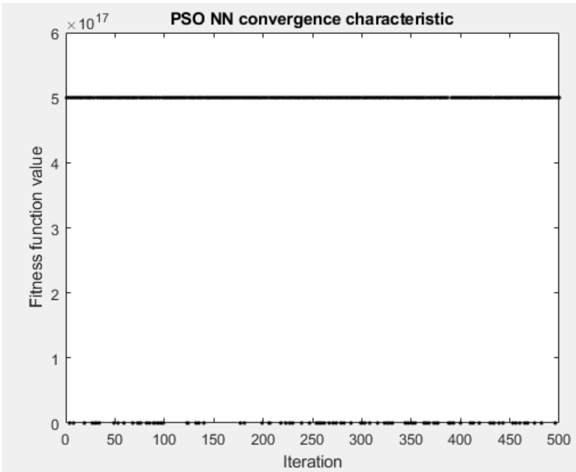

Figure 5. Convergence characteristics of the hybrid algorithm. Source: authors.

According to Figure 5, each particle tracks coordinates determined by the problem space associated with the best value of the objective function. The algorithm takes one step at a time by changing the particle's velocity, where the target function determines its values. As neural networks optimize the step and the best value of the objective function, the *pbest* is the best local value found, and the *gbest* is the best global value found. The acceleration, a parameter associated with the ability of the algorithm to find the optimum in fewer iterations, is determined by a random number that causes the swarm of particles to search in the given space for the optimal solution.

6. Conclusions

This article presents a proposal for integrating active demand into the distribution system. A comprehensive and collaborative vision is presented to address the current and future challenges of the system. The rapid transformation of this system requires technologies that administer, manage, and evolve flexibility, decentralization, and resilience. Variables such as non-conventional renewable energy sources, data science, and new enabling technological infrastructures must be integrated to achieve this, implying a profound distribution system transformation.

Several significant challenges in today's distribution system require attention and practical solutions. These challenges include the need to massify renewable energy sources, overcome dependence on centralized infrastructure, implement multi-track consumption tracking systems, and encourage the participation of prosumer users in the system.

Promoting a comprehensive and collaborative vision that involves all actors, including technological innovation, adequate regulation, and the participation of energy consumers and generators, is necessary. Adopting the transactive system, which allows the integration of renewable energy and a more efficient management of demand, represents a promising alternative for the evolution of the electricity distribution system.

Integrating active demand and using metaheuristic techniques, such as Machine Learning and Deep Learning, are crucial elements in the evolution of the distribution system. These techniques allow the prediction of energy consumption and the planning of the integration of distributed generation. Digitization and enabling technologies, such as infrastructure 4.0, Blockchain, and cloud computing, are necessary to achieve greater efficiency and optimization of the system.

The implementation of the transition to a transactive system should be evaluated considering the specific conditions of each country, avoiding disturbances in the market and the distribution system. It is necessary to consider the delay time needed to integrate the correct elements and analyze the impact through roadmaps and prospective analysis.

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