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Towards transactive energy systems: An analysis on current trends

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A B S T R A C T

This paper presents a comprehensive analysis on the latest advances in transactive energy systems. The main contribution of this work is centered on the definition of transactive energy concepts and how such systems can be implemented in the smart grid paradigm. The analyzed works have been categorized into three lines of research: (i) transactive network management; (ii) transactive control; and (iii) peer-to-peer markets. It has been found that most of the current approaches for transactive energy are available as a model, lacking the real implementation to have a complete validation. For that purpose, both scientific and practical aspects of transactive energy should be studied in parallel, implementing adequate simulation platforms and tools to scrutiny the results.

1. Introduction

Nowadays, the management of power distribution networks is becoming more difficult than before, mainly due to high electricity demand and large penetration of Distributed Energy Resources (DERs) including renewables. The penetration of renewables as a mean of electricity production is expected to increase in the years to come up to around 30% by 2022 [1] and up to 60% by 2050 [2]. Renewable energy sources (RES) and DERs promise benefits such as the reduction of environmental concerns due to energy production, but at the same time will pose numerous challenges of technological, social, and policy related nature [3,4]. Therefore, the hierarchical and centrally-controlled approach of existing power distribution networks is moving toward a smart power grid paradigm in which the unforeseen peaks of distributed local energy production and uncertainty of renewables can be properly managed [5,6]. Smart grids are intelligent electrical networks employed for enhancing critical features of typical power system, such as flexibility, reliability, sustainability, efficiency, etc., by making the grid controllable, automated and fully integrated [5]. In such a new paradigm, the concepts of Demand Response (DR) programs and Transactive Energy (TE) are widely discussed in the scientific and research societies, with the purpose of balancing the network in term of consumption and generation [7]. In most of the cases, DR programs are only focused on the consumption part of the network, which brings flexibility to the grid by paying incentives to the electricity consumers in exchange of altering their consumption profiles [8–10]. However, only concentrating on the consumption management based on the generation rate might not fully exploit the capabilities of future smart power systems. Due to this, TE is discussed as a mean to not only focus on the consumption part of the network but also to provide solutions to manage the rate of generation in both grid and demand sides [11].

Smart grids, therefore, provide a basis for the implementation of TE systems. To do this, several requirements are essential in this context, such as two-way communication, merge of Information and Communication Technology (ICT) and electricity grid, intelligent and remote supervision, Advanced Meter Infrastructure (AMI) and smart metering [4]. In fact, TE systems expand the current concepts of wholesale transactive power systems into retail markets with end-users equipped with intelligent Energy Management Systems (EMSs) to enable small electricity customers to have active participation in the electricity markets [12]. TE systems can also enable peer-to-peer (P2P) management in smart grids by using intelligent devices in which each device has its own decision and objective.

Both DR and TE open new opportunities in power grids regarding the optimization of power flows, stability of the grid, and energy efficient. At the same time, distributed resources used for DR and TE are intermittent (e.g., in the case of renewables) and nonuniformly deployed, which possess new challenges to be faced in the management of resources [13]. These challenges can be tackled through centralized and decentralized approaches, each of which has its own advantages and disadvantages [14]. Therefore, proposed methodologies should be well tested and validated through several real case studies to identify the strengths and weaknesses on the implementation and preventing future problems.

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This paper presents a comprehensive survey and analysis on the latest advances of TE and their applications in the new paradigm of power systems. The main contributions of this paper are related to:

- TE definition and how TE systems are being integrated in the smart grid context.
- An analysis and comprehensive survey of TE research works, industrial projects and demonstrations.
- A classification of TE research based on the grid level of application into three broad areas: (i) transactive network management (management sector); (ii) transactive control (control sector); (iii) P2P markets (P2P sector).
- Identification of current challenges of TE systems and future work directions.

After reviewing up to 140 works (including articles, scientific reports, projects, and demonstrators) produced between 2006 and2019[1] related to TE, analyzing the keywords from those works, and identifying the grid level of application, the authors propose three areas in which TE concepts can be classified, namely: (i) transactive network management; (ii) transactive control; (iii) P2P markets. Fig. 1 shows the overall view of the identified concepts related to TE and how they can be positioned on the different layers of the power system. Transactive network management is considered as the first category since it is related to management sector of the electricity supply chain. Transactive control is considered as control sector, enabling network operators in the upstream side to control and manage the rate of consumption/generation of the electricity customers in downstream side. Finally, P2P markets are energy exchange methodologies in the P2P sector of electricity system allowing all consumers and prosumers to bid and offer for transacting energy. While this classification is not unique or universal, it can help the reader to positioning the area of study/application, and to devise the interconnection and reaches that a given TE system might have. The details of the topics in this classification are covered in Sections 3, 4, and 5 respectively.

In a complex multidisciplinary paradigm such as TE, both scientific and practical aspects should be considered, learning from past experiences to estimate and prevent probable future issues. Besides, adequate models and tools are essential to address the manners on how TE would be integrated within the current form of power systems. Therefore, this paper aims at surveying TE works to identify gaps and critical aspects in different sectors of the energy chain and to respond and overcome issues that might arise in the coming years.

The paper is organized as follows: After this introduction, Section 2 presents and discusses the main concepts that are used throughout the paper. Section 3 focuses on transactive control methodologies and how they can be integrated into the various kinds of buildings in the demand side. Also, a general overview and a critic analysis of the recent research work in this area is presented. Section 4 presents an overview of P2P markets from both network operator and end-users standpoints. A comprehensive analysis of energy negotiations and contracts for energy trading between customers is also presented. Section 5 surveys centralized and decentralized TE-based network management solutions, covering both models and studies proposed in the literature. Section 6 focuses on the implemented TE research and industrial projects and demonstrations. A classification of projects, differentiating the ones implemented in the United States and the ones in Europe, is also provided with the goals and achievements of each project. The challenges and issues identified through this paper for TE are mentioned in Section 7, along with suggested solutions as future work. Finally, the conclusions provided in Section 8 summarize the relevant points identified throughout the document, including advances and limitations that lead to emerging research paths.

[1] The reviewed work was obtained by searching keywords related to TE into scientific data bases such as: Scopus, IEEE, science direct, and official project websites.

2. Background

At the first stage, it is essential to survey the definitions of TE. There are various definitions proposed for TE in the current literature:

- *"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."* [15]
- *"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. Transactive energy 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."* [16,17]
- *"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."* [18].
- *"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."* [19].

Despite variations on the TE definition over different works, one of the most accepted definitions is the first one proposed by the GridWise Architecture Council (GWAC) (see for instance Refs. [13,20,21] in which this definition is used), defining TE as the economic and control methodologies for managing the rate of consumption and generation resources and the energy trading within a power distribution network based on market mechanisms. Other definitions (such as the ones presented above) are variations of this idea depending on differences in the context of application. Therefore, in this paper we adopt the definition from the GWAC to avoid any confusion to the matter. In this regard, a TE system is defined as the electric power systems in which TE concepts have been implemented and deployed across the levels of electricity grid for facilitating the integration of large numbers of Distributed Renewable Energy Resources (DRERs) [22]. To complement key TE related definitions used in this work, TE markets are related to electricity markets in which grid parties, agents, operators, and end-users provide bids and offers for exchanging energy with their own perspective of financial profit maximization [23,24]. Fig. 2 shows a diagram for a separation of the power grid into TE sectors.

The architecture shown on Fig. 2 is based on the infographic proposed by the GWAC in Ref. [25]. In fact, Fig. 2 illustrates how TE applies at all levels of the grid. As it is clear in the same figure, there are four layers in this diagram: residential, microgrid, local grid, and regional. In the residential TE network, all customers can produce and sell their energy surpluses as well as select a specific resource or multiple sources for purchasing energy. In the microgrid layer, advanced control and management of the network players enable the system to provide flexibility to the upstream networks. In the local TE grid, new services and opportunities might be provided to the customers to have active participation in the electricity markets. Finally, in the last layer (regional), interoperability is increased and efficiency and reliability of the network are enhanced [25]. Furthermore, some of the grid players on a comprehensive TE system as the one depicted in Fig. 2 have a crucial role in linking actors from different layers. For instance, Distribution System Operator (DSO) is accountable for the balancing of the electricity demand and supply at the distribution level, and also connecting the retail and wholesale market agents [25]. For this reason, some entities, e.g. the DSO or Transmission System Operator (TSO) in Fig. 2, are placed between two layers making interoperability possible between market participants.

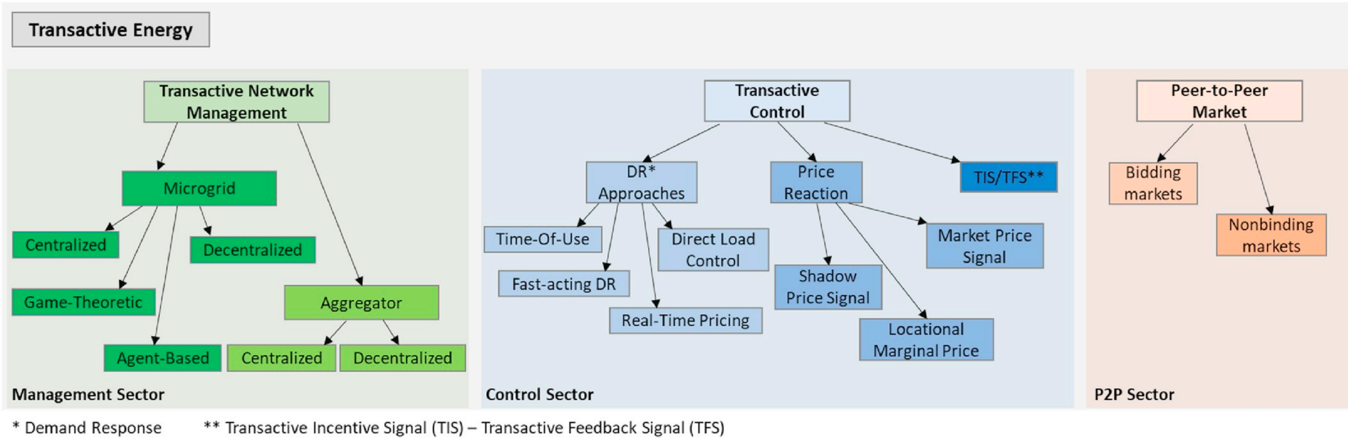

Fig. 1. A taxonomy for categorization of TE related concepts.

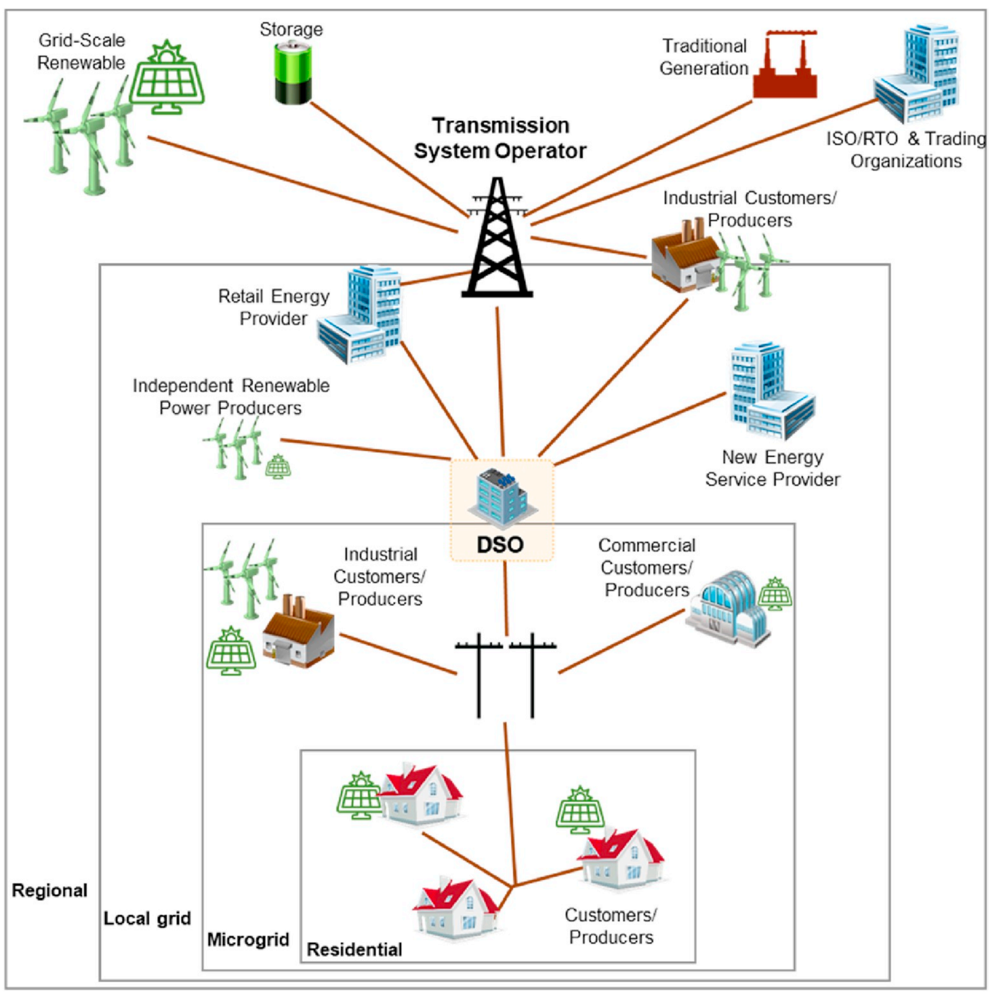

Fig. 2. The GWAC transactive energy diagram (adapted from Ref. [25]).

In a TE market, grid players (e.g., VPP, microgrids or buildings) and grid assets (e.g., storage units, DERs) can be considered financial drivers and active participants [21]. In line with the diagram presented in Fig. 2, using the GWAC TE framework, the costs and benefits of DRERs can be classified as in Ref. [26]:

- TE Products:
  - o Energy: electricity generated by a TE participant in a specific time and place;
  - o Transportation: The produced energy is transferred to another TE participant to be consumed or transferred to another participant;
- TE Markets:
  - o Forward Market: This market operates by relying on future delivery (producers mostly use this market);

- o Spot Market: This market is used for instantly delivery of products;
- TE Participant:
  - o Distributed Renewable Energy Resources (DRER): Generating electricity from renewable resources;
  - o Utility network: Including generators, consumers, and system operators e.g., DSO for delivering the electricity from producers to consumers;
  - o Consumer: Requesting energy for its internal demand;
  - o Regulator or Government: An entity for ensuring a safe and efficient transaction in the marketplace.

Following the above classification, in this paper, we consider that energy is a product in a TE system. Therefore, it can be transacted between different TE participants. Fig. 3 shows the process of energy negotiations and transactions in the TE systems. At the beginning of this process, the generated energy belonging to producers/prosumers (e.g., DRERs considered as a product) are located. Also, at the end of the process, consumers in the demand side are placed, where they are always purchasing energy. Based on the reviewed research works in this paper, it was found that energy can be traded on one of the following options depending on the costs and benefits impact into the system [27]: (i) to the TE markets, (ii) to a third-party entity, such as an aggregator, (iii) directly to the consumers. In correspondence consumers can also choose from where they intend to purchase energy. However, those choices for both energy resources and consumers depend on the capacity of production/consumption, since the small-scale resources could not directly participate in the TE markets [18].

One of the interesting points of the TE markets is the ability of multi-interactions with several platforms and markets. According to the definition of TE markets presented previously, it can be seen that TE markets have a feature of interacting with the wholesale markets and third parties, and simultaneously including local and P2P platforms to make the small-scale producers and consumers capable for trading energy directly and locally.

TE systems can also perform self-optimization to keep the stability and reliability of the grid while it controls DERs, especially renewable resources, and transacts power between heterogeneous participants [28]. In order to perform the self-optimization (or distributed-based optimization), price signal plays a key role, since it is a universal language for all type of devices and systems for making a decision and performing the optimal usage of the resources [27]. In the traditional distribution network, customers deal with a retail market, where they are commonly offered simple or double tariffs. However, this simplistic tariff schemes hide multiple components that constitute the consumer price such as use-of-system fees, taxes, retailer margin, among others [29]. Unlocking these components can be used as a basis for TE approaches in which consumers can exploit their flexibility to their benefit and the benefit of the system by taking profit of only the components related to them.

In a TE system, the DERs are integrated into the electricity markets. This can be done by encouraging the customers to invest in small and medium DERs in order to rapidly integrate DERs and take advantage of them in the wholesale markets [30]. In smart grids, the owners of DERs can control the rate of generation based on their own decisions as long as they do not affect the network balance and cause grid congestions. When the TE systems have been integrated in the smart grids, the concept of DR programs could not be limited to only consumers, and might expanded to the generation resources paying financial incentives to them for maintaining the network balance in real-time. This manner would be applied through a decentralized, autonomous and real-time methodology. Furthermore, TE-based power systems allow faster and two-way power flow and communication and utilize the demand-side resources to manage the network and perform energy transactions in the retail markets by employing decentralized intelligent devices and systems. Employing such systems has no time and location restrictions [31], however, such system face the challenge of data privacy and trust between network players and entities. Recently, the European Commission presented a proposal for a directive of the European Parliament focused on common rules for the internal market in electricity [32,33]. In this proposal, data privacy and protection are particularly addressed, and some specific rules have been presented for the privacy of smart metering systems, which are fundamental infrastructures for TE systems.

Based on the presented information, in the downstream level of the TE system, consumers and prosumers, no matter their size, can bid and offer energy. In this regard, the grid operator (i.e. the DSO) has a new minimal set of functional responsibilities, including reliable operation and coordination of employed DRERs (e.g., by the activation of available flexibility from end-users), and scheduling the energy exchanges with the upstream levels of the grid, such as TSO [22]. For instance, based on the universal smart grid energy framework (USEF) [34], the DSO can apply different actions to use the flexibility from the end-users available in the grid, namely reducing peak loads on congestion point, limiting connections when market-based coordination mechanism cannot

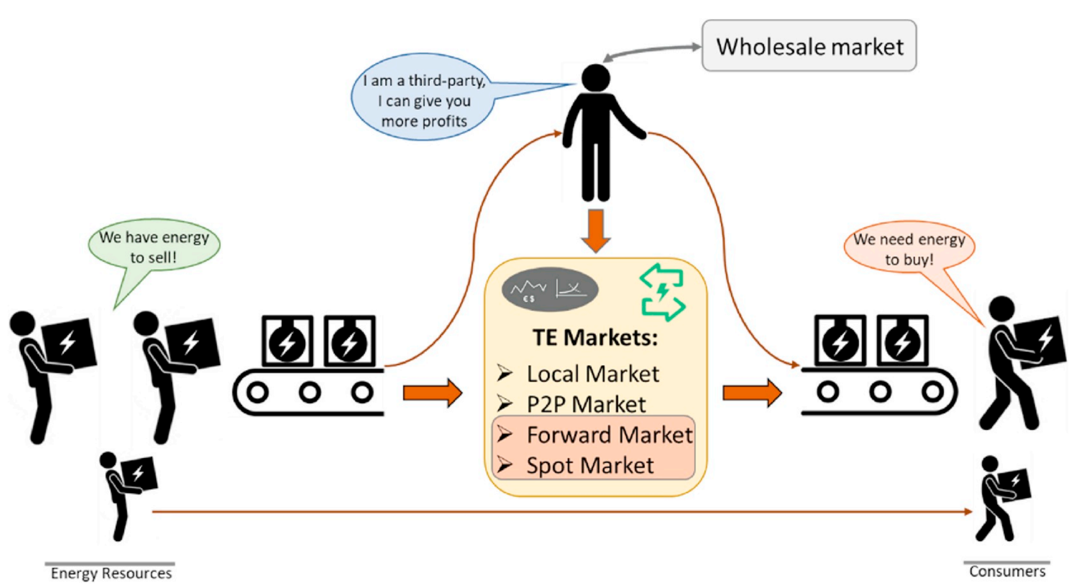

Fig. 3. Energy negotiations and trading process in a TE system.

resolve the congestion, or even activating primary grid protection systems to prevent damage to the grid.

In a TE system, consumer, producers, or prosumers equipped with specialized devices automatically negotiate with each other, and with dispatch systems of energy suppliers through market algorithms. Smart grid energy management approaches using TE system has been classified into four categories in Ref. [35] to discuss the advantages that such approaches can bring to the involved players. The categories are based on the way decision on local issues are made (i.e., centralized or decentralized) and the communication capabilities (i.e., one-way or two-way communication capabilities [35,36]). In the first category (i.e., centralized decision making and one-way communication), top-down switching is considered, where a centralized system makes decisions and transmits the results, such as optimal scheduling outcomes, to the end-users through a one-way communication. As an example, DR programs, in which a DR managing entity makes decisions to turn off/on the devices on the demand-side mainly through the use of Direct Load Control (DLC), are placed in this category. The second category (i.e., centralized decision making and two-way communication) is the centralized optimization methodology. This category includes the methods in which all demand-side customers transmit their information to a high-performance central optimizer unit, such as a VPP [37], and then the optimized output data is transmitted back to the customers. This methodology may have high operational costs as well as less reliability while the number of customers is increased. The third category (i.e., decentralized decision making and one-way communication) concerns price reaction systems. In this methodology, dynamic prices or a price profile for the next hours or next day are transmitted to a local automation system via a one-way communication, and the local system makes decision based on the received price rates and user preferences. The fourth and last category (i.e., decentralized decision making and bidirectional communication) is the most flexible one, referred as transactive control in Refs. [35,37]. This category includes the methods in which all demand-side customers, including residential houses, commercial and industrial buildings, provide a bid in a marketplace and perform energy transactions between each other in distribution level.

Transactive control is introduced as a methodology for managing the rate of consumption and generation of resources in demand-side through a transactive market. Transactive Nodes (TNs) are defined as connection points between different parts of the network for power flow [12]. All TNs constantly exchange information with each other sharing their latest status in order to make decisions locally. Therefore, they operate in a decentralized manner [12]. Distribution Locational Marginal Price (DLMP) is a basis for transactive control via electricity prices. Generally, DSO generates DLMP (based on marginal congestion cost, marginal losses expense, and marginal energy cost [38]) and provides it to the TNs. DSO utilizes DLMP as a control signal for dispatching economic optimization. While TNs received DLMP, they determine Transactive Incentive Signal (TIS) and Transactive Feedback Signal (TFS). Then, they transmit these signals back to the DSO as feedback signals. If TN tends to sell its energy surplus to the neighboring TN, it updates TIS. If this updated TIS is less than DLMP, the energy transaction is performed [24].

In order to exchange information between different levels of TE systems [39,40], proposed Open Automated Demand Response (OpenADR) as a useful tool for DR data transmission. By OpenADR methodology, all pricing and demand-side information can be exchanged between the TNs and upstream levels of TE system with a unique language. Fig. 4 presents the overview of OpenADR technique including Virtual Top Node (VTN), and Virtual End Node (VEN). As it can be seen in Fig. 4, the first layer includes the wholesale markets or ISO associated with VTN, whereas the last layer considers TNs as VEN. In the intermediate level, there are third-party entities, such as an aggregator, VPP, or retail markets considered as VTN/VEN. These entities are a bridge between the end-users (i.e., customers) and the upstream players of the grid (e.g., wholesale markets or ISO). By this way, any demand-side information or any trigger signal, namely price signal, can be transmitted between all infrastructure of the grid through a unique language, therefore, all network players would be able to transmit information.

3. Transactive control

A transactive control refers to the utilization of a fully decentralized methodology based on local information and market data in order to reach the network balance and smoothing network fluctuations [41]. Each TN is a physical point in the electrical network representing consumers/prosumers, substations, and utilities. The required data to be transmitted between each TN and the market or system operator is related to price signals and the desired consumption rate for consumers [42]. Transactive control can also be considered as distributed control method based on local information and preferences of the end-users [43,44]. In other words, if a typical end-user wants to participate in a transactive market, it should be capable of performing the following aspects [45]:

- Modifying its consumption based on market clearing price;
- Calculating the cost that it tends to pay for purchased energy;
- Biding its favorable amount of electricity.

Implementing DR programs in residential and commercial buildings using transactive control is a hot topic of a significant number of research works. Heating, Ventilation, and Air-Conditioning (HVAC) and Thermostatically Controlled Loads (TCLs) are the main targets for transactive control in residential and commercial buildings through DR programs [46–50]. A passive controller model has been designed in Ref. [51] for controlling the HVAC of an office building based on real-time market prices of TE system. Their simulation results demonstrated a significant amount of energy saving could be obtained by using the proposed passive controller model comparing to an office building with typical controlling methods.

A Home Energy Management System (HEMS) has been proposed and designed in Ref. [52], which can participate in the TE markets and modify the schedule of appliances based on price signals and local information defined by home inhabitants. The authors clarified the application of HEMS as TN and also its performance during the scheduling process. Fig. 5 shows the proposed modeling of HEMS for TE systems. The authors also considered the price signal as TIS and the power profile forecast as TFS. The use of this kind of transactive based HEMS brings flexibility to the power system that meets the objectives of both customers and network entities. Furthermore, the authors advanced a methodology for optimal scheduling of home appliances based on multi-objective optimization using a predictive control model. A case study has been presented in the same article, considering each HEMS would participate in the TE markets, and react individually to a price signal, such Time-of-Use (TOU) pricing scheme. Their results showed that there is lack of reliable management and coordination in the power systems when a considerable number of HEMS are applied.

Two transactive control strategies for residential HVAC have been surveyed in Ref. [53]. The first method investigates the cost savings by using transactive control without pre-cooling and in the second method it is considered to have a pre-cooling feature. In the first method, a cooling setpoint rate is defined by respect to the several factors, such as real-time market price, market price statistics, and user preferences and comfort. If a higher cooling setpoint selected due to the market price increment, the controller unit will not allow the cooling set point to go below the favorable temperature rate. In the second method, the controller unit lets the set point goes below the desired temperature rate while the market price is high. In the same article, actual model of a residential house, real market price data, and real weather data have been considered to compare and asses the two transactive control methods. The provided results illustrated that in a typical house under real-time pricing scheme, transactive control without pre-cooling is

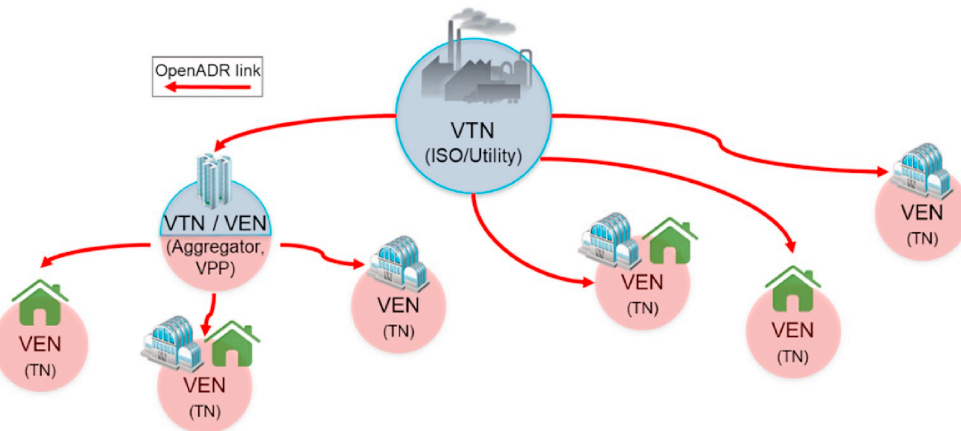

Fig. 4. An OpenADR methodology for TE systems.

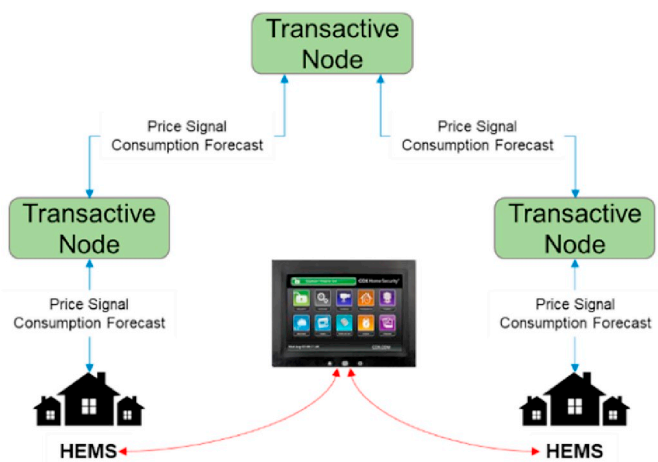

Fig. 5. Application of HEMS in a TE system.

more cost-effective and it can reduce the electricity bill costs.

Transactive control can also be implemented in commercial or industrial buildings with little or no additional development in their typical Building Automation System (BAS) [54–56].

A transactive control methodology has been presented in Ref. [54], which can be employed in a typical BAS. For this purpose, HVAC devices in several commercial buildings have been targeted in order to be controlled and modeled in a transactive control manner by using market data and price signals. In the same article, the authors provided several mathematical formulations regarding the desired temperature defined by users, outside temperature, and market prices. A case study has been presented in the respective article considering a commercial building with several offices and laboratories in Washington to implement, test, and validate the transactive control of HVAC devices based on market data. Although their results confirmed that the model can be implemented in the typical buildings without significant investment on the controlling and automation infrastructures, the authors pointed out that implementation of transactive control requires more investigation and survey since several practical issues, such as technical faults in the hardware devices are needed to be solved first. Similar work was developed in Ref. [55] focusing on experimental analyzes of a green building in Australia with respect to the transactive control over TCLs. Although both [54,55] proposed that transactive control can be implemented in a BAS with little or no capital investment, the experimental results demonstrated the need for a more efficient design and control in BAS since the inefficient operation and unexpected faults in sensors and communication protocols lead to have a gap between the expected and real results.

More focusing on residential transactive control and DR programs, a demonstration project so-called gridSMART [57,58] managed by Pacific Northwest National Laboratory (PNNL) was implemented in Ohio, United State, from 2010 to 2013, to survey the behaviors of residential consumers while they utilize bidding transactions of supply and end-use HVAC devices interfacing with a real-time electricity market. The results of project showed that applying transactive control with a 5-min basis in real-time pricing market, the majority of customers are able to configure their HVACs based on preferences and choices, also the efficiency and reliability of the distribution system can be improved by 30–40%.

Transactive control is also applicable to the EVs in a TE system [59–62]. Based on the work presented in Ref. [63], efficient and optimal charging of EV would be possible using transactive control in TE systems. Suppose that in a fully decentralized TE system, a DSO provides a DLMP for each TN (e.g., a house) in the network. Therefore, the end-users select the most affordable period for charging their EV based on the received price signal, and then, end-users transmit TFS back to the DSO. This will enable the DSO to determine the price signal for the next periods and provide new demand pattern for TN. The presented methodology is useful for DSO since it can manage the local demand by providing desired signal prices to the TN. According to the results of the case study presented in Ref. [63], this method not only is cost-effective for the DSO but also it can decrease the charging bill of EV owner by 60–75%. For reducing the network congestion and to prevent voltage violations due to the high penetration of EVs, the works presented in Refs. [62,64] introduced the transactive control as a solution for this issue. In the presented methodologies, a fleet operator is considered as a supervisory entity on the lower level of the network, which controls the charging schedule of the EV owners. Also, DSO located on the upper level of the network manages the fleet operator in a transactive control manner. By this way, DSO always supervises charging schedule of the fleet operator to check if there are any network operation violations. If violations in operation are encountered, the DSO can propose a shadow price[2] to the fleet operators to alleviate the congestion problem. On the other hand, the scheduling of fleet operator would be approved by DSO when no violations exist.

In order to summarize this section, Table 1 compares the analyzed works underlying their main characteristics and comparing the employed methodologies.

Moreover, Table 2 shows a classification for the articles produced in the scope of transactive control, which have been categorized according to the target control nodes.

[2] Shadow price can be a distribution marginal price from the marginal cost calculation and can be used as a price in the markets.

Table 1
Transactive control at distinct levels of the electric system.

Ref.	Target Loads	Target customers	Controlling Approaches	Purposes/Achievements
[45]	HVACs	Residential	DR	Transactive control in a residential double-auction market
[46]	HVACs	Residential	DR, DLMP	Hierarchical control of DERs and DR for a large-scale integrated transmission system coupled with multiple distribution systems
[53]	HVACs	Residential	Market price signal	The economic impact of transactive control for HVACs with and without pre-cooling considering user comfort and preferences
[57] [58]	HVACs	Residential	DR	Behaviors of residential consumers equipped with HVACs in bidding transactions
[47]	HVACs	Commercial	DR	A double-auction market framework to coordinate HVACs for DR programs
[51]	HVACs	Commercial	Market price signal	Advantages of transactive control for commercial buildings
[54] [56]	HVACs	Commercial	Shadow market signal	A market-based control strategy for typical BAS with little or no additional development to enable the commercial buildings more demand responsive
[55]	HVACs	Commercial	Market price signal	Experimental results of energy efficiency in a commercial building considering DRERs and transactive control over HVACs
[41]	HVACs	All customers	Market price signal	Power fluctuations in microgrids by considering a baseline load for HVACs control
[48]	TCLs	Residential	Fast-acting DR, DLMP	An agent-based method for TCLs to participate in real-time electricity markets
[49]	TCLs	Residential	Real-time pricing	Transactive control-based strategy for residential TCLs supporting real-time pricing
[50]	TCLs	All customers	Market price signal	Transactive coordination mechanism for TCLs considering market coordination signals
[52]	All loads	Residential	TIS/TFS	Transactive-based HEMS for home appliances considering signal prices
[44]	All loads	All customers	DR	Cyber-physical attacks through the transactive control mechanism
[42]	All loads	All customers	TIS/TFS	A simulation platform for evaluating hierarchical transactive control
[43]	All loads	All customers	Fast-acting DR	Balancing network authorities for power regulation in high renewable generation periods
[59]	EV		Real-time pricing	A multi-agent transactive control with high penetration of DRERs and EVs by respect to the customers preferences and voltage regulation constraints
[60] [61]	EV		Real-time pricing	Participation of EV owners in real-time pricing and double auction electricity markets based on transactive control
[62] [64]	EV		Shadow market signal	A multi-period network-constrained transactive control for EVs with respect to the energy inter-temporal features of EVs
[63]	EV		TIS/TFS	A transactive control methodology for optimal charging of EV

According to the information provided in Tables 1 and 2, research on some concepts of transactive control (indicated by gray in Table 2) is still poor. Most of the systems and models developed so far, apart from the type of the building, have chosen TCLs and HVACs as targets in order to implement transactive control. However, focusing only on those types of loads (e.g., TLCs and HVACs) might have an undesired impact in the inhabitants' comfort level. Thus, transactive control should be expanded to consider all types of the loads and devices in the buildings. Also, more attention should be given to residential buildings, as the consumption from those buildings accounts from the %35 of total consumption in the United States [52], making them a good target for transactive control implementation. Furthermore, a significant number of the articles focused on the modeling and theoretical aspects of transactive control. They tested and validated their developed approaches through the simulation platforms. There are a few numbers of research works focused on real demonstrations and testbeds for validating and examining transactive control case studies. Therefore, this bring an opportunity for the research society to cover these gaps and focus on such areas in future.

As a conclusion, transactive control will enable end-users to have active participation in TE markets. In fact, transactive control, especially at residential and commercial level, provides the means for optimal management of consumption and generation by taking advantage of technologies such as blockchain and Internet-of-Things (IoT), and giving network operators accessibility to manage end-users' devices and benefit from local flexibility.

4. Peer-to-peer markets

As it was mentioned in section 2, from DSO standpoint, high penetration of DRERs, especially renewable resources by their intermittent nature, may bring network management issues [65]. However, from electricity customers standpoint, DRERs are interesting since they can reduce the electricity bills by consuming their own generation. In this context, TE was proposed as a control method for integrating high penetration of intermittent DRERs in the grid while operating the system safely and efficiently [27]. However, P2P markets can be envisaged as a complete solution in order to satisfy both sides of the network. While TE is viewed as a control method, a P2P market is defined as energy sharing and trading among all consumers equipped with DRERs, which converts them into active customers (prosumers) in the market by selling/buying energy from each interconnected nodes of the network [66]. Therefore, P2P markets are fully related to TE system by representing one of the most promising paradigms for implementing TE markets. Notice that all these processes should be done at the distribution level of the network [67]. In other words, P2P energy trading allows direct energy sharing among consumers and prosumers in the local electricity grids [68]. Several research and industrial projects have currently surveyed the concepts of the P2P markets, focusing on energy trading on the distribution level to integrate all small and medium scale DRERs [69,70]. In

Table 2
Classification of research articles in the scope of transactive control.

<table>
<tr><th>Target Load</th><th>Transactive Control Method</th><th>Residential</th><th>Commercial</th><th>All customers</th></tr>
<tr><td rowspan="3">HVACs</td><td>DR</td><td>[45] [46] [57] [58]</td><td>[47]</td><td></td></tr>
<tr><td>Price Reaction</td><td>[46] [53]</td><td>[51] [54] [55] [56]</td><td>[41]</td></tr>
<tr><td>TIS/TFS</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">TCLs</td><td>DR</td><td>[48] [49]</td><td></td><td></td></tr>
<tr><td>Price Reaction</td><td>[48]</td><td></td><td>[50]</td></tr>
<tr><td>TIS/TFS</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">All loads</td><td>DR</td><td></td><td></td><td>[44] [43]</td></tr>
<tr><td>Price Reaction</td><td></td><td></td><td></td></tr>
<tr><td>TIS/TFS</td><td></td><td></td><td>[42]</td></tr>
<tr><td rowspan="3">Home appliances</td><td>DR</td><td></td><td rowspan="3" colspan="2"></td></tr>
<tr><td>Price Reaction</td><td></td></tr>
<tr><td>TIS/TFS</td><td>[52]</td></tr>
<tr><td rowspan="3">EVs</td><td>DR</td><td colspan="3">[59] [60][61]</td></tr>
<tr><td>Price Reaction</td><td colspan="3">[62] [64]</td></tr>
<tr><td>TIS/TFS</td><td colspan="3">[63]</td></tr>
</table>

section 6, the most relevant projects on this topic are briefly presented and compared.

In a P2P market, each prosumer has its local controller leading to have a totally decentralized market, which decisions will be made locally based on users and market information. For instance, the work presented in Ref. [71] considers each prosumer as a TN, and all TNs participate in P2P markets. In the same article, TNs submit a bid to the market and choose the trading partner considering several constraints to obtain the optimal and cost-effective performance.

All consumers in P2P markets become prosumers and they can trade the generation surpluses for the ones that request energy. This energy trading is performed based on several long-term or ad-hoc contracts between all grid players. Two kinds of contracts have been proposed by Ref. [72]: (i) between prosumers (as an example, one prosumer produces electricity and trades it to another prosumer); (ii) between the energy provider and consumers (for instance, one unit only produce electricity and the other one only consumes).

The energy transactions between prosumers in a P2P market are similar to the concept of internet when people share information. On the internet, there are several equivalent nodes that can be considered as "Client" or "Server" at the same time. This means each node of the internet simultaneously is client and server, which enables the network to share information and exchange data among the internet network. This fact is true also for P2P energy markets. All prosumers in a P2P market are simultaneously energy buyer and seller, and they can exchange information and make bids for selling/buying the surplus of generation [73].

Four operation modes in a fully P2P system have been presented in Ref. [23], where each prosumer, retail entities, and other market players are considered as a transactive agent or TN in the system. These four modes include:

1. Operating in autonomous mode where each agent or node makes decisions locally and based on its preferences and comforts;
2. Responding to bidirectional bids and offers presented by each agent or TN;
3. When the network players are operated in response to a trigger signal, such as DLMP;
4. When the system operates based on the instructions provided by a network manager, namely DSO.

In fact, the first two modes have fewer limitations for the agents and TNs in the network, although, they may reduce the reliability of the grid since DSO (or the system operator) is not entirely coordinating agent actions [23]. However, the last two modes are more restricted for the prosumers, but the network reliability and stability may be increased.

According to Ref. [74] and the hierarchical nature of the power distribution grids, P2P energy trading can be performed in three phases, as Fig. 6 illustrates:

- Phase 1: P2P energy trading inside of a local grid (e.g., microgrid);
- Phase 2: P2P energy sharing among several local grids inside of a cell (e.g., multi-microgrids);
- Phase 3: P2P between several cells (e.g., multi-cells).

Different arrangements have been investigated to perform energy trading in local distribution networks, such as the local pool concept in which aggregated distributed generation is used to balance local supply and demand with minimum generation cost [68]. On the other hand, the recently proposed "P2P economy" energy trading arrangement allows peers (e.g., consumers, producers or prosumers) to decide with which peer they want to trade the energy according to their particular objectives (e.g., cost, profits, pollution, reliability, and so on). For instance, to perform energy trading in a P2P market in Ref. [68], energy sellers broadcast messages with the amount of generation surpluses for the next time intervals. After that, all energy buyers make bids with the required energy rates and the favorable prices to buy energy. After the energy sellers receive and collect all the provided bids, orders are either accepted or rejected by suppliers with the intervention of the DSO whose decision is based on network constraints. After the order acceptance or rejection, the winners of the auction are announced and transacts energy between them. Since energy is delivered through the distribution network, all these operations should be done with surveillance of the upstream network entities (e.g., DSO).

Besides the hardware requirements and infrastructures for implementing P2P energy trading systems, a software layer is also necessary to implement. A software platform in the P2P market enables the network operator to control and monitor the energy trading, and also it allows data transitions between all P2P market participants. ELECBAY [68,75] is an example of these software platforms allowing P2P energy trading in a grid-connected microgrid. In this platform, energy sellers list the products for sale (e.g., energy surplus for the next 30 min), and energy buyers look on the listed products by all energy sellers, and then they select the most preferable case and place the order.

Nonbinding TE market can also be considered in the P2P markets. In this market, the energy trading is performed between flexible DRERs,

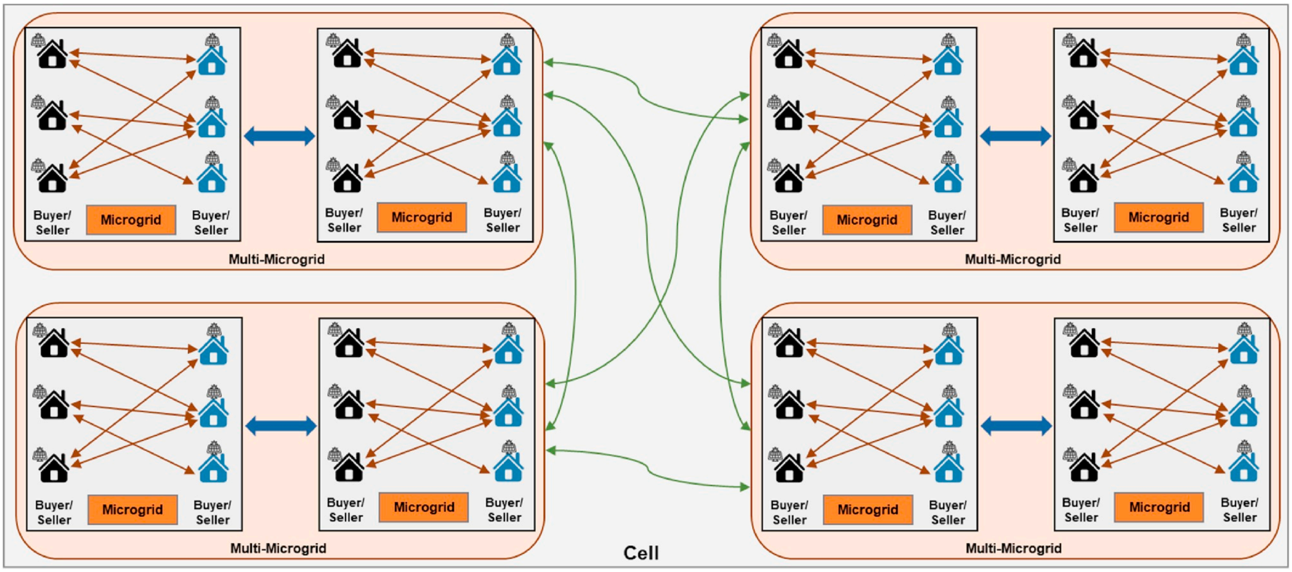

Fig. 6. Different levels of P2P markets.

which are transactive agents and DSO. In this market, the transactive agents publish their intentions for energy transaction and wait for receiving a permission signal from DSO. This means there is no obligation and commitment between the agents and DSO in advance to provide energy, and also, DSO is not obligated to purchase energy from the agents for a specified time [76].

A P2P market can also be combined with a VPP for energy transaction [77]. In fact, a single VPP deals with the demand-side, such as consumers and prosumers, and manages their consumption and generation rates in order to bring flexibility to the wholesale markets and DSO as well. In a P2P market, consumers and prosumers trade energy in demand-side, in order to fully benefit from their DRERs and they are in touch of a retailer as a coalition. The single VPP and the P2P market can be combined and be presented as a Federated Power Plants (FPP). In this way, all consumers and prosumers are in one side of the network as an FPP, which allows them an easy energy trading between each other as well as trading with other groups of prosumers. On the other side of the network, suppliers, large-scale generators, DSOs, and wholesale markets are placed, and a P2P energy transaction platform recognizes flexibilities for the network operator and provides them as contracts to the prosumers to manage the consumption and generation rates with respect to the contracts established for grid services.

With the increment use of aggregators (e.g., VPP) in the electricity markets, DR programs can be applied in the P2P markets as well. This enables the aggregator to react to DR signals by allowing P2P energy sharing between its clients. Several research works focused on the mathematical modeling and decentralized optimization methodologies for P2P markets. A P2P energy sharing model has been proposed in Ref. [78], where the authors developed a framework for the P2P market in three stages: in the first section, the model concerns about the value identification, which maximum available energy for trading in a region should be calculated and evaluated before any specific trading. In the second stage, the overall energy bill for the energy trading is estimated and modeled, and in the last stage, the economic operation index of energy sharing in the P2P market is defined and modeled. Furthermore, a game-theory-based algorithm is used in Ref. [79] for modeling the reactions of prosumers in a P2P trading market, and high penetration of DRERs is considered at the distribution level to calculate DLMP based on the power losses. In Ref. [80], the authors focused on a challenge of P2P markets that the pricing schemes should confirm that all P2P market participants could take financial benefits. For this purpose, they presented a two-stages control method that can overcome the proposed barrier through a constrained non-linear programming optimization to minimize the energy costs of the whole P2P market. The proposed model in the same article utilizes a rule-based control approach, which updates the respective set-points according to the real-time measurement data.

In a full P2P market [66], however, a crucial question that may be addressed is: how the upstream network entities can guarantee that all energy that a typical customer purchases from a peer producing clean energy, comes from a fully clean source? This means that energy buyers may have no information regarding the origin of the purchased energy. To overcome this issue, a power flow tracking algorithm [81] can be merged in the P2P markets for providing more information to the customers, such as the origin of the energy, transportation costs, and power losses. On the other hand, while a significant number of customers are integrated into the P2P markets, the systems may be faced with several challenges, such as the establishment of trust, proposing clearing prices and exchanging money between them after energy transactions. Blockchain technology and smart contracts are possible solutions for overcoming these barriers [82–84]. Implementation of smart contracts in a P2P market with a set of consumers and prosumers equipped with PV systems are demonstrated in Ref. [82]. In the same article, the authors proposed an architecture with respect to the blockchain technology where each energy seller and bidder send/receive a message to the blockchain with an encryption key pair to address the respective prosumer and sending the signed transactions. More focusing on the blockchain P2P markets, the work presented in Ref. [85] provided a smart management system to enable prosumers to trade energy in a fully decentralized market considering local DRERs. In the same work, contract theory has been employed to develop a smart contract for minimizing the necessity of surveillances in a real-time energy trading market.

In sum, P2P markets allow the participants to have energy transactions in the demand side. Most of the works are focused on the concepts of P2P energy trading, presenting several mathematical and optimization models in order to perform P2P energy trading. However, there is a lack of actual pilots for these models, and only a few numbers of works and research projects provide facilities to technically validate the models. There are some research and industrial projects that presented software platforms allowing P2P energy trading and data transitions between all market participants. However, the establishment of trust, proposing clearing prices and exchanging money between them, are still challenges in this context.

5. TE-based network management

This section focuses on the methodologies proposed for the management of TE-based grids, including microgrids and aggregators models. In fact, microgrids are capable to have local control on their electricity consumption and generation resources aiming at self-supply with minimum or no dependence on the main grid [86,87]. TE systems bring opportunities for microgrids to achieve their economic advantages as well as aiding the reliability of the entire distribution system [88]. Integrating TE systems into the bulk power systems and DSO enable microgrids and aggregators to improve the mutual benefits between themselves and the power system by providing the flexibility of the available resources [89].

In a residential microgrid, energy sharing among neighborhoods is an alternative to overcome network congestions and grid stability since the microgrid can supply its demand based on the local resources and independent from the main grid [90,91]. Furthermore, a group of TE microgrids[3] can provide flexibility to the distribution and wholesale markets by bidding transactive services, as Fig. 7 illustrates.

In this structure, load aggregator intends to maximize its benefits by bidding transactive services in the market. Based on the model shown in Fig. 7, the load aggregator is considered as an independent player interacting with distribution and wholesale markets, which has no control over the microgrids players. By this way, the load aggregator can maximize its profit by cooperating with microgrids in order to determine the capacity of energy transaction that can be transferred from a market to the other [92].

Aggregator can directly be in touch with the demand-side, coordinating the enrolled customers, including consumers and prosumers, and assigning the costs and remunerations among the customers [93,94]. To implement this concept, an EMS with several layers should be utilized in the community of enrolled customers. Based on the work presented in Ref. [95], the base layer of this EMS is the measurement devices, which measure the real-time state of the consumptions and generations. In the top layer of EMS, there is a processor in aggregator in order to compute the coordination signals, such as power references or price signals. Also, there is a communication layer between the base and the top layers of EMS, which is responsible for transmitting the measured data from the users to the aggregator as well as moving the coordination signals from the aggregator to the customers. In other related works in this topic, an optimization-based aggregator model has been presented in Ref. [96], which operates as a local market and optimally manages the controlled devices. The aggregation model provided in Ref. [96] allows energy trading between the consumers and producers in a small area, which brings flexibility for meeting the requests of upstream levels of the distribution network, such as DSO. The experimental results of the same article validate the performance of the developed optimization-based aggregator in real-time for controlled devices.

Energy transactions and management in microgrids or aggregators can be tackled in two ways [97]: centralized (optimization-based) and decentralized (transactive control), each with their own advantages and disadvantages. The centralized approach is not referred to a centralized unit control, rather, it refers to a centralized management optimization, in which controlling signals are transmitted to the TNs, however, this approach presents extensive communication infrastructure and huge computational burden. On the other hand, in the decentralized solution, the optimization and management are performed fully distributed, meaning that there is no centralized unit. The level of decentralization is defined by the intelligence of local controller units, which can be utilized just to execute commands and orders from upstream controller units or make their own decisions. This means, decentralization of the system is related to flexible operation, intelligence level of the local controllers and the capability of avoiding failures in the entire system when a single point fails [98]. Both centralized and decentralized methods have their own benefits and drawbacks and the suitability of the application of each is determined based on the type of microgrid or geographic attributes [98]. Table 3 shows the main differences between the two presented network management methodologies.

In the centralized management methodology, also known as optimization based TE microgrid [99–101], a central controller engages with solving several mathematical problems mainly focused on an optimal solution for minimizing the operational costs of the entire microgrid. This is done through the defined objectives for managing the energy resources and controllable loads [99,102]. The work presented in Ref. [101] is an example of centralized management, which provides an optimization algorithm for optimal scheduling in a centralized EMS of the distribution network (e.g., microgrid) based on TE concepts. In the same article, the cost minimization of the network is considered as an objective function by considering real-time pricing scheme. Furthermore, a mixed integer linear problem has been developed in Ref. [103] for co-optimizing microgrid behaviors based on TE concepts, such as reacting to the signal prices, by using Monte Carlo simulation for dynamic price signals computation. Moreover, in Ref. [104] the authors utilized a two-layers optimization method at the aggregator and customer levels, in order to solve two mathematical problems, both aiming at maximizing its own profits. In the same article, after performing the algorithms, aggregator transmits the optimal incentive signals to each consumer and prosumer, which enables them to participate in the TE markets whenever they prefer.

On the other hand, in a decentralized way, sometimes referred as transactive control [105–107], the management unit relinquishes solving complex optimization formulations. However, it provides optimal operational solutions by involving all network consumption and generation resources in a local energy auction bidding process. In a microgrid using transactive control, energy trading occurs between the consumer loads and energy resources in the local microgrid marketplace [108]. Beside this, layered decentralized optimization is another vision to manage a TE-based network in a distributed and decentralized way. In this approach, the optimization is performed at any layer of the system, and it only involves visibility to the interface points of upstream and downstream layers and there is no need to be aware of nature those layers [109]. In a decentralized management scenario, a failure of one node will affect only a localized part of the system, which can be diagnostic using P2P communications with other sections (e.g., agents), while the entire network will not be affected [110].

In the decentralized energy trading methodologies for both microgrids and aggregators, the system operator may witness with a challenge, which is determination of a reasonable pricing scheme for all resources that all participants could take financial benefits. This shows the need for comprehensive study on designing dynamic pricing approaches to optimize financial benefits for all energy resources (e.g., DERs), as the methodologies presented in Ref. [111].

On the other hand, neighborhood energy sharing in a residential microgrid can be considered as a solution instead of injecting the surplus of energy back to the main grid in order to maximize the use of local small-scale energy resources in demand-side [112]. Interconnecting microgrids, with the capability of energy trading between them, provide ancillary services for synchronizing and stabilizing of the power system [113]. This also leads to a reducing of feed-in tariffs in power distribution networks [114].

Several methodologies for energy sharing in TE microgrids are proposed in literature, which most of them aim to maximize the benefits of both energy buyer and seller. However, all proposed methods should be well tested and surveyed before the massive implementation of models. Transactive Energy Market Information Exchange (TeMIX) [115] is a pilot demonstration for live implementation of TE concepts developed by Cazalet Group [116]. In fact, the results obtained from the experimental tests shows the gap between the expected and real results, since

[3] In this work, in a general sense, a TE microgrid is referred to a microgrid that uses TE system to enable the energy sharing.

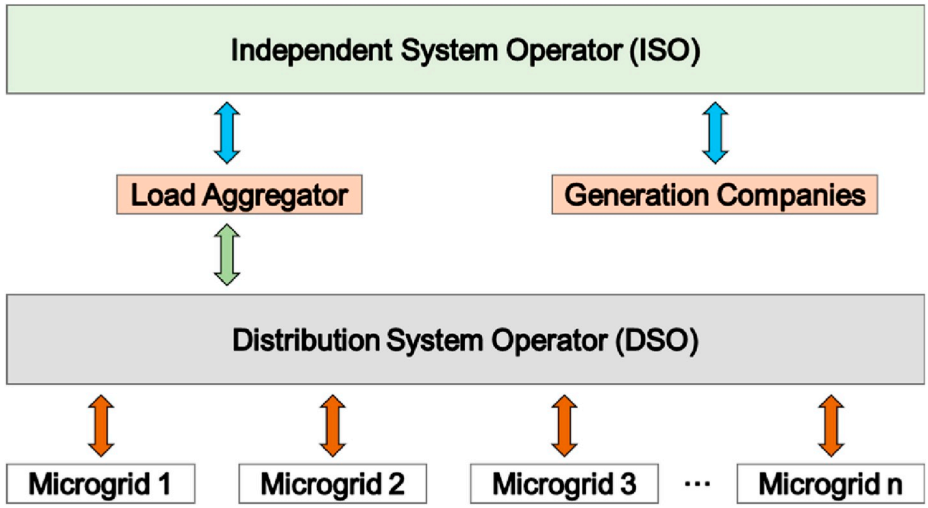

Fig. 7. TE Market structure including TE microgrids.

Table 3
Comparison of centralized and decentralized network management methods [98].

Features	Method	
	Centralized	Decentralized
Flexibility/Expandability (Reconfiguration, adaptability with other systems/agents)	Low	High
Reliability (Single point of failure)	Low	High
Installation Difficulty (Time and cost)	Low	High
Computational Cost (Complexity, space and time)	High	Low
Communication Facilities Cost (High speed control infrastructures)	High	Low

practical issues are typically hidden in simulation tests. Therefore, demonstrations such as TeMIX can be employed by research society to identify the strengths and weaknesses of business models before massive production. Furthermore, VOLTTRON [117] and C2WT-TE [118] are two other platforms that can be applied in this context.

Two approaches for a local TE microgrid have been analyzed in Ref. [119]. In the first approach, a pre-defined strategy is considered for energy exchanging between different nodes of the TE microgrid based on the energy shortage of the consumers and prosumers. The second methodology presents more flexibility to the microgrid players for energy trading by providing an open and competitive local TE market using a game theoretic method with a multi-player game. Based on the results presented in Ref. [119], it can be concluded that the second method brings more flexibility to the microgrids and its participants, while there is no significant difference in cost reduction compared to the first method. Moreover, different methodologies for TE network management in microgrids have been surveyed in Ref. [120] considering the collective and individual interests of microgrid clusters as well as each microgrid itself. In those methods, each microgrid can trade energy with other microgrids of the cluster in order to minimize its operating costs and maximize the energy savings. The proposed methods in Ref. [120] are validated in a local transaction market including 16 microgrids, and the results showed that the energy price can be optimally calculated through the presented models, while the cluster of microgrids can achieve 15% cost saving comparing to the microgrids without clustering.

Multi-agent solutions and islanded TE microgrids are also widely discussed in literatures [121–124]. A rural off-grid microgrid has been modeled in Ref. [122] based on multi-agent transactive scenarios for energy trading between each node of the microgrid. The proposed solution in Ref. [122] focused on multi-priority load clusters with parallel control of typical devices for managing demand/supply of microgrid. Beside this, a multi-agent based Comprehensive Energy Management System (CEMS) has been presented in Ref. [123] for energy transaction in a multi-microgrid market. The CEMS in each microgrid optimally managed the local energy resources available inside of microgrid and allowed microgrid participants to trade energy between each other in an internal auction-based electricity market. Also, the proposed model in Ref. [123] enabled all microgrids to trade energy with the neighboring microgrids in the wholesale markets for maintaining the network balance.

As a result of this section, Table 4 compares all surveyed articles focusing on TE management approaches underlying their main achievements.

Based on the information presented in Table 4, it can be concluded that most of the developed models focused on the centralized management method for residential microgrids and aggregators. This shows the lack of in-depth scientific surveys regarding the commercial and industrial sectors who are merged in the microgrids and aggregators. Therefore, it is required to have more investigations about the commercial and industrial buildings from both mathematical models as well as practical implementations standpoint.

Furthermore, Table 5 demonstrates a classification of analyzed articles and scientific reports, which are categorized based on the management approaches and the related entity. As Table 5 demonstrates, most of the articles considered the implementation of TE concepts on microgrids using different approaches, such as centralized, decentralized, game-theoretic, and multi-agent modeling.

The most important point that can be figured out from Tables 4 and 5 (as highlighted with gray in Table 5) is that there are no references or research articles that specifically address and investigate the aggregator using TE systems through decentralized approaches or other similar methods such as multi-agent modeling. The role of aggregator in the current power system architecture is becoming more important all around the world. For example, several countries are currently accepting the participation of aggregators in several energy markets (e.g., United States, France, Finland, Denmark, and Austria) [127,128]. Furthermore, the centralized and hierarchical structure of the power system is being decentralized and distributed. Consequently, studying the dynamics of TE systems under a decentralized scheme for aggregators provides a path for future research worth to be explored. The integration of TE systems in the current role of aggregators will require different management approaches (e.g., decentralized or multi-agent modeling) in order to comply with the decentralized nature of a TE system and identify barriers that may arise in this scenario.

Table 4
TE sharing approaches.

Ref.	Management Approaches	Manager Entity	Purposes/Achievements
[86] [88]	Centralized/ Decentralized	Microgrid	Identifying practical remarks and restrictions for TE microgrids
[89]	Centralized	Microgrid	TE approaches in microgrids for DRERs at bulk power/transmission operation level
[92]	Centralized	Microgrid	Remarks and challenges of energy transaction between a group of microgrids in distribution networks considering wholesale markets
[99]	Centralized	Microgrid	TE management model for a rural village DC microgrid based on market data and DR programs for multi-priority grouping control of non-smart devices
[100]	Centralized	Microgrid	Two dispatch optimization tools for controlling TE systems
[101]	Centralized	Microgrid	A centralized optimization-based EMS in a distribution network (e.g., microgrid) for optimal resources scheduling based on TE system.
[103]	Centralized	Microgrid	Co-optimizing microgrid behaviors based on TE system, for dynamic price signals
[112]	Centralized	Microgrid	A hierarchical TE network management methodology in a residential microgrid
[120]	Centralized	Microgrid	Various methodologies for TE network management in a cluster of interconnected microgrids
[93]	Centralized	Aggregator	A flexible and scalable TE system for optimization-based multi-energy aggregators
[94]	Centralized	Aggregator	Transactive market modeling with hierarchical optimization levels considering PV and DR
[95] [96]	Centralized	Aggregator	An optimization-based approach for energy sharing in demand-side coordinated by the aggregator
[104]	Centralized	Aggregator	A two-layers optimization method at aggregator and customer levels aiming at maximizing financial profits for both levels
[90] [125]	Decentralized	Microgrid	Blockchain methodology for energy trading in a microgrid
[97]	Decentralized	Microgrid	A distributed optimization technique for TE market of a residential microgrid to optimally charge and discharge the energy storages
[106] [107]	Decentralized	Microgrid	A distributed based energy management solution for energy systems (e.g., microgrids) using energy hub and local autonomous optimization
[108]	Decentralized	Microgrid	The decentralized dynamic market mechanism for microgrids considering the optimal automated transactive procedure
[114] [119]	Game-theoretic	Microgrid	Prioritizing customers for trading energy within a residential microgrid
[126]	Game-theoretic	Microgrid	Event-driven TE system for energy trading between microgrids based on a consumer-oriented and aperiodic market model
[121] [122]	Agent-based	Microgrid	Multi-agent modeling for energy trading among a rural off-grid microgrid
[123]	Agent-based	Microgrid	Multi-agent based TE system for energy sharing in a multi-microgrids market as well as the internal auction-based market.

6. Implemented TE projects

The primary goal of this section is to present and summarize the implemented projects in the United States and Europe regarding TE to have an overall perspective on the developed TE systems so far. Some projects aim at the development of TE system, whereas others focus on the local controls and decentralized methodologies to adequately address the TE concept. Table 6 and Table 7 show a clear comparison and overview on the implemented projects, pilots, and testbeds in the United States and Europe respectively, which have been classified based on the main purposes and the scope of each project.

According to the information shown in Tables 6 and 7, three categories can be proposed for TE projects: (i) projects that only study and survey the trend of TE concepts for future smart grids; (ii) projects that provide testbeds and laboratory facilities for testing and validating TE system; (iii) industrial projects that implement TE concepts in the current form of power system and enable the society to be familiar with those concepts. These advancements in TE systems show the intention of network management entities all around the world to utilize TE in power systems. In the United States, transactive control is the hot topic of TE systems, and most of the presented projects focused on this topic by providing several demonstrations and testbeds for transactive control. Although, in Europe, P2P energy trading attracted the attention, and most of industrial and research projects implemented and surveyed all features of P2P energy trading systems.

7. Trends, identified challenges and future research directions

Most of the research work about TE systems are focused on the mathematical models and formulations, paying almost no attention to the real and practical issues that might arise in the implementation phase. Regarding transactive control, most of the implemented works are focused at the residential and commercial levels by taking advantages of new technologies, such as blockchain and IoT, to have optimal management on consumption and generation rates in demand side. Also, the current trend on P2P market is centered on surveying the P2P energy trading in a theoretical phase, including mathematical and optimization models, and providing software platforms for P2P participants to have management on energy trading through local electricity markets. Furthermore, in TE-Based Network Management, the trend is centered on the optimization methods and application of blockchain in microgrids considering both centralized and decentralized management approaches. Microgrid cost optimization models considering customers reacting to the signal prices is another popular topic in the current trend.

In this regard, adequate simulation platforms and tools are required to scrutiny the practical challenges of the TE system, such as implementation costs, required automation infrastructure, network assets response time, devices and communication failures, physical or cyber-attacks, and also electrical grid conditions, namely voltage and frequency variations. In fact, only a few articles surveyed the implementation of TE systems, which also demonstrates a wide gap between the expected and real results. Therefore, the need of technical verifications of the TE systems by the emulation tools and prototypes is obvious for avoiding the failures in the implementation phase. There are a few industrial and commercial projects that have implemented TE systems in real infrastructures, such as energy trading in some residential microgrids [139]. Furthermore, some of the projects provided emulation-level platforms enabling operators to validate the TE system [132,133]. However, it should be stressed the importance of moving towards TE projects and demonstrations that include a validation phase since different of the mentioned practical issues that might arise during the implementation of TE systems remain hidden in the simulation level (which is the case of many of the articles surveyed in this work).

More specific challenges in TE systems can be identified in the transactive control, such as data security and privacy, speed of financial transactions, resiliency to failures and energy footprint [13]. The current

Table 5
Classification of research articles and reports in the scope of TE management methods.

	Microgrid	Aggregator
Centralized	[89], [92], [99], [100], [101], [103], [112], [120]	[93], [94], [95], [96], [104]
Decentralized	[90], [97], [106], [107], [108], [111], [125]	
Game-theoretic	[114], [126], [119]	
Agent-based	[121], [122], [123]	

Table 6
Implemented TE projects in United States (TC = Transactive Control; TM = Transactive Management).

Ref.	Project Name	Objectives	Outcomes	TE Area		
				P2P	TC	TM
[129,130]	Olympic Peninsula GridWise	Test and validate TE systems experimented with actual energy pricing and smart appliances	Automatic load responding to price variations in a very short time scale		**	
[57,58,99, 131]	AEP gridSMART	Controlling residential HVACs in response to 5 min pricing signals	Intelligent software platform for acting in the real-time market		**	
[129,132] [133]	Clean Energy and Transactive Campus	TE implementation in large-scale buildings with high penetration of DERs	A multi-campus testbed for transactive control and TE management researches		**	+
[58,129] [134–136]	Pacific NorthWest Smart Grid	Evaluation of transactive control approaches in the current state of smart grids	Many key functions for future smart grids including TE concepts		**	
[137]	Connected Homes	The transactive control operation in residential buildings	Integrating IoT devices to automatically adapt them to transactive control		**	
[89] [138]	OATI Microgrid Center	Implementing a microgrid center including DERs and renewable sources	A microgrid testbed with sophisticated control and optimization software			+
[139] [140]	The Brooklyn microgrid	P2P TE microgrid using the blockchain	A live demonstration of energy trading between prosumers in typical power networks	*		
[115,129] [141]	TeMiX	Automated energy transaction and decentralized network management	TeMiX: A cloud-based software platform for energy trading.	*		+
[142]	Kealoha	Implementing P2P markets by considering solar generation	Solar implementation and a software platform for trading the excess of solar generation between houses	*		

Table 7
Implemented TE projects in Europe (TC = Transactive Control; TM = Transactive Management; ICT=Information and Communication Technology).

Ref.	Project Name	Country	Objectives	Outcomes	TE Area		
					P2P	TC	TM
[129] [143]	PowerMatcher	Netherlands	Smart grids coordination mechanism by considering DERs and flexible loads	A TE platform as a bridge between network operators and smart devices		**	+
[144] [145]	EMPower	Norway	Local electricity market to advance the role of prosumers in smart grids	A trading platform for local energy exchange in local markets	*		
[146]	Couperus Smart Grid	Netherlands	Using PowerMatcher technology for coordinating energy demand and reducing peak load	Around 300 apartments equipped with heat pumps for optimization and participating in TE system		**	
[147]	Powerpeers	Netherlands	Blockchain energy markets for P2P energy sharing among residential buildings	Implementing a P2P market for energy trading in Netherlands based on Blockchain	*		
[148]	Share&Charge	Germany	Blockchain energy markets for EVs	A decentralized protocol for EV charging, transactions, and data sharing	*		+
[149]	Piclo	UK	Selling and buying smart grid flexibility services and P2P energy trading	A software platform for network operators for P2P energy trading	*		
[150]	Vandebron	Netherlands	P2P energy trading from suppliers and customers standpoints	A platform for electricity consumers to select the desirable local sustainable producers	*		
[151]	Peer Energy Cloud	Germany	Local energy sharing by considering local sensors and actuators in demand side	Smart Microgrid Cloud services: A cloud-based platform for local energy trading and smart homes	*	**	
[152]	P2P–smarTest	Finland	Smarter electricity systems by considering ICT and P2P approaches	Demonstration of a smart grid based on TE concepts able to perform P2P energy trading	*		+
[153]	Smart Watts	Germany	Novel methodologies for energy optimization through ICT	A gateway for smart meters to be used on the Internet of energy			+
[154]	Sonnen Community	Germany	P2P energy trading considering solar and storage systems	P2P energy sharing platform considering a virtual energy pool	*		
[155]	Lichtblick Swarm Energy	Germany	An energy management platform for the distribution network	An IT platform for customers to be connected to each other and optimize the use of local DER			+
[156]	ELECTRON	UK	Decentralized solutions for electricity markets based on Blockchain	A flexible system for electricity metering and bills for energy sectors			+

stage of research works on transactive control is limited to HVAC and TCL in the residential and commercial buildings using DR programs as well as price reaction approaches. Cooling and heating processes are vital for all types of the buildings, and controlling the HVAC is directly affecting the inhabitants comfort level, and the reliability of HVACs and TCLs in transactive control may be reduced while the user comforts and preferences are violated. Therefore, focusing only on the implementation of transactive control in HVAC and TCL is not an ideal approach. In fact, transactive control should be dispatched to the all types of the loads and devices in the building. As an example, the lighting systems of the commercial buildings (e.g., office buildings), are an appropriate target for transactive control, since they are much more flexible in term of control comparing to the HVACs and TCLs [157,158]. Surveyed work shows a progress on the combination of TCLs and lighting systems of commercial buildings (e.g., office buildings) as suitable targets for applying transactive control (such as TIS/TFS). Furthermore, more attention should be given to apply transactive control on residential buildings, since they account for a significant part of consumption all around the world (36% of the electricity load in United States are dedicated for the residential building [52]). Moreover, implementation of the transactive control on the home appliances provide flexibility to the network and enable the grid operator to optimize the operational costs by performing the decision making less dependent on communication with web-based energy management optimization [121].

Similar to transactive control challenges, a significant part of articles on TE network management is dedicated to a few specific topics. Through this paper, it has been identified that microgrids and aggregators are two main entities in most of the articles presenting TE network management models. Also, centralized microgrid management method is the hot topic of those articles. Although centralized aggregator approaches have been surveyed through some articles, aggregators using decentralized TE system for management of resources are not well investigated, and the issues and challenges are not yet identified. The role of aggregators is becoming more evident nowadays in electricity markets, and several countries are accepting the participation of the aggregators in the electricity markets [127,128]. Furthermore, the centralized and hierarchical structure of the power system is being decentralized and distributed. Consequently, studying the dynamics of aggregators using decentralized TE system provides a path for future research worth to be explored.

In P2P markets, more prototypes, laboratory platforms, and tools are needed to enable the research society to validate and test the performance of models before implementation in the electricity markets. Moreover, in a near future where it is expected a significant number of customers participating in P2P markets, the system may face challenges such as the establishment of trust between customers and the way of exchanging money between them. Currently, there are some articles providing solutions for overcoming these issues, such as blockchain technology and smart contracts [82–84]. However, the studies and surveys around these approaches still lack maturity and validation in real case studies is required to prevent future problems thoroughly. Another identified issue in P2P markets is to recognize the origin of the transacted energy properly. In a P2P market, the energy buyer may not have any information about the origin of purchased energy, and this is a challenge for the grid entities that should guarantee that the transacted energy has been produced by a fully clean energy source (e.g., a demand-side renewable source). A few numbers of research papers focused on this challenge and provided some solutions, such as tracking algorithm [81], to overcome the particular issue. However, more attention should be paid to P2P markets to identify how the blockchain technologies and smart contracts will operate in a real complex P2P energy trading, while a lot of small-scale prosumers merged into the power distribution network.

8. Final remarks

Transactive energy concept goes forward in the energy transactions with deep concern on the local, distribution level, perspective. In fact, most of the current approaches are available as a model, lacking the real implementation in order to have a complete validation. Before such implementation, however, it is needed to develop and implement adequate simulation platforms and tools to scrutiny the results. Also, it is evident the need for a more efficient design in all TE systems in terms of reliability, flexibility, and accuracy of results.

In this paper, a taxonomy has been provided for the classification of the TE concepts, which can help the reader to positioning the area of study/application, and to devise the interconnection and reaches that a given TE system can have.

On the control technology level, several technologies are available for air conditioning and other appliances, but additional efforts should be made to cover all the consumption appliances, so the full potential of transactive energy is achieved at residential and small buildings level. A restricted focus only on some specific consumption appliances might have an undesired impact in the inhabitants' comfort level. Thus, transactive control should be expanded to consider take advantage of all types of the loads and devices in buildings.

In a more specific business model approach, the management in peer-to-peer markets can bring several challenges, including the trust between customers and the way of exchanging money between them. Blockchain technology and smart contracts are an excellent basis to support the money exchange, but additional work is needed in the trust topic. Finally, the share of information concerning peer-to-peer transactions among the players and entities operating technically and economically the energy system requires discussion, so the relevant information is made available only for the necessary players and entities.

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Declaration of competing interest

The authors declare that they have no competing interests.

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