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Review

Overview on Transactive Energy—Advantages and Challenges for Weak Power Grids

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Abstract: This document lists some challenges that researchers face when implementing transactive energy in weak power grids. These challenges often include high voltage fluctuations, limited generation, high line loadability, and unbalanced grids. The operation of transactive energy, as well as optimization techniques, are also considered, highlighting the performance and functionalities depending on power grid characteristics and market topology. Some of the most used optimization techniques for market clearing, considering the characteristics and topology, are presented as part of the research work.In addition, this paper compares different market topologies and highlights their advantages and challenges. Furthermore, this paper contains a brief description of the interoperability frameworks applied to a smart grid.As a result, it was determined that interoperability is necessary for the proper functioning of the grid. Moreover, all methods were found to be effective for their purpose from the user's point of view as each technique has different characteristics relevant to the user and the grid. It was concluded that it is convenient to combine the optimization techniques to consider different constraints in the market clearing.

Keywords: interoperability; markets topologies; transactive energy; optimization techniques

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1. Introduction

Recently the incorporation of smart grid technologies, distributed energy resources (DER), and smart prosumers, have triggered significant changes in the electricity sector. As a way of adapting to these changes, in recent years, the concept of transactive energy (TE) has emerged, which is defined by the U.S. Department of Energy as follows "a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter" [1]. However, TE is a mechanism to clear the market, i.e., a mechanism that finds an equilibrium price between supply and demand, assuming an ideal power grid. The transactions between the different voltage boundaries and the power flow are depicted in Figure 1. Regardless of the number of energy transactions required, TE can always be achieved without affecting power quality and prosumer generation systems. Applying TE to weak power grids, such as the one in Puerto Rico [2], which is characterized by out-of-range parameters, voltage fluctuations, and unbalanced phases can pose many challenges.

Voltage fluctuation is one of the challenges faced by distribution networks with the inclusion of distributed renewable generators. It can be reflected in voltage rises or drops, causing high variability throughout the entire feeder where the distributed generator is

connected, and, in turn, can lead to phase unbalance. The inclusion of renewable resources also produces low inertia and lower system strength [3–6].

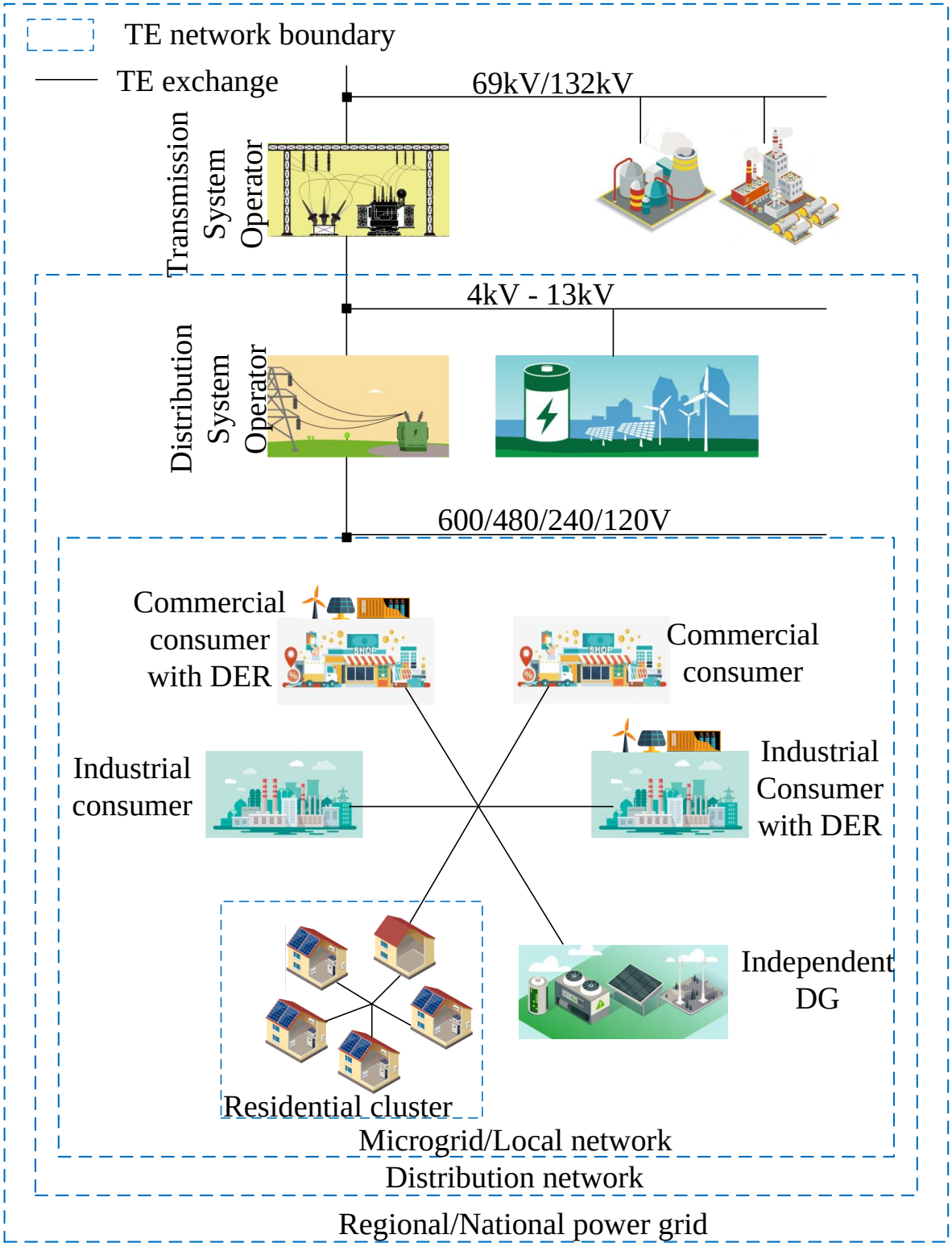


Figure 1. TE with different levels of the power system.

The operation and business models of utilities can be affected by these changes in the way they operate due to distributed generators. The inclusion of the local energy market

can be reflected in the definition of the market topologies that involve the technical and the business requirements for energy sharing considering distributed energy resources [3,7–10].

In addition, due to demand share, the conventional operation of the electric power system with a one-way flow of energy from bulk generation through the transmission system and the distribution system to end-users has also been affected. At the same time, it is switching the one-way flow of information from field equipment and user facilities to the distribution and transmission control system [11]. The new concept of the distribution system operator (DSO) is one of the possible changes that have been emerging. Operating the distribution system reliably and economically is the DSO's responsibility, as is enabling a retail transactional exchange between prosumers [12]. The DSO requires a platform with new applications and user interfaces to perform these tasks efficiently, as well as new implementation metrics, controls, and analytics to operate the distribution system reliably and cost-effectively while developing incentives to maximize benefits and minimize costs for prosumers. Transactional exchange of product information to arrange prosumer investment determinations with operational distribution needs and provide for DER project delivery should also be included as provisions in the platform's capabilities [13]. As a new way to address changes in the distribution system, new market topologies are proposed to help meet the needs of the changes associated with distributed generators [8].

The concept of interoperability is related to smart elements, so some transactive energy research has included the interoperability framework presented by the smart grid reference architecture that includes different operational layers [14,15]. Layer frameworks involve different challenges, such as the component layer, communication, information, business, and optimization function within which different methods are applied. The component layer engaged the site and voltage level where the TE is produced; in this case, it can be in the generation, transmission, distribution, and distribution of energy resources [14,16–19].

To find a balance between energy supply and demand, different operation frameworks have been developed using the concept of transactive energy. It is emphasized that these operation techniques use optimization subject to the constraints and needs of the power grid [8]. Some of the techniques contemplate the search for a balance between the participants, while others divide a complex problem into several simple problems [20,21].

Since research in the field of transactive energy has not addressed the challenges of weak grids, this paper discusses some of them faced by the new emerging market topologies in weak grids, as well as those that must be solved by each of the layers that make up the interoperability framework. In addition, this paper attempts to list some of the optimization techniques used in transactive energy, highlighting their characteristics and objectives.

The remainder of this paper is structured as follows. Section 2 presents and compares the commonly used topology markets in TE. The information layer used in TE is provided in Section 3. Section 4 presents optimization techniques used in TE, and Section 6 present the conclusions of this paper.

2. Transactive Energy Market Topologies

Markets have existed since the inception of the power system. However, the increment of new decentralized energy sources requires a market according to its decentralized generation and consumption. The electricity market complexity arises from the interactions between the different participants and service providers. For this reason, new topologies in the energy market have been proposed to help meet the challenges.

In [8], four architectural markets are described, peer-to-peer (P2P), prosumer-to-interconnected, prosumer-to-island, and organized prosumer groups. In [9], three P2P market structures are proposed, namely the full P2P market, the community-based market, and the hybrid P2P market; whereas [21] presents an overview of two different market structures, the full P2P market and the community-based market. In [10], three market structures are considered: the community-based market, P2P, and hybrid. However, the most commonly used topologies are defined in Sections 2.1–2.3.

2.1. Peer to Peer

The design of this market is based on bilateral negotiations between the seller and buyer of electricity. In a P2P market, negotiations take place to reach agreements on the amount and price of electricity exchange. One of the characteristics that differentiate this market from the classic one is that its structure is decentralized, and exchanges are carried out without intermediaries. In a P2P market, each prosumer is responsible for optimizing its local generation and consumption resources after receiving prices from other prosumers. Local resources may include renewable energy and energy storage devices. This market retains the privacy of prosumers; the only information exchanged is the price [9,10,22]. In Figure 2, the topology of the P2P market is represented, where there is a direct relationship between the prosumers represented by the orange line, and each prosumer represented by an orange circle.

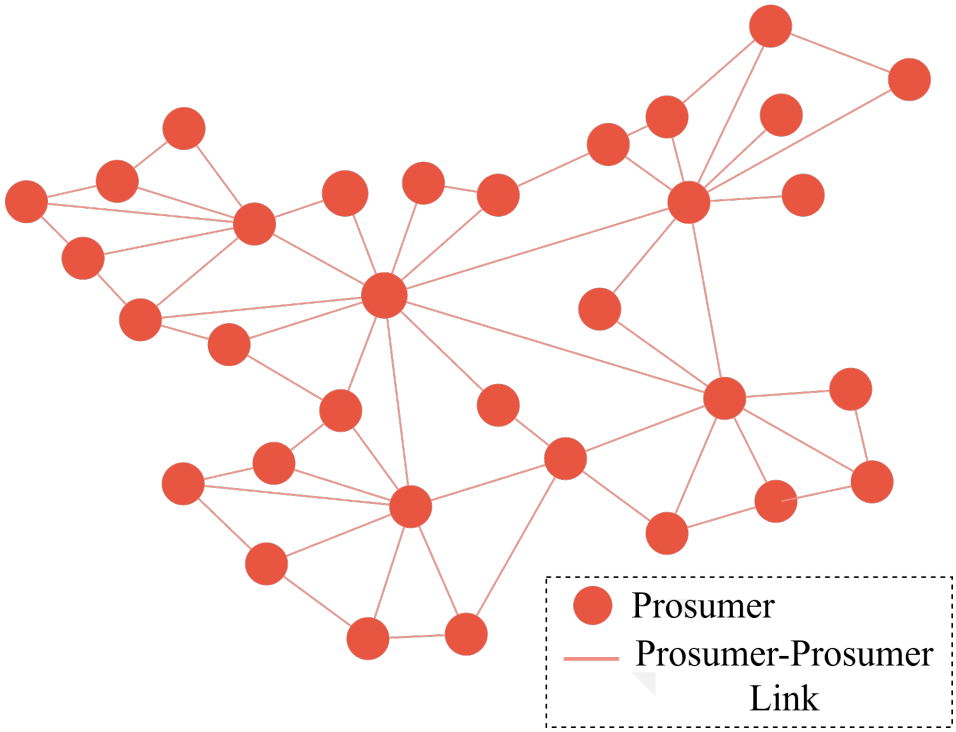


Figure 2. Peer-to-peer topology.

One of the encountered challenges in the P2P market topology of weak power grids is power quality assurance, such as constraints in renewable energy penetration, voltage violations, and thermal limits. The optimization method used does consider these constraints since it is assumed that all transactions are realizable and that the power system will not be affected, which is not valid in a weak system. An additional challenge to be considered in this topology is that the more distant pairs require the construction of additional infrastructure for communication.

2.2. Community-Based Market Topology

In this market, an operator is needed to coordinate electricity trading between buyers and sellers. Each prosumer communicates with the administrator, but there is no communication or exchange of commercial information between prosumers. The market operator collects demand and supply bids to clear the market. This type of market is helpful in nearby communities with similar interests, where trade can develop cooperatively and competitively [9,10,22]. Some of the characteristics of community-based market topology include community resilience and improved relationships among community members. However, there are also some challenges, such as the type of energy generation preferred

by the community and the difficulty of implementation. The representation of this topology is shown in Figure 3.

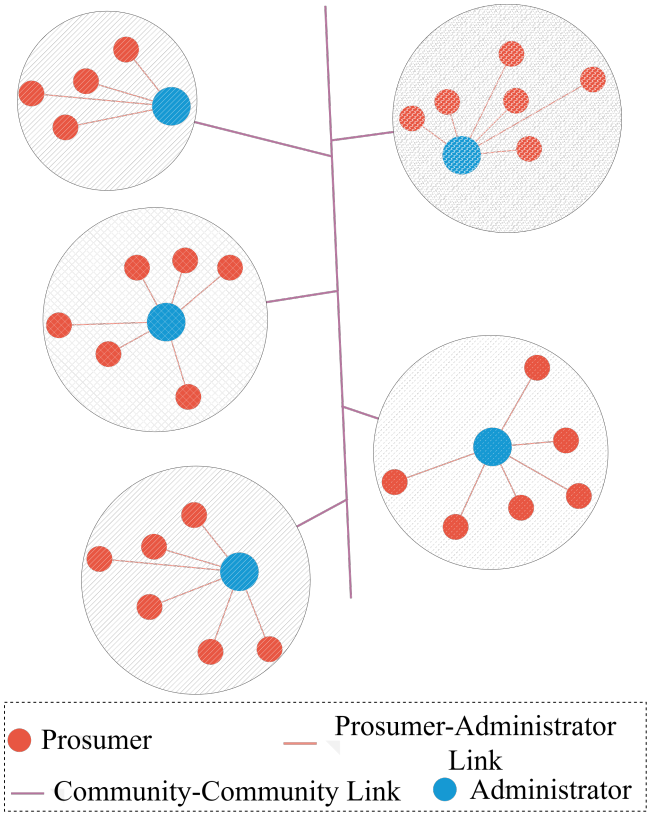


Figure 3. Community-based market topology.

From the weak grid point of view, the same challenges mentioned in the P2P topology are encountered. This is because the overall objective of the method is to clear the market with the cheapest option, but power quality constraints are not considered. However, there are other challenges, such as processing a large amount of data, and community energy preferences. These challenges can be solved through the use of smart meter monitoring and installation, in order to keep track of the additional constraints that must be considered in weak grids. The information provided in this type of topology can be used to the benefit of networks with these characteristics when implementing this type of market.

2.3. Hybrid Market

This market is a combination of P2P and community-based markets. This market offers the best of both topologies. In addition, it provides advantages such as improved scalability. This market is characterized by its hierarchical structure. Typically, at the top level is the P2P energy exchange and at the other level is community-based energy exchange [9,10,22]. The representation of this topology is shown in Figure 4.

Table 1 summarizes the topology markets defined so far, highlighting their benefits and challenges.

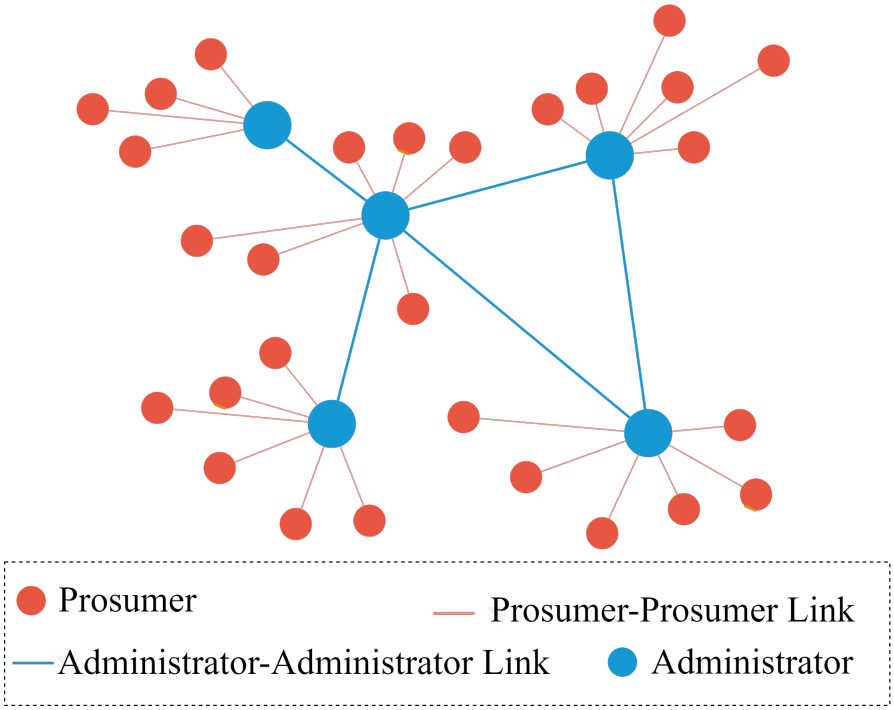


Figure 4. Hybrid market topology.

Table 1. Comparison between topology markets.

Market Topology	Benefits	Challenges
Peer-to-peer, P2P, Full P2P [8–10,21]	• Freedom of choice, active consumers. • Democratization of energy use. • No interaction with the third party.	• High cost of building and maintaining a distributed network. • Accountability assurance for high-quality energy service. • Slow convergence to obtain a consensus.
Organized prosumer groups, Community-based market [8–10,21]	• Enhancing the relationship between community members. • Resilience in Community. • New services for the grid operator.	• Processing of a large amount of data. • The high transaction cost of managing, optimizing, and balancing the group. • Preferences of energy use for the entire community. • Unbiased energy sharing among the community. • Difficult implementation and not easy to expand.
Prosumer-to-interconnected, hybrid P2P, hybrid [8–10]	• The computational effort is scalable. • Co-exist designs with centralized structures. • Predictable to grid operators.	• Coordinate low-level trades with high-level agents.

3. Interoperability Layer

TE is classified as a smart grid as it contains different smart elements, such as grid operators, smart meters, smart substations, integrated communication, and phasor measurement units. These elements must operate through communication modules between their main components and their relationship. Therefore, it must include an architecture that considers and complies with interoperability, defined as the ability to exchange information between two or more devices from the same vendor. The interoperability categories suggested in the smart grid reference architecture are depicted in Figure 5 [15].

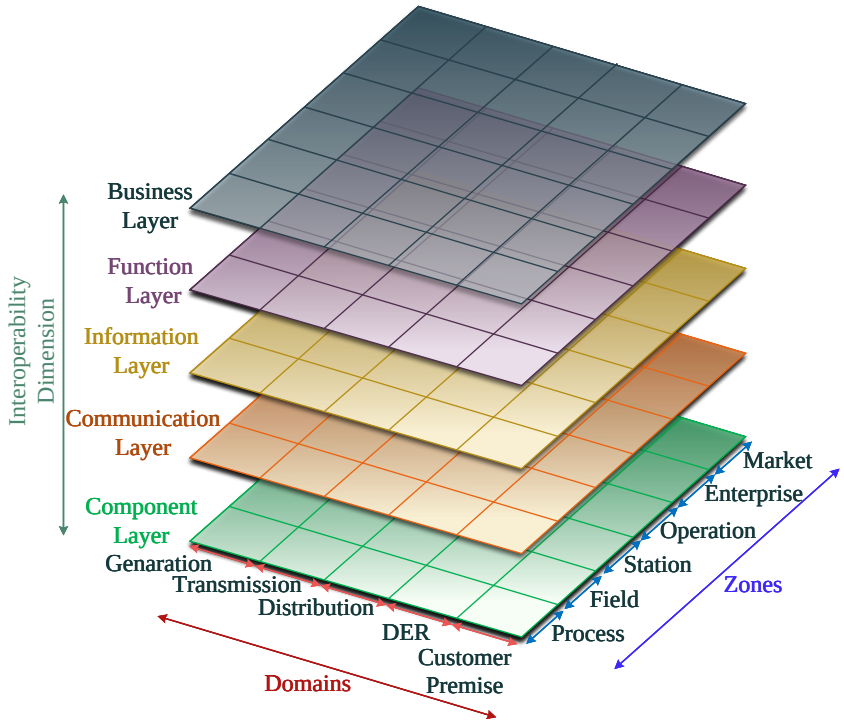


Figure 5. Interoperability Layers.

3.1. Business Layer

The business layer represents the business vision that relates to the exchange of information that occurs in smart grids. To ensure a level playing field for all market participants, smart grid architecture models are used to find economic and political regulatory structures. This layer also considers business capabilities and processes to create a methodological structure that ensures the smooth functioning of the market, which must develop consistently and coherently regardless of the nature of the business.

One of the challenges encountered in this section is the lack of regulation for transactive energy, requiring additional considerations, such as privacy and data management.

3.2. Function Layer

The functions layer describes the functions and services and their commonalities from an architectural viewpoint. The functions vary according to the nature of the case, which is independent of the actors. They should consistently be implemented regardless of the applications of the physical implementations, systems, and components. Section 4 describes some common methods employed to carry out TE.

One of the challenges encountered in the functions layer is the availability of the different existing methods to clear the market, which depends on the type of topology selected for the distributed generators. This is because each topology has other characteristics, which must be considered at the time of the functions to be clear about the functions and services they will provide.

3.3. Information Layer

Describing the mechanisms and protocols for the interoperable exchange of information between components is the objective of the communication layer. It contains classical information and data models representing the semantics with which information can be represented and described to enable information exchange.

From the TE point of view, a challenge encountered in this layer is selecting the type of information to be shared, considering privacy, and information use. For example, in any

market topologies, the only information required is the amount of energy and the cost to be paid for that energy.

3.4. Communication Layer

The objective of the communication layer is to describe the protocols and mechanisms for the interoperable exchange of information between components.

The Smart Grid Coordination Group of CEN, CENLEC, and ETSI published the document smart grid Reference Architecture [15]. This document proposes the SGAM model and presents a communication standard for a smart grid.

The standard makes some recommendations for implementing a communication system for smart grids.

- The smart grid must manage the quality-of-service (QoS), reliability, and security requirements, applying current communication standards.
- A technical document must be written with the service level of availability, resilience, and denial-of-service (DoS) in the communication service.
- The communication technologies applicable to different sub-networks on the communications architecture must be defined.

Many communication protocols are included in the standard. Reference [15] presents the interception of domains, zones, and sub-networks. Sub-networks cover several domains and zones. For example, the Industrial Field-bus Network includes Generation and DER domains, as well as Station, Field, and Process zones. Likewise, [15], for the Industrial Field-bus Network, suggests the IEEE 802.3/1 standard [23], the Ethernet standard.

The protocols are represented in Figure 6 and Table 2. Figure 6 shows the intersections between domains and zones by means of an ellipse. Each intersection is represented by capital letters of different colors, each color representing a different sub-network. Table 2 lists the different sub-networks present at the intersection. The sub-networks are recommended in [15] as an example but are not normative for all business types.

The biggest challenge in this section lies in full compliance with standards protocols and requirements according to the interoperability domain where the transactive energy is to be implemented. The intersection between domains and zones must be considered to ensure the right communication.

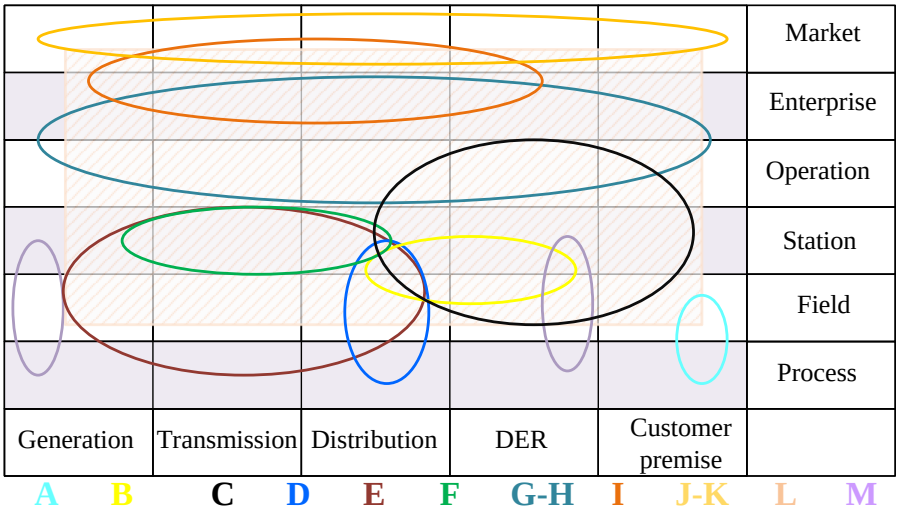


Figure 6. Communication Network mapping.

Table 2. Subnetwork list.

Intersection	Subnetwork Name
A	Subscriber
B	Neighborhood
C	Field Area
D	Low-end intra-substation
E	Intra-substation
F	Inter-substation
G	Intra-Control Center
H	Enterprise
I	Balancing
J	Interchange
K	Trans-Regional
L	Wide and Metropolitan Area
M	Industrial Fieldbus Area

3.5. Component Layer

The objective of the component layer is to physically distribute the components that integrate and intervene in the smart grid. Components include system actors, applications, power system equipment, protection, control devices, network infrastructure, and computers. Similar to the previous dimension, the challenge for the component layer lies in knowing the scope in which the transactive energy will operate to select and put into operation each of the necessary devices or components, i.e., use the essential components in each zone, e.g., the circuit breaker in process components, protection relay, and gateway in field components.

4. Optimization Techniques in TE

This section describes some of the most commonly used optimization techniques used in TE. It also gives a brief description of their mode of operation. The techniques mentioned fulfilling the objective of clearing the market and finding a balance between supply and demand. These techniques vary depending on the specific topology of the market, the behavior of prosumers/agents, and the particular rules of each topology. These techniques can be used separately or together to obtain better results depending on the desired objective [8].

4.1. Game Theory

Game theory can be used as an effective tool to intervene in the decisions of various actors in energy trading. Some of the main actors are consumers, generators, or companies whose main objective is to maximize profits, but often, some complications arise [20].

For that reason, the game theory allows an approach to formulate problems related to energy trading. A game comprises essential elements: the strategies, the players, and the benefits. Some of the most commonly used games include:

- *Cooperative games*: These games focus on mutual agreements between the players, that is, they are all in Nash equilibrium. Therefore, no player or alliance can have any advantage over the others [24]. Cooperative games have contributed to implementing energy trading mechanisms using blockchain [25].
- *Non-cooperative games*: These games study the optimization process in each participant's decision to maximize their interests, without any communication or coordination in the actions of the players involved. They can be divided into static and dynamic games. They are used as a strategy in the pricing of electricity by the time of use [26].
- *Evolutionary Game*: These games consist of a large number of players who repeatedly play a particular game against each other, to find the best strategy based on their opponent's past behavior. They are used to model transactions between private companies and citizens where many unknown factors exist [27].

Table 3 shows some of the applications of the game theoretic optimization technique, presenting the applications of the games described in this paper.

Table 3. General applications using game theory.

Game Method	Features	Application	Refs.
Cooperative	Mutual agreements between players, looking for Nash equilibrium	Generating companies, load serving entity, demand response providers.	[28] [24] [25]
Non-cooperative	Each player decides based on their interest without coordination with others	Trading electricity market with hybrid electric vehicles and batteries	[26] [28]
Evolutionary	Repetitive games to find the best strategy	Stability analysis of electricity markets, Power suppliers, consumers	[20] [28]

4.2. Decomposition-Lagrange and Karush–Kuhn–Tucker Methods

The Decomposition Method divides a complex optimization problem into multiple simple optimization problems [21].

The Karush–Kuhn–Tucker (KKT) optimization method is one of the most used in the decomposition method. In [29–31], the KKT method is used to reduce a bilevel problem into easier problems by optimizing cost. Cost optimization searches for the best prosumer profit. A simple representation of the KKT method is shown in Figure 7.

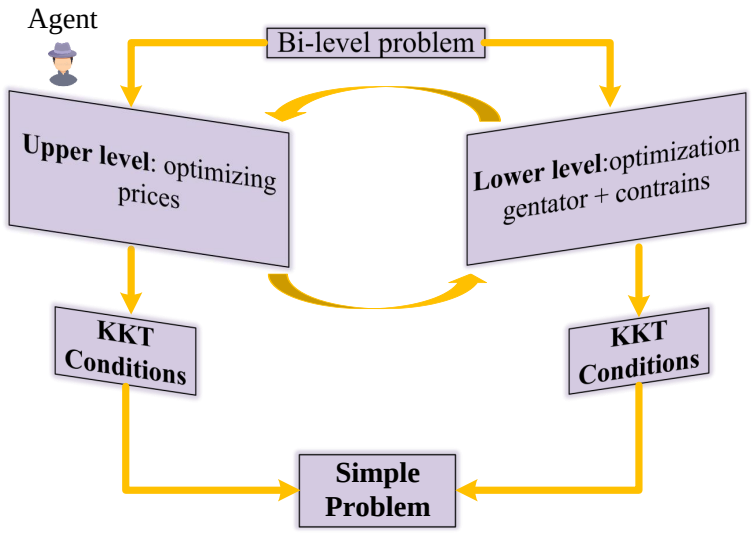


Figure 7. KKT Representation.

Multiple energy management strategies in smart communities are proposed in [29] through a TE framework. In the paper, they develop a solution to a bilevel optimization problem. At the upper level, there is an energy hub responsible for optimizing prices, which in turn are fed back to each of the distributed generators in the system, located at the lower level. At the lower level, optimization is performed for each generator subject to constraints. To transform into a mixed integer linear programming problem, the bilevel optimization model proposed, and KKT conditions are used. The optimization performed at a low level is reformulated using the KKT conditions. The reformulation is performed for each of the DGs, i.e., an objective function is formulated for each DG subject to equality and inequality constraints. Using a case study, the authors demonstrate that the result obtained in the decentralized optimization problem with respect to cost is the same compared to a centralized optimization problem. Thus, it is shown that internal behaviors (DGS) are considered, but the intervention of external control is unnecessary.

Similar to the work performed in [29], the authors of [30] propose an equilibrium framework to model P2P energy transactions at multiple nodes of the power system. The

main difference to [29] is that the framework presented in [30] considers transactions between peers and the grid, in which the cost functions and constraints are approached from KKT. This provides the possibility for the prosumer to perform the energy transaction at the lowest cost. The authors perform a case study with a 6-bus radial power system. A comparison is made between the presence and absence of P2P power sharing. It was found that the optimization and the break-even point satisfying the cost functions of consumers and prosumers were more profitable for both market participants when peer-to-peer power exchanges occurred.

Similarly, the authors in [31] propose an arbitrage strategy of renewable-based MGs via P2P energy trading, where they use KKT conditions to solve a two-level optimization. Where this optimization is a stage of general optimization, which is divided into three stages. The first stage is a stochastic schedule to calculate prices against a day-ahead generation scenario. The second stage is a bi-level optimization for TE. In the third stage, real-time interval optimization is performed. In the next stage, the equations for each stage are presented, considering cost functions and their constraints. Then, the reformulation is carried out using the KKT conditions, which allows for solving the optimization problem, at a single level. For the validation of the proposal, a modified 33-node system with different distributed generators was used. From the proposal, the authors obtained a good performance, with lower standard deviations compared to previous works. In addition, it proposes a useful arbitrary strategy when using renewable resources with high variability. It allows the selection of the available and least-cost resource according to the consumers' needs.

4.3. Networked Optimization

Like KKT, networked optimization is a special kind of decomposition technique related to graph theory [21].

In [32–34] the authors discuss a method named Graph Based Loss Allocation Method (GBLA) to determine the optimal P2P transaction, focusing on minimizing the losses that originated during the energy's trajectory. Networked optimization is depicted in Figure 8 [35].

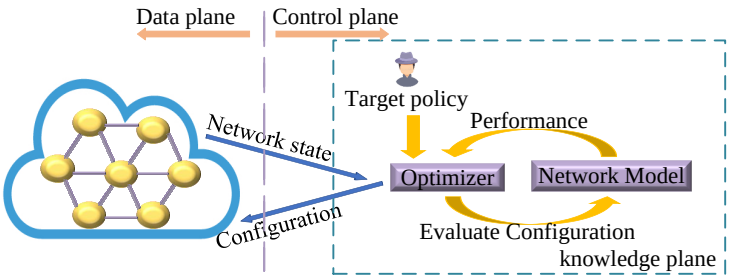


Figure 8. Networked architecture [35].

In [32], the authors present the description of the loss allocation under three different scenarios. Through loss allocation, the method aims to generate traceability for energy transactions. This is performed by allocating losses equally among all participants during the TE performance. The scenarios included (1) no distributed generators, (2) distributed generation units, and (3) distributed generators with load unbalance between phases and neutral. For each of the scenarios, assumptions were made regarding the distribution system. For example, for the first case, a single-phase distribution system is considered, which can be extrapolated assuming it is balanced. The three cases share the representation by more detailed graphs, separated by individual phase layers. The other two cases consider an unbalanced system, which, when performing the tests according to the proposed method, may lead to errors, due to the amount of energy flowing through the neutral in unbalanced systems. In addition, researchers found that the method with graphs had higher accuracy than the branch current decomposition-based loss allocation method.

In [33], the authors compare the performance of two-loss allocation methods. Two critical factors were considered, the nodal demand and the set of lines for the energy path from the slack node to the demanded node. For the first case, a converging power flow is used. The losses are allocated as a function of the node and the use of the lines from the slack node to the demanded node, for which the graphical representation is advantageous. Case number two uses the results of the converged power flow of the network. Losses are allocated to each participant based on each node's power and voltage levels. Comparing the two methods for a case study of a 33-bus single-phase balanced system without distributed generators, it is found that method number two is more efficient. By considering real-time measurements, losses accurately.

Similar to [32,33], ref. [35], proposes a loss allocation framework. Researchers performed a case analysis for energy transactions with peer-to-peer market topology and energy communities. An unbalanced system was used for the analysis, in addition to separating the phases using layers, one layer for each phase and another for the neutral. Achieving the representation through graphs. Through this framework, it is possible to obtain accurate data for loss allocation. This proposed method provides more accurate data when transactions are performed between nodes (P2P) of different phases (layers). This generates an advantage when performing energy transactions in unbalanced systems.

4.4. Agent-Based Optimization Method

The objective of the agent-based method is to model dynamics in the electricity market. Agent-based techniques are characterized by being scalable, adaptable, and capable of modeling the dynamic interaction between market participants such as agents. The agents interact with other agents and this interaction is carried out until an equilibrium point is found based on the decisions of each agent [17,18,21,36]. Figure 9 presents the sequence of steps for agent-based modeling.

To assess grid overloading and cost optimization of buildings in a residential neighborhood. The TE management framework is presented in [17]. The authors also emphasize that TE was used for grid power balancing by developing an electric power management system for residential buildings, which enables consumers the utility to participate in the local transactional market. TE involves different agents in the transaction to minimize the energy cost while maintaining the desired comfort level in the building and satisfying the operational constraints of the devices as the primary objective function.

On the other hand, the authors in [18] propose a system architecture that integrates blockchain tools to perform energy transactions between buyers and sellers. With the use of the blockchain, no third-party intervention is required for P2P energy trading. The blockchain tool uses a smart contract to perform the transactions by calculating the market equilibrium price and quantity of the respective market intervals using double action.

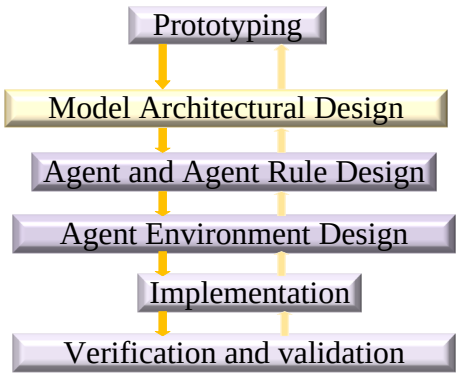


Figure 9. Agent-based modeling, this figure was recreated from [17].

4.5. Blockchain as a Technology Application in Transactive Energy

Blockchain technology is defined as a computer program that allows a single transfer of values; these values can have different characteristics or types, such as contracts, money, and property. There are several types of blockchain implementation, including the classic one that requires a verification process that requires more time and computational effort. On the other hand, there is the blockchain through smart contracts that are generally used for financial applications. A smart contract allows a verification and trusted transaction to be performed through a computer protocol [37]. There are different protocols and guidelines for developing a smart contract to carry out a TE, such as [38] developed by the Pacific Northwest National Laboratory in collaboration with the U.S. Department of Energy. In this report, the details and main components of the stages of a transactive energy system are articulated. This report also includes blockchain features and the relationship between those requirements and elements. It also discusses data security, resilience, decentralization, and the reliability of smart contracts, performance, etc.

Figure 10 illustrates the implementation of blockchain technology in TE. The highlighted components at the top of the figure are presented. Furthermore, a timeline is included at the bottom, outlining the usage of blockchain in TE and the sequential steps required to complete a transaction.

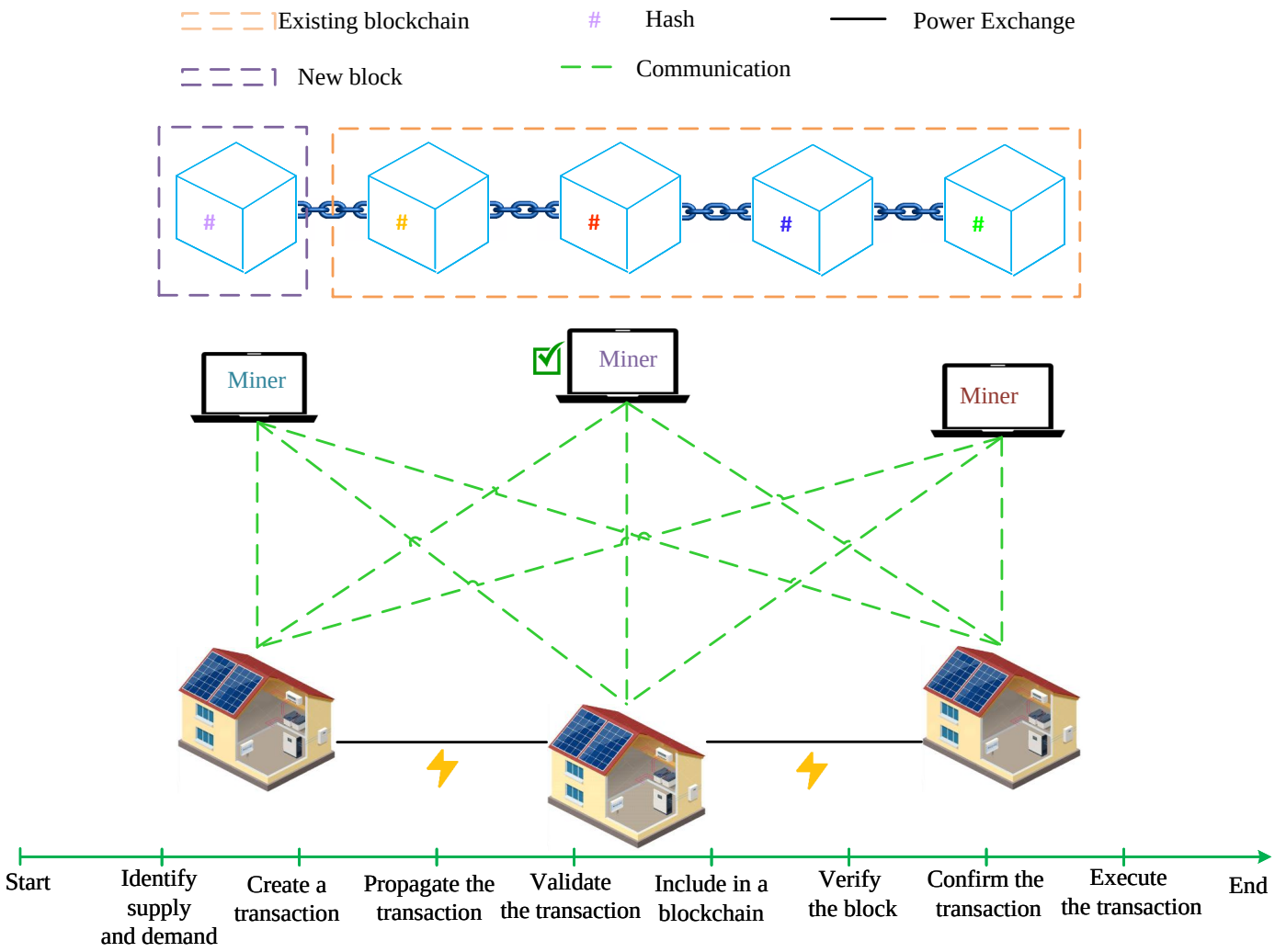


Figure 10. Blockchain applied in TE.

To understand the steps involved in executing a TE using blockchain, two key concepts need to be clarified: miner and hash.

Miner: A participant in the blockchain network responsible for validating and confirming transactions. Miners use computational power to solve complex cryptographic puzzles, such as proof of work, to add new blocks to the blockchain. They ensure the network's security and integrity by verifying transactions and preventing double-spending [39].

Hash: A mathematical function that converts data of any size into a fixed-size alphanumeric string. In the blockchain, hashes are extensively used to represent blocks, transactions, and data. They ensure data integrity and security, as even a small change in the input data results in a significantly different output hash [39,40].

The detailed steps are as follows:

- Identify supply and demand: Participants within the network identify their energy supply and demand requirements.
- Create a transaction: A participant generates a transaction, specifying the desired amount of energy and relevant details.
- Propagate the transaction: The transaction is broadcasted across the blockchain network, reaching participating nodes and miners.
- Validate the transaction: Miners verify the transaction's legitimacy by confirming the sender's adequate funds and ensuring the offer meets the required criteria.
- Include in a block: Once validated, the transaction is grouped with other transactions into a block.
- Verify the block: Miners compete to solve a cryptographic challenge (proof of work) for the opportunity to add the block to the existing blockchain.
- Confirm the transaction: As additional blocks are appended to the blockchain, the transaction becomes confirmed and nearly irreversible. The number of confirmations required may vary.
- Execute the transaction: Once confirmed, the energy transaction is executed, involving the physical transfer of energy, adjustments to the supply, or financial transactions based on predefined smart contract agreements.

Blockchain technology is employed by TE to provide flexibility, demand response, automatic execution, and privacy protection. It highlights features such as a consensus mechanism and encryption algorithms, where smart contracts and decentralized storage can be applied [22,41]. Blockchain technology can operate decentralized, where each of the blocks that make up the chain has the same information, making the process very reliable. Similarly, in [42], the authors present the reasons to use blockchain in TE, such as providing a distributed and secure data storage mechanism that cannot be modified retroactively, supporting the open transaction environment used, and improving the reliability of transactions. Hence, this leads the authors to propose a smart contract and architecture to solve these challenges using blockchain.

An alternative architecture system is proposed in [18], where a tool is proposed, which uses a smart contract to carry out transactions by calculating the market-clearing price and quantity of the respective market intervals.

In [43], the authors find that some challenges in the blockchain are unsatisfactory speed and scalability, given that they are mostly managed with smart contracts and the only way to modify them is to create a new contract. Blockchain challenges are the lack of regulatory policies and the absence of privacy protection. However, it is critical to remember that a blockchain is an unnecessary tool when you have a reliable central authority and no abuse of power [43].

Each of these techniques has the objective of clearing the market. In addition, they offer characteristic and unique services presented in Table 4.

Table 4. Features and applications of optimization techniques.

Optimization Technique	Market Topology 1	2	3	Features/Characteristic Application
Game Theory	✓	✓	✓	• Includes demand response feature • Models trading electricity market • Enables the stability analysis
Decomposition-KKT	✓			• Model power-sharing with the power grid
Networked optimization	✓	✓	✓	• Obtains accurate results in unbalanced systems • Uses graph theory • Allows allocation feature
Agent-based optimization technique		✓		• Power balancing • Smart contract for TE using Blockchain
Blockchain application	✓	✓	✓	• Added value of the security • Flexibility, demand response • Smart contract

1: P2P, 2: Community-based market, and 3: Hybrid market.

5. Summary and Final Discussions

The widespread DER deployment in weak power grids, along with the adoption of transactive energy strategies, significantly affects grid performance. Throughout this paper, various challenges have been mentioned. One of the encountered issues in the implementation of market topology in weak power grids is the assurance of power quality. In a study conducted in [3], challenges related to power quality in implementing local energy markets in the distribution system are described. Some of them are voltage variations, phase imbalance, and increased complexity of control, all of which negatively affect the proper operation of the system. These challenges have a greater impact on networks with low capacity to respond to changes, particularly in weak grids.

DERs in weak grids can lead to significant voltage variations, exceeding the specified voltage ranges (typically 0.9 to 1.1 p.u) [4,6]. This issue can be effectively addressed through the implementation of a transactive energy framework. By facilitating multiple transactions simultaneously based on the strategies of prosumers and the market topology this framework enables better management of voltage fluctuations. This problem can be managed by including power flow equations and voltage constraints in the optimization model. Furthermore, the implementation of voltage controllers can play a vital role in regulating and curtailing specific transactions.

Moreover, the majority of research conducted on the integration of local energy markets focuses on the assumption of balanced phases. However, it is important to consider that an imbalance between phases in the network can result in increased voltage rises and losses. In [3], the potential advantages of local markets are highlighted, such as improved efficiency in grid utilization by reducing the need for exchanges between the local market network and the main grid in a specific local area. This is achieved through the local balance of energy supply and demand. Although, it is crucial to notice that the implementation of local markets may also introduce challenges within the distribution network.

Related to information and communication technologies, an additional detected challenge is the need for reliable communication and data management infrastructure to implement the TE topologies. The inclusion of advanced grid infrastructures (AGI) will improve the monitoring of events in weak grids by integrating advanced measurements, applications, and capabilities. As a result, efficiently managing substantial volumes of technical data, along with integrating socio-economic considerations such as community energy preferences, will require the implementation of advanced methods such as big data analytics and intelligent decision-making.

Within the business layer, a notable challenge arises from the absence of regulations surrounding transactive energy. This calls for additional considerations, particularly in the areas of privacy and data management. One of the prominent challenges revolves around

the absence of regulations pertaining to TE. Consequently, this situation calls for additional considerations, including privacy and data management.

The function layer encounters a notable challenge in terms of the availability of various methods for market clearing, which is contingent upon the selection of the appropriate topology for the distributed generators. Each topology possesses unique characteristics that must be thoroughly considered when determining the specific functions, roles, and services they will provide.

Finally, the comparison of different optimization techniques for market topology highlights the distinct purposes and applicability of each technique. The choice of technique is contingent upon the specific goals, constraints, and characteristics of the market topology under consideration. It is important to acknowledge that each optimization technique possesses its own strengths and areas of application. However, it is crucial to recognize that the optimization method employed in this context may not adequately address the challenges posed by weak power systems. Weak grids present unique obstacles that must be carefully addressed to ensure the reliability and stability of the system.

One key aspect in addressing these challenges is the implementation of smart meter monitoring and installation. Smart meters enable continuous monitoring of electricity consumption, generation, and other critical parameters at the consumer level. By collecting and analyzing this granular data, network operators and market participants gain a deeper understanding of the constraints and limitations specific to weak grids.

By leveraging smart meter data, market operators can better comprehend the intricacies of weak grids and incorporate these constraints into the optimization process. This allows for more accurate modeling and forecasting of power flows, voltage levels, and potential system bottlenecks. As a result, market participants can make informed decisions regarding energy transactions, taking into account the specific limitations of the weak grid they are operating in. Furthermore, the utilization of smart meter data facilitates the identification of potential areas for infrastructure improvements. It helps pinpoint regions within the grid that require targeted investments in transmission or distribution infrastructure to enhance system resilience and capacity.

In weak grids, the power system's stability and voltage profile can be highly susceptible to fluctuations caused by variations in demand and intermittent renewable energy sources. Unlike strong and robust grids, weak grids may experience voltage drops, frequency deviations, and other undesirable phenomena. Consequently, when designing and operating electricity markets in these contexts, it becomes vital to consider these additional constraints that can significantly impact system reliability.

In summary, the integration of smart meter monitoring and installation plays a crucial role in overcoming the challenges posed by weak grids. By capturing and analyzing detailed consumption and generation data, market participants can adapt their strategies and optimize their operations while considering the unique constraints and characteristics of these systems. This approach enables more efficient and reliable energy transactions and promotes the development of resilient power systems even in the face of challenging operating conditions.

6. Conclusions

This document summarizes some of the challenges that weak grids face when implementing transactive energy, where additional considerations must be considered at each stage. For example, interoperability is necessary for the correct operation of the network. Moreover, this paper presented some of the most widely used optimization techniques for market clearing, highlighting the characteristics and type of market topology to which they are applicable. It was found that all methods were effective for their purpose. However, the techniques have different features relevant to the user and the power grid. Therefore, it is convenient to combine the techniques to consider different constraints in market clearing, such as generating an optimization technique that considers unbalanced systems and securely provides power quality using blockchain.

Additionally, this paper presents an overview of transactive energy. Emphasis is placed on the different market topologies used to clear the market, highlighting the benefits and challenges of each of them. For example, the peer-to-peer market is decentralized where the interaction is directly between prosumers without any intervening entity, but with a high cost of construction and maintenance. In contrast, the community-based market presents resilience in the community but requires large amounts of data for processing. Similarly, it was found that the computational effort is scalable for the hybrid market. However, low-level operations are coordinated through high-level agents. Therefore, it is recommended to understand the needs of the place where a market is to be implemented to select the topology that best suits this need.

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Nomenclature

CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
DER	Distributed Energy Resource
DG	Distributed Generator
DoS	Denial-of-service
DSO	Distribution system operator
ETSI	European Telecommunications Standards Institute
KKT	Karush–Kuhn–Tucker
P2P	Peer-to-peer
QoS	Quality-of-service
SGAM	Smart Grid Architecture Model
TE	Transactive Energy

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