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Review

The Role of Transactive Energy in the Future Energy Industry: A Critical Review

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Abstract: Transactive energy is a highly effective technique for peers to exchange and trade energy resources. Several interconnected blocks, such as generation businesses, prosumers, the energy market, energy service providers, transmission and distribution networks, and so on, make up a transactive energy framework. By incorporating the prosumers concept and digitalization into energy systems at the transmission and distribution levels, transactive energy systems have the exciting potential to reduce transmission losses, lower electric infrastructure costs, increase reliability, increase local energy use, and lower customers' electricity bills at the transmission and distribution levels. This article provides a state-of-the-art review of transactive energy concepts, primary drivers, architecture, the energy market, control and management, network management, new technologies, and the flexibility of the power system, which will help researchers comprehend the various concepts involved.

Keywords: blockchain; energy markets; network management; power system flexibility; transactive energy

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1. Introduction

Every day, the number of new renewable energy power producers added to the world's collective electrical grid continues to grow gradually. The number of assets needed to maintain the balance between supply and demand on that collective grid also is increasing. They increasingly rely on an intelligent and interactive networked system based on economics and market principles, where transactions are utilized to regulate the grid and maintain reliability and efficiency rather than on a standalone system [1]. It is a collaborative effort between companies, utilities, transmission operators, balancing authorities, government agencies, and standards organizations to define clearly the appropriate use of transaction energy (TE) systems and promote their implementations. Back in the day, most utilities were responsible for managing a limited number of power plants (e.g., 10–20) which required the same number of control points instead of massive points of control on the demand side now. The number of control points on the supply side of any given utility is expanding exponentially right now. TE is simply the system's name that assists in managing a multitude of points of control in a system that can generate electricity. With the existence of a TE system, a network can facilitate communication between all points of supply and demand; thereby, this will ensure creating an environment of interoperability in which every point can exchange energy information and, in essence, discuss the value of energy at any time [2]. The paper attempts to analyze several aspects of TE-based power systems to ensure that future power systems are adaptable and operate more reliably and efficiently.

A great deal of literature discussed TE in the recent decade, where the concept of TE was defined in different contexts. The heavy dependence on renewable integration in recent days by power grids invites consumers' participation as prosumers, thereby facilitating utility restructuring. The coordinated integration of renewable generations for achieving operational and economic objectives is imperative. On this note, several TES architectures have been discussed. Decentralized transactive-based control is also essential to evade network fluctuations for yielding power balance and management. Network energy hubs in spatial scales also require continuous examination via transparent market mechanisms for energy trading. Technologies such as blockchain and IoT prioritize transactive control, optimal consumption, and management. Combined efforts considering the above facets to bring power system flexibility were not comprehensively discussed on a common platform in the literature. This motivated the authors to systematically enlighten each relevant item about TES for present-day renewable integrated power transmission and distribution systems. The purpose of this article is to conduct an in-depth analysis of a number of topics, including the following:

1. Emerging aspects, which may include fundamental drivers and designs for transactive energy, energy markets, control and management.
2. An examination of recently developed technologies and innovations pertaining to TE-based management and control.
3. The part that transactive energy plays in network hub systems, the new technologies and innovations that have been developed for TE, and the part that TE plays in the flexibility of power systems
4. A variety of initiatives and challenges based on TE that have been completed and are still underway in their implementation.

The review involves the screening of various papers and reports of the last ten years related to the transactive energy from the databases of IEEEexplorer, ACM, WOS, Springer, ScienceDirect and internet sources. Out of the total 245 papers and sources screened, 93 have been finally selected. The paper selection process involves the search, duplicate screening, title screening, abstract screening and full-text screening.

The paper is organized as follows. The TE and critical drivers are explained in Sections 2 and 3, respectively. TE architectures and energy markets are reviewed in Sections 4 and 5. Sections 6 and 7 provide an overview of transactive-based management and control and new technologies and innovations, respectively. The power system flexibility and conclusion are presented in Sections 8 and 9, respectively. The motivation and structure of the paper are presented in Figure 1.

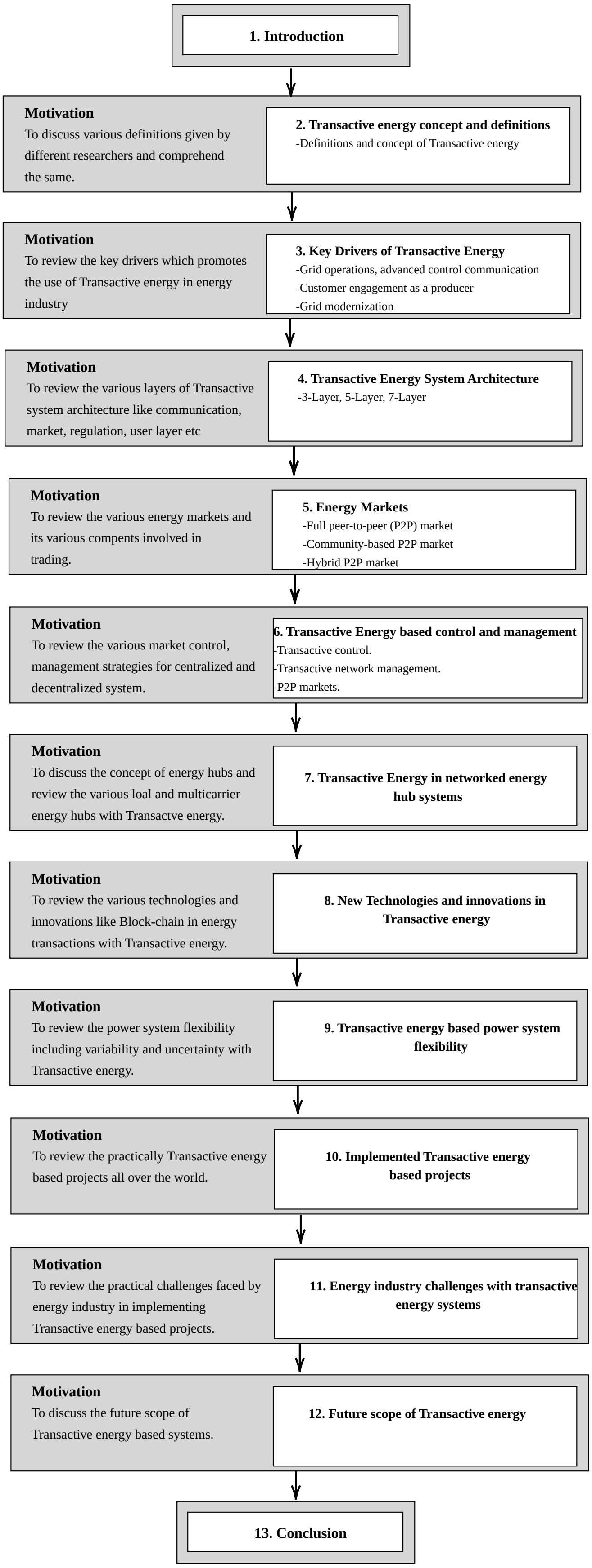

Figure 1. Structure of the study.

2. Transactive Energy Concept and Defintions

The TE modifies the traditional hierarchical grid structure and encourages a network environment for decentralized energy nodes. With TE, all energy producers and consumers can communicate with each other. TE provides increased consumer satisfaction, reduced energy cost, efficient use of energy and reliability compared to traditional energy systems as systems can share data and communicate with preservation of service and operational constraints. Various definitions of TE have been proposed by different individuals and organizations as follows:

> "An internet-enabled free market, where customer devices and grid systems can barter over the proper way to solve their mutual problems, and settle on the proper price for their services, in close to real time." [3].

> "Techniques for managing the generation, consumption, or flow of electric power within an electric power system through the use of economic or market-based constructs while considering grid reliability constraints." [2].

> "A software-defined grid managed via market-based incentives to ensure grid reliability and resiliency. This is done with software applications that use economic signals and operational information to coordinate and manage devices' production and/or consumption of electricity in the grid. TE describes the convergence of technologies, policies, and financial drivers in an active prosumer market where prosumers are buildings, electric vehicles, microgrids, VPPs or other assets." [4,5].

> "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].

The most decent definition as stated by Gridwise Architecture Council [6,7]. TE is "techniques for managing the generation, consumption, flow of electricity within the power system that allow the dynamic balance between demand and supply keeping in view the constraints of the entire network".

In view of these definitions, it seems that the TS system enables multiple buyers and sellers in which energy will be effectively distributed from sellers to the buyers through a decentralized system, i.e., market, etc. Figure 2 shows the conceptual diagram of TE with different players involved. TE can be defined as software-defined grid driven by market incentives to provide stability and resilience and for controlling the generation, consumption, and flow of electricity in the power system in order to balance demand and supply. It comprises of several levels of market, system, control mechanism, etc., which maintain a dynamic equilibrium between load and generation using economic or market-based designs to increase electric power system reliability. It uses operational data to coordinate and manage device production and grid utilization.

It consists of a layer-type structure (i.e., independent system operators (ISOs), distribution system operators (DSOs)) or even a single customer can act as one layer), and there is an exchange of only boundary information as communication with others, i.e., each layer has its optimization objectives. However, in some cases, local management and distributed techniques are required to alleviate the issue of stability and reliability, which arises due to the obstruction of information exchange by the decentralized system [2,8]. This issue can be taken care of by distributed ledger technologies such as blockchain by removing the central control management [9,10] and facilitating distributed transactions. The distributed nature of renewable energy sources (RES) at the load end is also the reason for a decentralized framework for future TE markets [11,12].

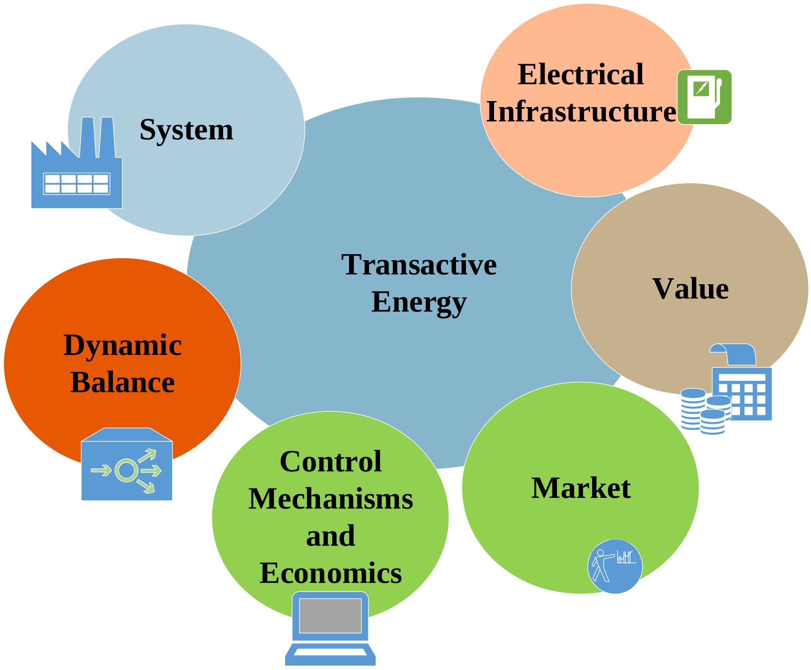

Figure 2. Transactive Energy Concept [13].

3. Key Drivers of Transactive Energy

With the growing penetration level of renewable energy systems (RES) in conventional power systems, some new concepts and innovations are introduced, which includes decentralization, marketing, modernization, and digital transformation [14]. This also includes consumers' participation and the activation of their role in managing electricity services as both consumers and producers of electricity. In general, the main drivers identified are:

1. Grid operations, advanced control and communication technologies, microgrids, etc.
2. Customer engagement as a producer.
3. Grid modernization activities that includes incentives of the state.

At the distribution level, the move toward the TES involves restructuring the utility into different entities, e.g., generation, transmission and distribution, and deregulation, which is possible through grid modernization. From the technology perceptive, TES involves innovations in conventional power systems and the cross-discipline integration of communication networks, control data science, and artificial intelligence. For example, the cross-technology integration of sensor layers includes an IEEE 802.15-based personal area network, low-power WAN, and power line communication. Cross-domain data integration includes various sources such as smart homes, smart living, etc. Cross-hardware integration includes sensors, actuators, gateways, and network equipment from various manufacturers. Cross-data integration includes different areas such as advanced metering infrastructure (AMI), meter data management systems, distribution management systems, etc.

From the society perceptive, innovation in TES involves the real-time management of energy supply and demand, vehicle to the grid, building to building, and vehicle to building, all of which are called decentralized clean energy services that can help contain carbon emissions. Society consider TES as promising technology enabling greater customer participation and a cleaner environment. From the people perceptive, it enables the customer-friendly smart interface for decision making, participation in energy trading, optimization strategies to enable energy-efficient usage, and comfortable living environments that involve smart home, smart health, etc. [15].

Figure 3 shows the basic concept of different players involved in TE. Different players observe TE as advantageous to their own goals with greater consumer participation and beneficial particularly to small players.

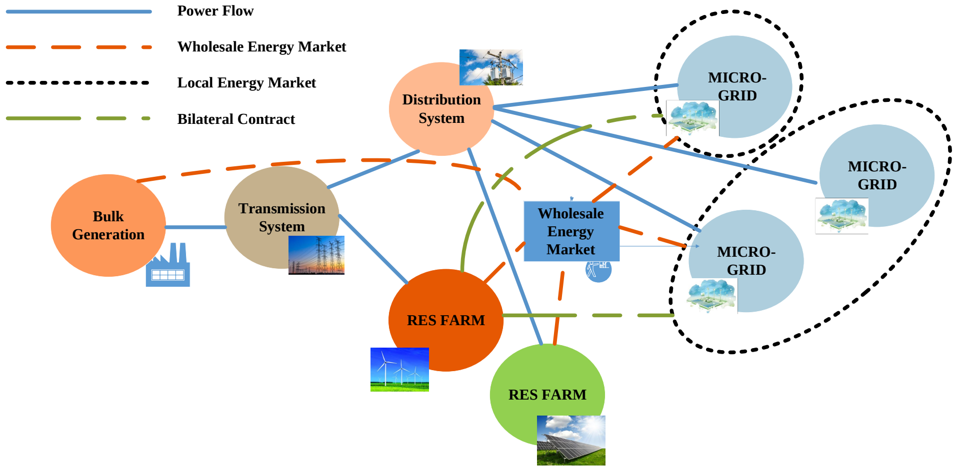

Figure 3. Transactive power system concept [13].

4. Transactive Energy System Architecture

The transactive energy system (TES) artitecture is of decentralized form, whose main idea is to achieve the operational and economic objectives with the coordinated integration of power producers, prosumers and DERs. The key feature of TES includes reducing the intermittency problem of RES with the engagement of more active consumers and prosumers in energy transactions [13]. Different researchers have proposed architectures of TES from different points of view, as shown in Figure 4.

A three-layer architecture has been proposed in [16], containing an aggregator, communication and user layers. Energy transactions are performed in the user layer where the users can give their preferences and objectives. The communication layer deals with the communication of participants and servers, which in turn depend on the availability of such infrastructure. The aggregator layer can be controlled by a DSO or aggregator and includes a data center which analyzes data for virtual energy exchange. However, it does not include the determination of energy price or the regulation of electric power network layers and has a simplistic approach for TES.

A five-layered TES has been proposed in [17], which contains a communication layer, market layer, regulation layer, energy management layer, and user layer. In the user layer, distributed ledger technology and communucation devices are used by the participants to send their bids and offers, which are used by EMS to start the energy transactions. The energy management layer deals with the operational and economic objectives of the system which ensures dynamic demand–supply balance, reliability, etc. The market layer initiates the energy transactions while considering the energy bids to find the local optimum minimum clearing price. The communication layer is required to facilitate the information exchange using wireless and wired communication platforms. The regulation and governance of TES operation are made by the regulation layer, which is required for transparent energy transactions. The five-layer TES system lacks the network layer, which is needed to include the losses and congestion of transmission and distribution lines; for that, a seven-layer TES has been proposed in [13].

It consists of a user layer that communicates using distributed ledger technology with other participants. The network layer consists of a communication and power network responsible for the dynamic supply–demand balance. For monitoring the operation, analyzing and storing the data during energy transactions is completed by the system operator layer. The MCP for energy transactions among the different players involved is taken care of by the market layer. The distributed ledger layer consists of a blockchain, hash graph, etc., which is responsible for providing the platform for exchanging information for economic and energy transaction validations. A communication layer is used for information exchange and reliable and secure communication among participants. Finally, for the successful implementation of TES, regulation policies and other related policies must be defined, which the regulation layer takes care of.

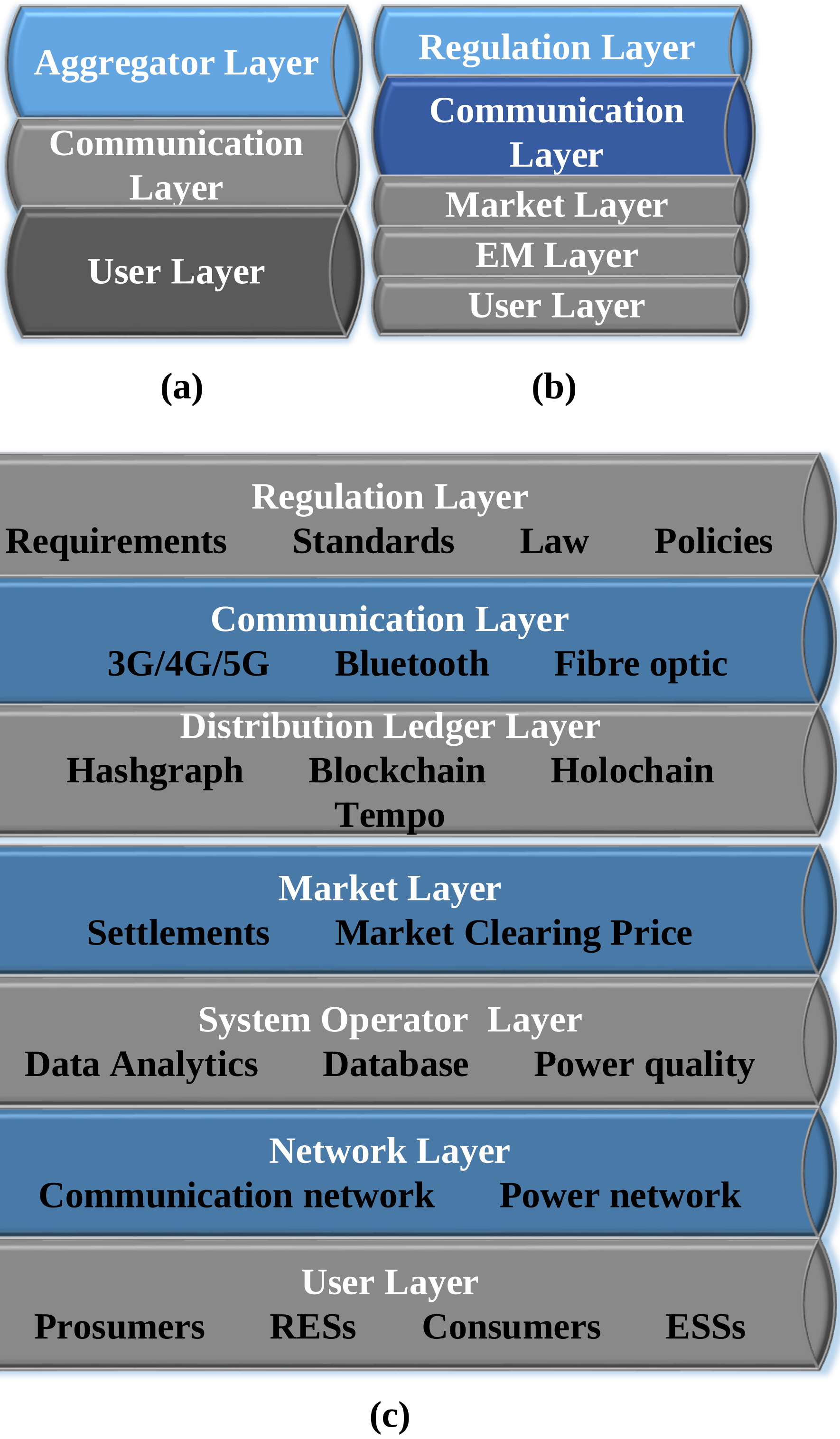

Figure 4. TE architecture: (**a**) 3-Layer [16] (**b**) 5-Layer [17] (**c**) 7-Layer [13].

5. Energy Markets

The energy market is a very complex structure with various players involved, e.g., consumers, prosumers, etc. that can be categorized into (as shown in Figure 5) [18]:

- Full peer-to-peer (P2P) market;
- Community-based P2P market;
- Hybrid P2P market.

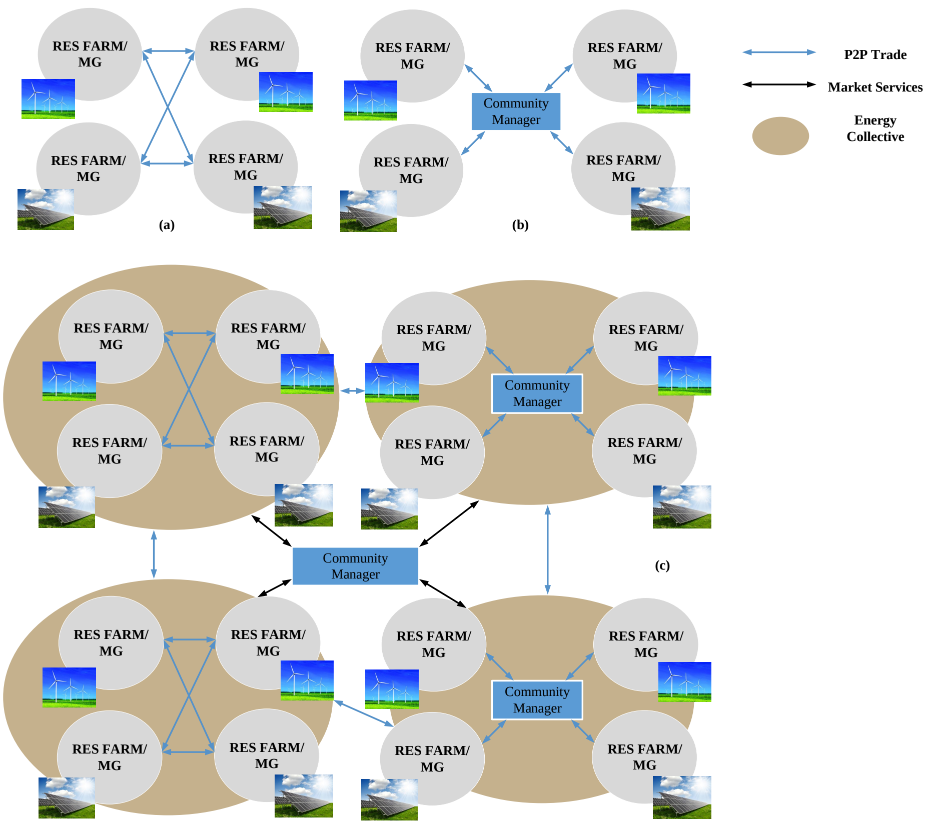

Figure 5. (**a**) P2P energy market, (**b**) Community-based P2P energy market, and (**c**) Hybrid P2P energy market [18].

There is an interaction of participants directly with each other in a P2P market without any intermediary with fully autonomous architecture. In this type of market, each peer sets its preference such as green energy, local generation, etc., as per the requirement [18].

The community-based P2P market has a community manager to manage the trading activities inside the community and the rest of the system. In a hybrid P2P market structure, both transactions are possible with two layers, i.e., P2P among themselves along with a community-based market.

With high-speed communication and data measurements in a market-clearing mechanism involving TE, bidirectional information and power flow are possible. The TE network has a vital role in pricing signals and will be classified as auction, bidding, and uniform price. The auction can be static and dynamic where bidders cannot change their preferences in former and preferences can be varied with time. Different researchers have proposed other auction, bidding, and pricing signals; however, game theory is most effective due to its rationality. All the consumers have to pay a uniform price in the energy market according to a uniform pricing signal while sellers pay different zonal prices [18].

6. Transactive Energy-Based Control and Management

Based on [19], the TE concepts can be classified, namely into (as shown in Figure 6):

1. Transactive control.
2. Transactive network management.
3. P2P markets.

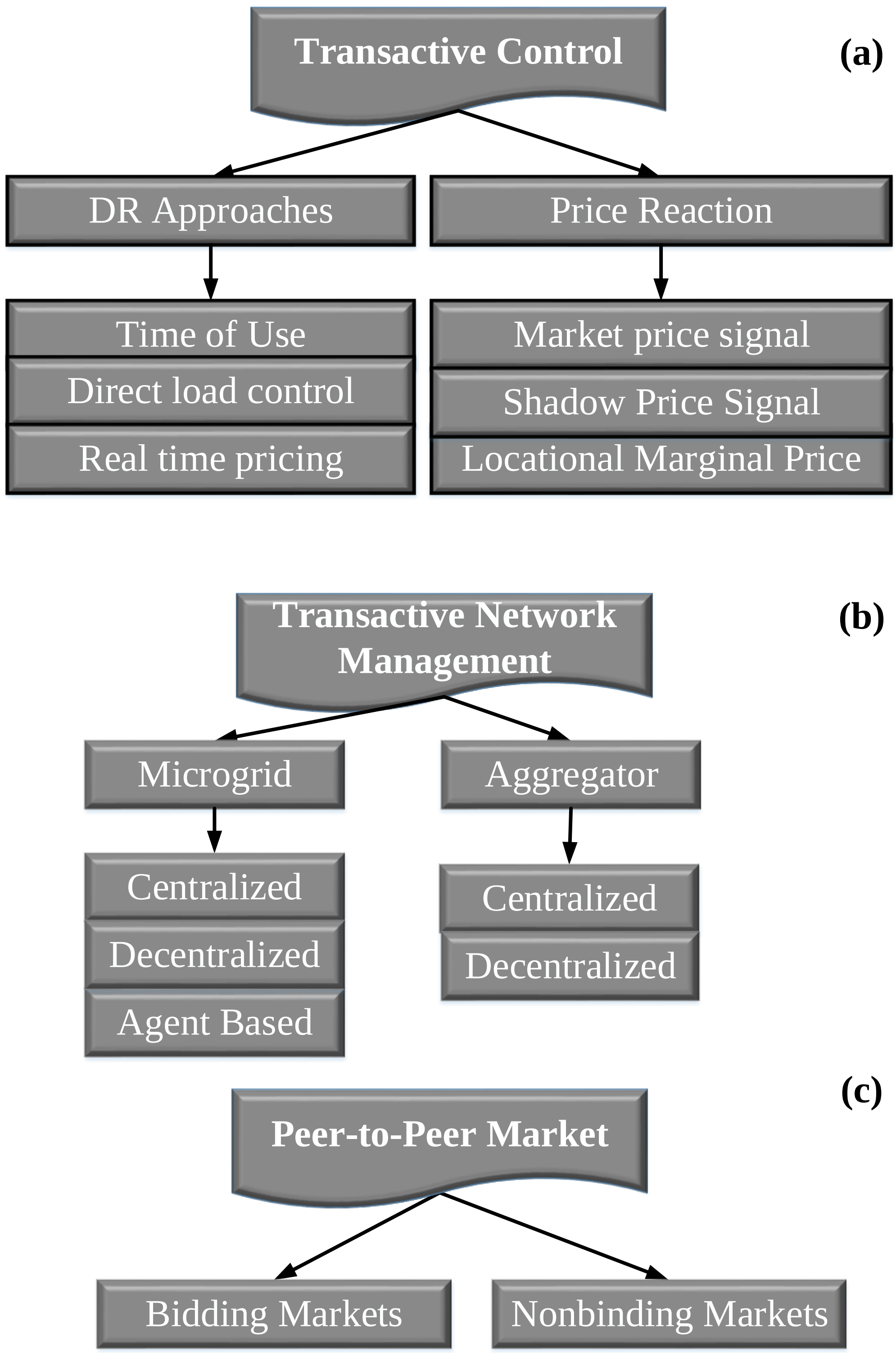

Figure 6. (**a**) TE-related concepts in control (**b**) TE-related concepts in management (**c**) TE-related concepts in P2P market [19].

6.1. Transactive-Based Control

A transactive control involves using market data and local information in a fully decentralized environment for smoothing network fluctuations and network balance [19,20]. In an electrical network, the utilities, substations, and consumers/prosumers are represented by a physical point and desired consumption rate for consumers, and the price signal is transmitted between the system operator and node [21]. Since the local users and preferences of end-users are available, transactive control can also be considered a distributed control method [22,23]. The end user's participation in the transactive market has to bid its favorable amount of electricity and consumption modification based on the market clearing price [24]. Transactive control has been used in commercial and residential buildings for thermostatically controlled loads (TCL), heating, ventilation, etc., which can be accomplished through demand response (DR) programs [25–29]. Figure 6a shows the TE-based concepts in control, which involves DR approaches and price reaction. Under DR approaches, we have time of use, direct load control, real-time pricing, under price reaction, market price signal, locational marginal price, and shadow price signal.

Various works have given various methods of trasactive-based control. In [30], high-voltage alternating current (HVAC) has been controlled by a passive controller in an office building with TE and real-time market prices with savings in energy compared to conventional controlling methods. In [31], a system, namely a home energy management system (HEMS), has been proposed which, based on price signals, modifies the schedule of appliances as defined by the home inhabitants' objectives of both network entities and customers. However, when many HEMS are applied, with a time-of-use pricing scheme, there is a lack of reliable coordination and management. In the building automation systems for commercial and industrial buildings, transactive control can be implemented [32–34]. Transactive control under a real-time pricing scheme has been proposed in [35] for residential HVAC with two transactive control strategies. In the first strategy, the cooling set-point rate is defined based on user preferences, comfort, and market price statistics. The second strategy, depending on the market price, fixes the desired temperature. Cost saving has also been studied for both these strategies, without and with pre-cooling features, real market price, real weather data, and the actual model of the residential house. In [32], a transactive control methodology has been adopted in which using the price signal and market data, several commercial buildings have been modeled and controlled in a transactive manner with several mathematical formulations. The developed methodology of transitive control has been validated in offices and laboratories in Washington using the market data without much investment in infrastructure. In [33], similar work has been presented in green buildings in Australia and in both cases, transactive control can be implemented with little or no investment. However, there is a gap between expected and actual results due to the unexpected faults in communication protocols and sensors requiring a more efficient control design. A demonstration project titled Pacific Northwest National Laboratory (PNNL) was implemented in Ohio, United States, from 2010 to 2013 with a real-time electricity market utilizing bidding transactions to survey the residential consumer behavior [36,37]. The result signifies improved reliability and efficiency up to 30–40% with a five-minute basis in a real-time pricing market, depending on their choices and preferences.

The transactive control in an electrical vehicle (EV) has been applied in [38–41]. Optimal and efficient charging was possible in [42] based on transactive control. A transactive control has been introduced in [41,43] to prevent high-penetration voltage violations and network congestion. The fleet operator has been supervising and controlling the charging schedule in the lower level of the network. The network manages the DSO fleet operator in a transactive manner. The DSO can check the network operation violations, and if congestion occurs, it proposes a shadow price to alleviate congestion. However, DSO approves the scheduling of the fleet under no violations.

6.2. Network Management Based on Transactive Energy

The TE-based network management helps the economical operation of the microgrid for the local control of its generation and consumption with the least dependence on the main grid, aiding in improving the reliability of the whole LV system [44–46]. TE provides the flexibility of available resources with profits between aggregators and microgrids [47]. Microgrids can share energy among their neighbors to overcome network congestion and improve grid stability, as microgrids can act independently of the main grid and balance the demand and supply based on local available resources [48,49]. Figure 7 gives an overview of the TE-based microgrids' bidding transactive services, which provides flexibility to the distribution system and wholesale markets. With this model, the profit of the load aggregator can be maximized by cooperation between microgrids by determining the energy transactions to market [50].

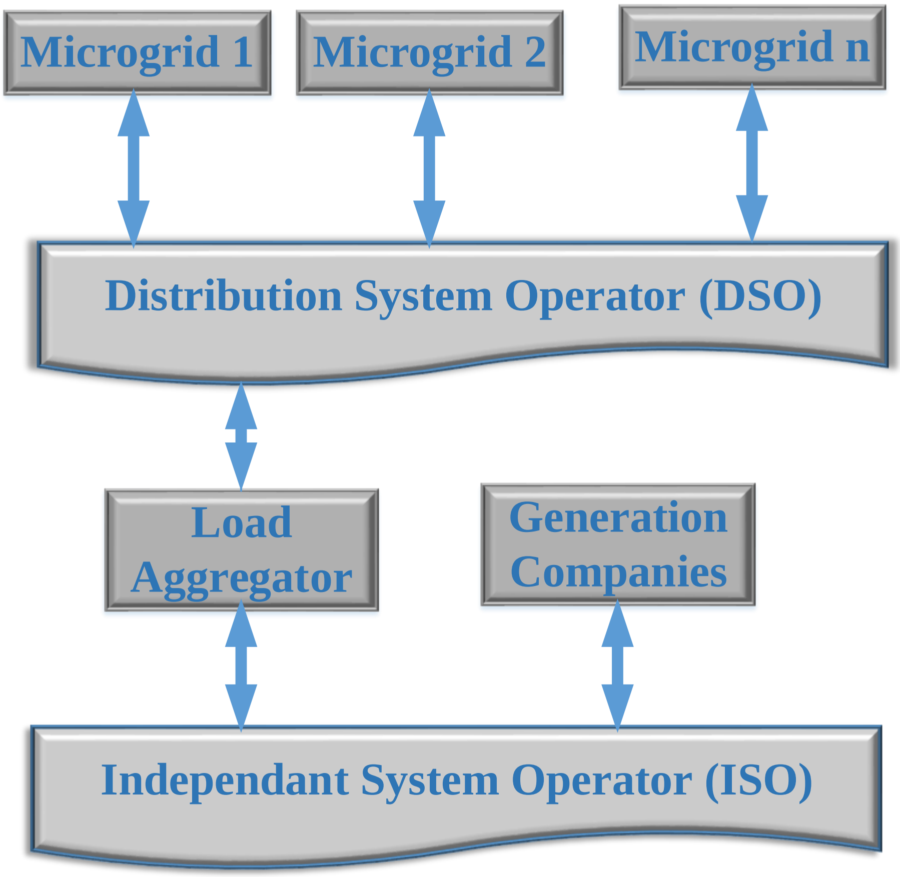

Figure 7. Market structure with TE [19].

The load aggregator has no control over microgrid players interacting with distributed and wholesale markets and is considered an independent player. An aggregator can assign cost and remunerations among the enrolled consumers and prosumers and thus directly coordinate with the demand side [51,52] with several layers of EMS in the community of enrolled customers. The base layer of EMS measures the generations and consumption in real time. It consists of measurement devices [53]. At the same time, there is a processor in the aggregator in the top layer to calculate price signals and power references. One more layer is responsible for transmitting coordination signals between aggregators to consumers and measured data from users to aggregators. This layer is between the base and the top layer of EMS. In [54], a model to manage the controlled devices that operates on the local market has been presented as an optimization-based aggregator model that allows a small area of energy trading between consumers and producers that brings flexibility in the upstream level requests of the distribution system. The validation of the aggregator based on optimization in real time has been performed for controlled devices.

6.3. P2P Markets

The energy market is Full P2P, Community-based P2P, and Hybrid P2P [18]. Without an intermediary, P2P market players engage directly with each other. The community-based P2P market features a community manager to manage trading operations. In a hybrid P2P market, both P2P and community-based transactions are available (as shown in Figure 5). Bidirectional information and power flow are achievable with high-speed communication and data measurements in TE's market-clearing system.

7. Transactive Energy in Networked Energy Hub Systems

Local generating systems deployed at load centers have the potential to provide significant flexibility to prosumers and grid operators [55]. Through multicarrier energy hubs, it is possible to serve the local electrical, heating, and cooling demands at the lowest possible cost in this paradigm. The primary function of energy hubs is to service loads of consumers within their utilization region. Figure 8 depicts the fundamental conceptual diagram of energy hubs, while Figure 9 depicts the energy and data flow through the energy hub system in an integrated and coordinated mode of operation.

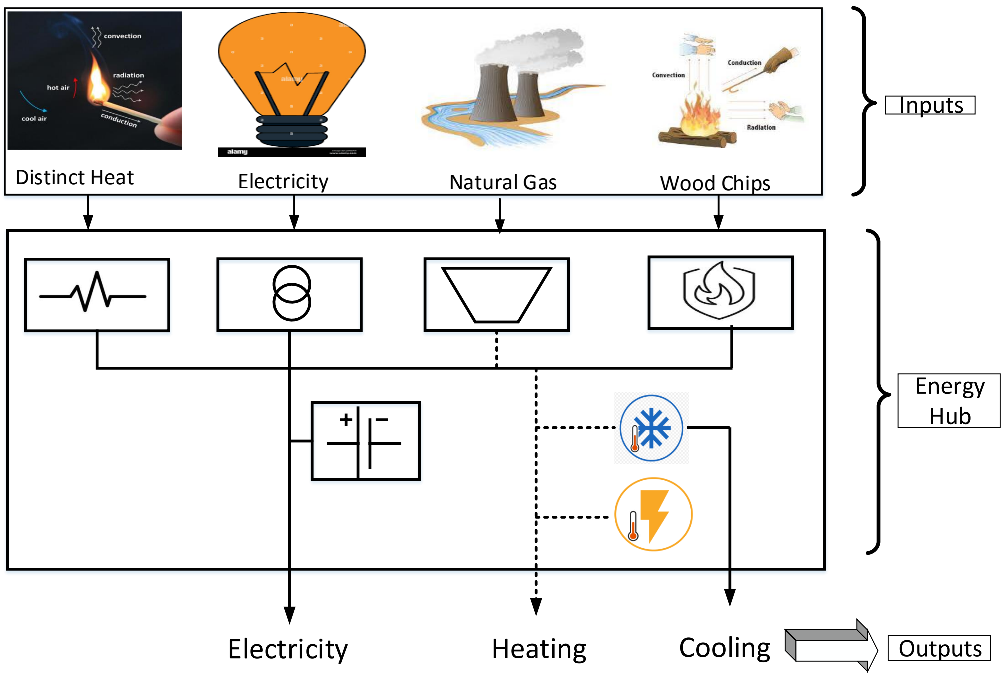

Figure 8. An energy hub concept [56].

Numerous technologies are utilized in the hubs to convert, store, and generate energy to meet end-user demands. In this sense, the operator of the energy hub is responsible for finding the ideal operating points for the hub's installed assets. Unlike traditional customers, energy hub operators can sell excess electricity to the upstream grid, transforming them into prosumers in this paradigm because they can operate as both producers and consumers [57]. This option for prosumers may boost the market flexibility of the energy hub operator. On the other hand, the ability of customers to trade energy within the P2P framework creates a new opportunity for end-users to trade electricity securely and cost-effectively. Clients can participate in a TE market in this environment and benefit from the ability to lower their electricity costs by sourcing energy from other energy hubs and increase their profits by selling excess power to other clients without incurring additional tax or grid service costs.

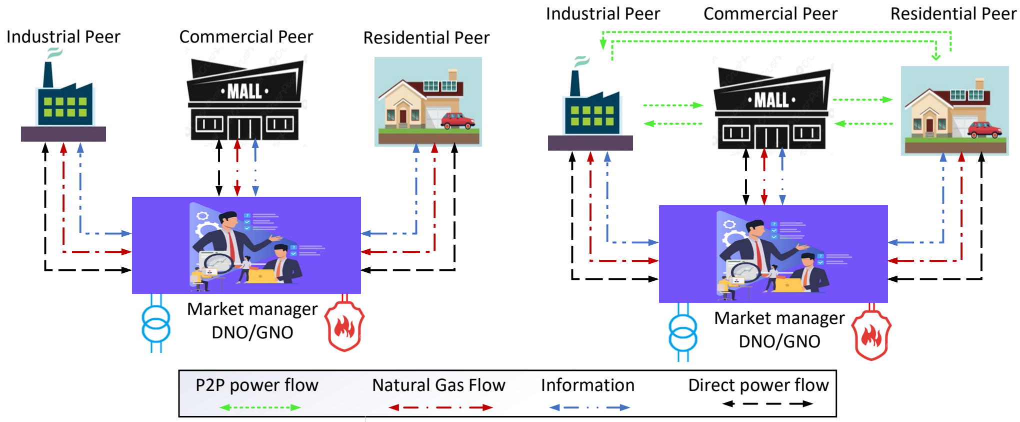

Figure 9. Energy flow in case of energy hub [57].

In [58], energy transactions across energy hubs were examined in the context of a transparent market mechanism for energy trading, with an emphasis on minimizing data exchange between clients. In [59], a leader–follower optimization technique is used to simulate the TE between DISCOs and networked microgrids. The suggested model considers the DISCO's profit, the cost of the microgrids, and energy that is not supplied while remaining independent of the MMG system. As the leader, DISCO sets the prices for TE used in power exchange with microgrids at the upper level of the optimization. Ref. [60] proposes an operational model for interconnected microgrids operating in the TE market. The goal of 100% clean energy generation was achieved by equipping each microgrid exclusively with renewable energy resources for energy generation and energy storage devices to mitigate the stochastic behavior of the renewable energy resources. Adopting novel technology and reliable methods was crucial for sustaining a continuous energy supply condition in systems powered entirely by renewable energy resources.

A bi-level energy transactive management structure has been proposed in [61] for communities of microgrids in order to address issues associated with aggregated demand responses, distributed energy resources, and user dissatisfaction with demand–response programs while still adhering to power system constraints. In [62], a robust stochastic optimization for energy sharing between multicarrier microgrids employing the TE management system has been developed. The coordinated operation of various industrial energy hubs (IEH) to realize local energy management concepts at strategic sites such as industrial parks has garnered the interest of power grid operators' interest globally. Deriving an operational model for integrating a wide collection of IEHs to trade energy in diverse markets is a basic challenge, and the strategic operation of a virtual energy hub with the provision of advanced ancillary services in industrial parks has been presented in [63]. In view of the remarkable advances in renewable and hybrid energy systems, there is an urgent need for creative models capable of reliably addressing the ever-increasing penetration of renewable energy resources. In [64], a TE trading model for modernizing energy hubs in a linked heat and electricity network was suggested and meant to address the aforementioned difficulty by effectively utilizing the environmental potential for clean energy production and achieving waste to wealth conversion.

8. New Technologies and Innovations in Transactive Energy

In recent times, researchers are paying the slightest attention to practical issues during the implementation of transactive control and mainly focusing on formulations and mathematical models. New technologies such as blockchain (as shown in Figure 10) and IoT have been used for transactive control optimal consumption and management at residential and commercial levels.

IoT-connected sensors, devices, and smart meters generate a large amount of data. To preserve the security and privacy of users, blockchain and Holochain-based distributed ledger technologies are required. A TE-based smart grid using distributed ledger technologies can be an effective solution for the smooth and effective working of TE systems. Blockchain technology can enable new business solutions and promise safe, flexible systems, store intermediary transactions, and lead to smart contracts execution [18].

Furthermore, the current trend involves providing software platforms to P2P participants to manage energy trading through local electricity markets with both centralized and decentralized management approaches. In the literature, cost optimization involving microgrids and consumers reacting to signals is a current trend of study which requires tools and simulation platforms to overcome practical challenges such as communication failures, cyber-attacks, automation infrastructure challenges, etc. There is a wide gap between real (sometimes referred to as actual) and expected results with TE systems for which emulation tools and prototypes are required for implementation [65]. However, there should be more emphasis on projects involving validations with TE for addressing the practical issues during simulation. Industrial and commercial projects have been implemented in some residential microgrids involving energy trading with TE [66].

In transactive control, researchers need be focused on financial transactions speed, data security, resiliency to failures, etc. [16]. Currently, the focus is on HVAC in commercial and residential buildings with demand response. All types of loads and devices, a combination of TCL and lighting systems of commercial buildings, must come under transactive control, as they are more flexible to control than TCL and HVAC in commercial buildings [67,68]. Since residential load accounts for a significant amount of total load worldwide, the application of transactive control must be explored for that [31]. For home appliances, transactive control makes the system less dependent on web-based energy management systems (EMS), and grid operators can optimize the operational cost by decision making [69]. The centralized microgrid management, aggregators, and decentralized transactive control for resources management are the areas that need to be explored, along with the role of aggregators in the face of a hierarchical and centralized structure of a power system [70]. One area that needs exploration is the aggregators dynamics with decentralized TE systems with more tools to validate the test performance. With many customers in P2P markets, there will be the issue of trust in the mode of money exchange, and for that, blockchain and smart contracts have been proposed in [71], which still needs validation in real cases. In [72], a tracking algorithm has been proposed to recognize the transacted energy origin, which is a significant challenge in P2P markets for a clean energy source.

Buildings' energy consumption is expanding at an alarming rate at the moment. With advancements in electricity technologies and growth in the integration of distributed energy resources into power systems, a TE system powered by Internet technology is an ideal tool for managing power grids. The smart grid's components communicate with one another using Internet technologies [73]. It is also used to improve the efficiency and productivity of the communication process between the main grid, smart homes, and their smart devices.

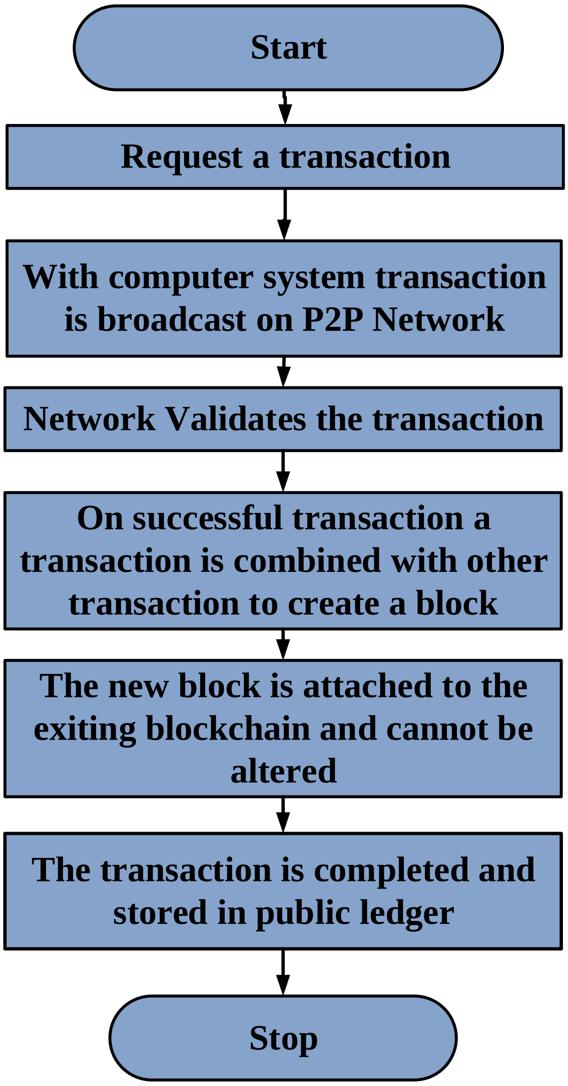

Figure 10. Working principle of blockchain [18].

9. Transactive Energy-Based Power System Flexibility

In recent times, there has been a paradigm change in the approach of system planners due to the competition resulting from deregulation and uncertainty, which leads to a flexible solution and not a minimal cost one. A flexible solution is a cost-effective one and will withstand various situations. The power system flexibility deals with the ability of the power system to cope with uncertainty and variability with the variation in generation and demand. TE maintains the dynamic balance between supply and demand by managing the flow of electricity, consumption, and generation [74].

Variability and uncertainty exist throughout a range of time periods. Long-term (more than a year) matching supply and demand becomes unclear due to the difficulties of forecasting variable renewable energy (VRE) development, consumer behavior evolution, economic growth, and other factors, all of which have implications for capacity expansion planning. On a medium-term (year, monthly, and daily) basis, power system operators must contend with cyclical variations in a residual load (load minus VRE generation), affecting dispatchable assets' unit commitment and economic dispatch. On a short-term (intraday) basis, power system functioning is hampered by uncertainty resulting from incidents and the forecasting capability of demand and VRE generation, which affects reserve sizing and activation. There are several strategies for dealing with these sources of variability and uncertainty, including providing flexibility. In general, (i) one can modify generating output (including VRE curtailment), (ii) modulate demand, (iii) store energy in a different form to smooth out time variations, or (iv) communicate with another system to smooth out space variations. These flexible solutions can be built, mothballed, or decommissioned to address long-term uncertainty. One can activate existing FS to deal with medium-term unpredictability and short-term uncertainty.

Numerous measures have been proposed to investigate various aspects of flexibility. Quantification approaches have been classified according to their address question: how much flexibility does the system require? How flexible has the flexibility solution been, and how flexible has the power system been? TE can act as a tool for making the power system more flexible to manage variability and uncertainty [74]. TE essentially has been an intelligent, multi-level communications method that coordinates energy generation, use, and distribution. Under the TE scenario, electricity suppliers, energy markets, the power grid, households, commercial buildings, and DERs, such as electric vehicles and batteries, will "talk" directly or indirectly with each other to negotiate energy needs and costs. The electronic procedure would instantly and automatically reconcile energy availability, consumer needs, cost preferences, and other parameters, boosting total energy system efficiency and flexibility.

10. Implemented Transactive Energy-Based Projects

Various transactive energy projects have been implemented globally, particularly in the United States and Europe. In [75], the Kealoha project established a software platform for the P2P exchange of excess solar energy between households. Temix, a decentralized network management and automated energy transaction initiative, has been implemented in [76]. In this project, energy trading software has been built. In [66], the energy trading between the prosumers in a typical power network has been demonstrated in a project titled The Brooklyn microgrid. In [46], a project titled OATI Microgrid Center which involves the sophisticated control and optimization software for a microgrid testbed has been implemented. The project integrating IoT devices to adapt them automatically to transactive control has been implemented in [77] with the title connected homes. In [78], a project titled Clean Energy and Transactive Campus implemented a multi-campus testbed for transactive control and TE management experiments. The Intelligent software platform for operating on the real-time market was deployed in the AEP gridSMART project in [36]. In [78], the Automatic Load Response to Price Variations in a Very Short Timeframe initiative has been implemented as part of the Olympic Peninsula GridWise project.

In the United Kingdom, the Energy ELECTRON project [79] has created a modular system for electricity metering and billing for energy sectors. In Germany, the Lichtblick Swarm Energy project, which involves the development of an IT platform to link users and maximize the usage of local DER, has been implemented [80]. Under project Sonnen Community [81], a P2P energy-sharing platform considering a virtual energy pool has been built in Germany. Novel approaches for energy optimization through ICT have been developed in Germany as part of the Smart Watts project [82]. Under the P2P–smarTest [83] project, a demonstration of a smart grid based on TE ideas capable of P2P energy trading has been established in Finland. Under the Peer Energy Cloud project [84], Germany has created a cloud-based platform for local energy trading and smart houses. In the Netherlands, the project Vandebron [85] has explored P2P energy trading from both the provider and client perspectives. Under the project Piclo [86], network operators' software platforms for P2P energy trading have been established in the United Kingdom. Germany has established a decentralized system for EV charging, transactions and data sharing through the Share&Charge project [87]. A blockchain-based P2P market for energy trading has been created in the Netherlands as part of the Powerpeers project [88]. The Netherlands has implemented the Couperus Smart Grid project, which uses PowerMatcher technology to coordinate energy consumption and reduce peak load [89]. Norway has established a trading platform for local energy exchange on local markets as part of the EMPower project [90]. In the Netherlands, the PowerMatcher [78] project has created a smart grid coordination mechanism that takes into account distributed energy resources and flexible loads. The various completed and undergoing Transactive Energy-based projects has been given in Table 1.

Table 1. Various completed and undergoing transactive energy-based projects.

References	Project Title and Features
[75]	Kealoha:- Established a software platform for the P2P exchange of excess solar energy between households.
[76]	Temix:- a decentralised network management and automated energy transaction initiative, has been implemented.
[66]	The Brooklyn microgrid:- The energy trading between the prosumers in typical power network have been demonstrated.
[46]	OATI Microgrid Center:- Sophisticated control and optimization software for a microgrid testbed has been implemented along with IoT devices to adapt them automatically to transactive control.
[78]	Clean Energy and Transactive Campus:- Implemented a multicampus testbed for transactive control and TE management experiments. Olympic Peninsula Grid-Wise project:- Automatic Load Response to Price Variations in a Very Short Timeframe initiative has been implemented. PowerMatcher:- Created a Smart grid coordination mechanism that takes into account distributed energy resources and flexible loads.
[36]	AEP gridSMART:- The Intelligent software platform for operating on the real-time market was deployed.
[79]	Energy ELECTRON:- Created a modular system for electricity metering and billing for energy sectors.
[80]	Lichtblick Swarm Energy:- Involves the development of an IT platform to link users and maximise the usage of local DER, has been implemented in Germany.
[81]	Sonnen Community:- P2P energy sharing platform considering a virtual energy pool has been built in Germany.
[82]	Smart Watts:- Novel approaches for energy optimization through ICT have been developed in Germany.
[83]	P2P–smartest:- A demonstration of a smart grid based on TE ideas capable of P2P energy trading has been established in Finland.
[84]	Peer Energy Cloud:- Germany has created a cloudbased platform for local energy trading and smart houses.
[85]	Vandebron:- Explored P2P energy trading from both the provider and client perspectives in Netherlands.
[86]	Piclo:- Network operators' software platforms for P2P energy trading have been established in the United Kingdom.
[87]	ShareCharge project:- Germany has established a decentralised system for EV charging, transactions, and data sharing.
[88]	Powerpeers:- A Blockchainbased P2P market for energy trading has been created in the Netherlands.
[89]	Couperus Smart Grid project:- Uses PowerMatcher technology to coordinate energy consumption and reduce peak load in Netherlands.
[89]	EMPower:- Established a trading platform for local energy exchange on local markets in Norway.

11. Energy Industry Challenges with Transactive Energy Systems

Most research on transactive energy systems uses formal models based on electrical engineering, software design, and economics. These studies focus on "internal" or technological issues in creating systems to apply economic models to real-time, automated electrical transactions. When transactive energy is used in field experiments that simulate "real-world" settings, extra "external" or implementation issues arise [91].

The GridWise Olympic Peninsula Project created a "shadow market" that rewarded the usage of distributed-energy and demand–response resources to minimize congestion [78]. Each client has an account to credit and debit their energy devices' contribution to the feeder's real-time demands. Participants could manage their responses online, from no response to maximum economy response. Participants might override this option anytime. The investigation discovered that customers responded to pricing signals and the system may ease feeder congestion, but it also found certain problems such as systematic risk or risk perception, user preparedness, and project economic feasibility.

The American Electric Power Ohio GridSMART Demonstration Project tested smart meters and new technologies and programs [36]. Within this larger project, the program tested real-time pricing for household heating, ventilation, and air conditioning devices. Customers could set the thermostat's minimum, maximum, preferred, and savings temperatures using a slider bar, automatically calculating the bid price. The aggregated preferences formed a demand curve to buy power, and the supply curve represented the utility's offer to sell power. Although the project lowered peak demand, it revealed difficulties. The research did not identify systemic risk as an issue, but it did raise user, technological, and economic challenges. The initiative required more customer service representatives to manage increased phone volume, and the company had to make several trips to residences to install and maintain the devices.

In the Pacific Northwest Smart Grid Demonstration Project, more security, technology, and interoperability are needed. Even when systems could communicate, they were not always TES-compatible [36,37]. Some smart meters could not communicate in less than a day, and some utilities could not collect real-time data or offer real-time load outage information. Real-time pricing on the supply side was also hindered by a lack of real-time information, so the TES had to simulate the price based on seasonal tendencies. Because of a simulated electrical supply price, the system could not be incorporated.

In general, the difficulties that are connected with the many different TE-based initiatives include the following: systematic risk or risk perception, user preparation, and project economic feasibility.

12. Future Scope of Transactive Energy

The future scope of concepts based on transactive energy includes:-

1. Developing mechanisms and methods for better usage of grid assets, which can reduce costs, especially during peak demand situations.
2. When the grid is overloaded, developing customer response mechanisms that lower energy consumption can lessen the need for new power plants. By providing clients with the means to regulate and change the timing of their energy consumption, substantial daily swings in energy consumption can be mitigated.
3. Increased usage of cost-effective, renewable energy generation (particularly from variable sources such as wind and solar) would necessitate new tools for running the grid, which TE may provide.
4. Developing mechanisms for transactive energy enabled more decentralized system for improving reliability and resilience. The various issues addressed and their salient features have been tabled in Tables 2 and 3.

Table 2. Various issues addressed and their salient features—I.

Issues Addressed	References	Features
Key Drivers	[14,15]	- Growing penetration level of renewable energy systems (RES). - New concepts and innovations like Decentralization, marketing, modernization, and digital transformation. - Consumers participation. - Grid operations, advanced control and communication technologies, microgrids etc. - Customer engagement as a producer. - Grid modernization activities that includes incentives of the state.
Transactive energy architecture	[13,16,17]	- A three layer architecture containing aggregator, communication and user layers and energy transactions are performed in user layer where the users can give their preferences and objectives. - A five layered TES contains communication layer, market layer, regulation layer, energy management layer and user layer. In the user layer, distributed ledger technology and communucation devices are used by the participants to send their bids and offers, which are used by EMS to start the energy transactions. - The five layer TES system lacks the network layer which is needed to include the losses and congestion of transmission and distribution lines, for that a 7-layer TES have been proposed.
Energy markets	[18]	- Full peer-to-peer (P2P) market, Community-based P2P market, Hybrid P2P market. - There is an interaction of participants directly with each other in P2P market without any intermediary with fully autonomous architecture. - With high-speed communication and data measurements in a market-clearing mechanism involving TE, bidirectional information and power flow are possible. - The TE network has a vital role in pricing signals and will be classified as auction, bidding, and uniform price.
Transactive energy based control and management	[19–29,44–54]	Transactive control, Transactive network management, P2P markets. *Transactive based control:-* - A transactive control involves using market data and local information in a fully decentralized environment for smoothing network fluctuations and network balance. - In an electrical network, the utilities, substations, and consumers/prosumers are represented by a physical point and desired consumption rate for consumers, and price signal is transmitted between the system operator and node. - Since the local users and preferences of end-users are available, Transactive control can also be considered as distributed control method. - The end user's participation in the transactive market has to bid its favourable amount of electricity and consumption modification based on market clearing price. *Network management based on transactive energy:-* - The TE based network management helps microgrid for its economical operation with local control of its generation and consumption with least dependence on main grid aiding in improving the reliability of whole LV system. - TE provides the flexibility of available resources with profits between aggregators and microgrid. - Microgrids can share energy among their neighbours to overcome network congestions and improve grid stability as microgrids can act independently of the main grid and balance the demand and supply based on local available resources. - The profit of the load aggregator can be maximised by cooperation between microgrids by determining the energy transactions to market. - Aggregator can assign cost and remunerations among the enrolled consumers and prosumers and thus directly coordinate with the demandside with several layers of EMS in the community of enrolled customers. - The base layer of EMS measures the generations and consumption in real-time. It consists of measurement devices.

Table 3. Various issues addressed and their salient features—II.

Issues Addressed	References	Features
Transactive energy architecture energy hub systems	[55–64]	- Local generating systems deployed at load centers have the potential to provide significant flexibility to prosumers, and grid operators. - Through multicarrier energy hubs, it is possible to serve the local electrical, heating, and cooling demands at the lowest possible cost in this paradigm. - The primary function of energy hubs is to service loads of consumers within their utilization region. In this sense, the operator of the energy hub is responsible for finding the ideal operating points for the hub's installed assets. - Unlike traditional customers, energy hub operators can sell excess electricity to the upstream grid, transforming them into prosumers in this paradigm because they can operate as both producers and consumers. - The ability of customers to trade energy within the P2P framework creates a new opportunity for end-users to trade electricity securely and cost-effectively.
New technologies and innovations in transactive energy	[16,18,31,67–74]	- New technologies like blockchain and IoT has been used for transactive control optimal consumption and management at residential and commercial levels. - To preserve the security and privacy of users, blockchain and holo-chain-based distributed ledger technologies are required. TE-based smart grid using distributed ledger technologies can be an effective solution for smooth and effective working of TE systems. - Block-chain technology can enable new business solutions and promise safe, flexible systems, store intermediary transactions, and can lead to smart contracts execution. - The current trend involves providing software platforms to P2P participants to manage energy trading through local electricity markets with both centralized and decentralized management approaches. - In transactive control, researchers need be focussed on financial transactions speed, data security, resiliency to failures etc. - The centralized microgrid management, aggregators, decentralized transactive control for resources management are the areas which need to be explored, along with the role of aggregators in the face of hierarchical and centralized structure of power system. - One area which needs exploration is the aggregators dynamics with decentralized TE systems with more tools to validate the test performance.
Transactive energy based power system flexibility	[16,19,76]	- The power system flexibility deals with the ability of the power system to cope with uncertainty and variability with the variation in generation and demand and TE maintains the dynamic balance between supply and demand by managing the flow of electricity, consumption, and generation. - Power system functioning is hampered by uncertainty resulting from incidents and the forecasting capability of demand and VRE generation, which affects reserve sizing and activation. - TE can act as a tool for making the power system more flexible to manage variability and uncertainty. - TE essentially has been an intelligent, multi-level communications method that coordinates energy generation, use, and distribution. Under the TE scenario, electricity suppliers, energy markets, the power grid, households, commercial buildings, and DERs, such as electric vehicles and batteries, will "talk" directly or indirectly with each other to negotiate energy needs and costs.

13. Conclusions

In this article, a comprehensive explanation of many TE ideas, such as their primary motivating factors, architectural design, the energy market, control/management, network management, and the adaptability of the power system, is presented. The following conclusions can be drawn from this paper:

1. When it comes to energy transactions, the concept of TE is progressing with a heavy emphasis on looking at things from a local, distribution-level point of view.
2. The majority of the currently available strategies are merely presented in the form of models; there is no actual world implementation to facilitate full validation. However, before such an implementation can take place, it is important to construct and deploy appropriate simulation platforms and tools in order to conduct an in-depth analysis of the data that were acquired.
3. In addition to this, every type of TE system needs to implement a design that is more effective in order to improve the reliability, adaptability, and accuracy of the results.

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Abbreviations

The following abbreviations are used in this manuscript:

AMI	Advanced metering infrastructure
DR	Demand response
DSO	Distribution system operator
EMS	Energy management system
EV	Electrical vehicle
HEMS	Home energy management system
HVAC	High-voltage alternating current
IEH	Industrial energy hubs
ISO	Independant system operator
PNNL	Pacific Northwest National Laboratory
RES	Renewable energy sources
TCL	Thermostatically controlled loads
TE	Transactive energy
TES	Transactive energy system
VRE	Variable renewable energy

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