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Paving the Path for Two-sided Energy Markets: An Overview of Different Approaches

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ABSTRACT The transition in the energy sector, initiated by increasing uptake of distributed energy resources (DER) and grid digitization, provides opportunities to improve energy efficiency through electricity market reformation. The development of a two-sided market allows delivering benefits of improved efficiency to energy customers. This paper discusses the opportunities and challenges related to transitioning to a two-sided energy market. The drivers to move toward a two-sided market, the benefits that this market can provide for different stakeholders, and enabling technologies for this transition are studied. An overview of different approaches that lay the groundwork for two-sided markets, including demand response (DR), virtual power plants (VPPs), peer-to-peer (P2P) trading, and transactive energy (TE) is provided. A classification of different approaches, along with examples of academic and industrial works, are presented to give some insights on the way each approach can pave the path to the market reformation. Finally, different approaches are compared and some of the challenges that need to be addressed in future works are identified.

INDEX TERMS Demand response, distributed energy resources (DER), negawatt trading, peer-to-peer (P2P) trading, transactive energy (TE), two-sided market, virtual power plant (VPP).

I. INTRODUCTION

THE deployment of distributed energy resources (DER) and renewable energy resources in electrical grids is significantly increasing throughout the world. In 2017, the installed capacity of rooftop photovoltaic (PV) systems reached 400 GW, which was 50 times higher than the installed capacity in 2007 [1]. By 2022, global renewables electricity generation is expected to reach 30%, up from 24% in 2016 [2].

At the same time, recent advances in technology have changed the nature of energy customers from passive to active players, enabling them to actively adjust their loads by responding to signals from the grid. Triggered by these changes, the electricity market needs a reformation. Electricity networks were initially designed by assuming one-sided power flow from large-scale generators to consumers at the edges of the distribution system. Correspondingly, the market was designed by placing a greater emphasis on the supply side to be dispatched to meet demand. However, advances in technology aligned together with the rapid growth in the customer adoption of DER are forming a decentralized environment, in which numerous small-scale generation units as independent entities are connected to the distribution grid, resulting in bidirectional power flows. Due to the large number of DER, and change in the nature of energy consumers to prosumers, it is challenging to design a centralized market that could serve customers in distributed locations [3]. Instead, two-sided markets can be established as an interface between end-users at distribution level and the wholesale markets to enable a more effective participation in the market by even small consumers like homes and small businesses.

A two-sided market is a market model that promotes direct interaction between suppliers and customers [4]. In simple terms, in a two-sided market, two user groups or agents interact through an intermediary or platform to the benefit

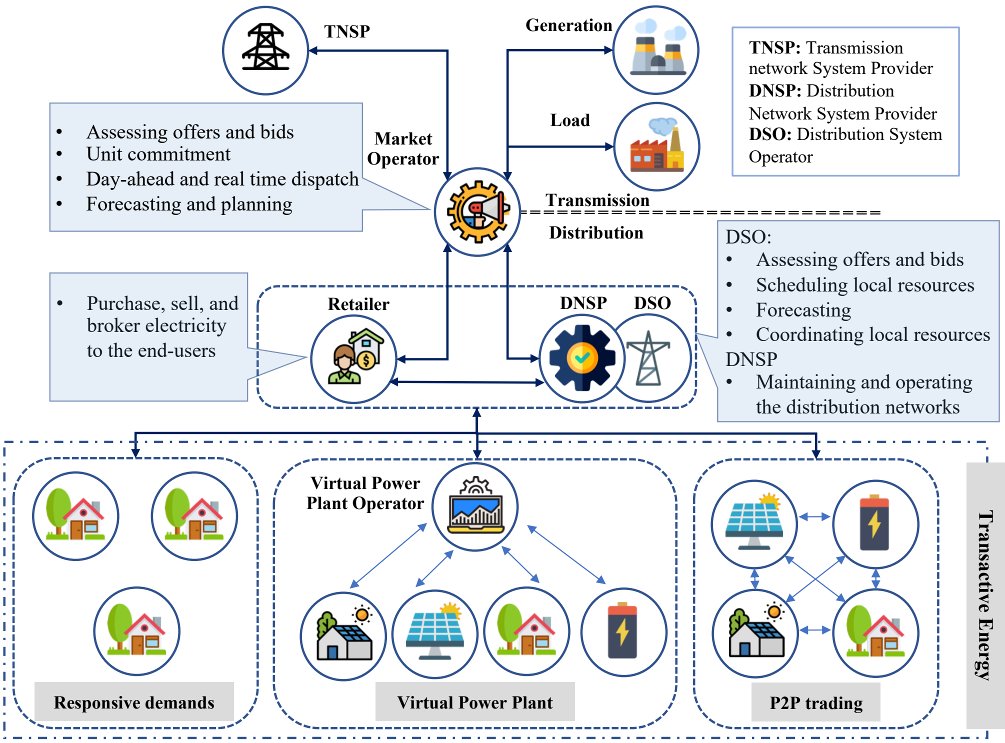

FIGURE 1. An overview of a two-sided market. Icons in this figure are made by Freepik, Eucalyp, Pixel Perfect, and Smashicons from www.flaticon.com.

of both parties, and the decisions of each set of agents affect the outcomes of the other set of agents [5]. In the case of electricity markets, a two-sided market would be formed by quantity and price inputs from both demand and supply sides of the electricity, which enables a more effective participation in the market by even small consumers like homes and small businesses. The concept of the two-sided market participation is already in place in wholesale markets, in which generating and load serving entities can participate in the forward markets and submit their bids in the pool market. However, the administrative, infrastructural and operational framework as is used in the wholesale market can not be employed for two-sided markets. The nature of end-users is different from load entities or retailers who participate in the forward contracts. Also, the number of market participants at the distribution level is significantly larger than the wholesale market. Therefore, there are some barriers such as rules around minimum bid/offer size and difficulties to get market access in replicating the same operational framework for the two-sided market at distribution level.

A range of various approaches can be employed in the path of transitioning to two-sided markets. These approaches can be classified into four groups based on their coordination structure, exchanged signals for integrating end-users in the market, and the extent to which demand and supply sides are involved. The first approach is demand response (DR), where the flexibility of demand-side is exploited for power adjustment. DR integrate demand-side in the market activities through direct or indirect control signals. An alternative approach for integrating DER and flexible loads in two-sided markets is to orchestrate and coordinate them as a virtual power plant (VPP) [6]. Through a top-down structure, a VPP coordinates end-users as a single entity in the two-sided market. The third approach is peer-to-peer (P2P) trading, which has emerged as a viable option for trading in a two-sided market and allows small-scale prosumers and consumers to actively participate in the market and exchange electricity and other services. Transactive energy (TE) is another approach for implementing the trading scheme in two-sided markets. It uses value based signals to manage both the supply and demand sides in the market [7]. Through employing price signals, TE systems coordinate DER and facilitate their integration in the grid, while maintaining the system reliability. Fig. 1 shows an overview of a two-sided market model, its key entities, and different trading arrangements which can be used in the market.

There are a few works in the literature that review the concepts related to DR, VPP, P2P and TE. Examples of these works include [8]–[17], which cover miscellaneous concepts related to DR, [18]–[22] in topic area of VPP, [23]–[27] on P2P trading concepts, and a few recent works [28]–[35] about TE mechanisms. As it will be better described and detailed in the next section, existing works have discussed DR, VPP, P2P, and TE essentially in a distinct way, but a comprehensive study on the requirements of a two-sided market also comparing and contrasting these approaches is still lacking. Therefore, in this paper a comprehensive study of two-sided energy markets, including the main drivers for

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two-sided markets, the benefits of these markets for different stakeholders, and enabling technologies for the market reformation is provided. The essential elements and requirements of a two-sided market are discussed. Then, a classification of different approaches facilitating the transition toward a two-sided market, along with examples of academic works and pilot projects for each type of trading are presented. The novel contribution of this paper are as follows:

- The essential elements and requirements of a two-sided market that promotes direct interaction of demand and supply sides are identified to provide a benchmark for a coherent and efficient market design.
- The leading technologies that expedite the transition to a two-sided market are discussed, including Internet of Things (IoT), blockchain, and machine learning (ML).
- An overview of different approaches for transition to a two-sided market are provided, with a detailed discussion on the way they facilitate a two-sided market implementation.

The rest of this paper is organized as follows. Section II provides a review of research works related to the two-sided market context. The motivations and benefits of a two-sided market are presented in Section III. In Section IV, key elements and the enabling technologies for a two-sided market are introduced. An overview of different trading arrangements in a two-sided market are presented in Section V, followed by a detailed discussion in Section VI. Finally, Section VII concludes the paper by summarizing topics valuable to investigate for future research.

II. LITERATURE SURVEY

A range of studies have been performed in the literature in the topics related to two-sided markets, including DR, VPP, P2P and TE. DR and its applications for demand-side management have been reviewed in several works. An extensive review of DR potentials and benefits, and enabling technologies that facilitate the coordination of efficiency and DR in a smart grid is presented in [8]. Shariatzadeh *et al.* [9] reviewed application and implementation strategies of DR programs in a smart grid. An overview of the literature on residential DR programs and the required information and communication technology (ICT) for the implementation is presented in [10], where challenges in implementing residential DR of smart grids are highlighted and analyzed. A comprehensive performance comparison of different pricing signals, and optimization methods used for DR is presented in [11]. Authors of [12] focused on the role of aggregator for participation of small loads in DR. A review of definition, classification, implementation mechanisms, and impacts of DR on power systems is presented in [13]. In [14], DR models are categorized based on their applicability for retail and wholesale markets. A classification and analysis of DR barriers and enablers in a smart grid context is presented in [15]. A review of advances in industrial and commercial DR programs is provided in [16], in which potential and technologies of DR in these sectors are investigated. In [17], a review of the current developments of the DR programs for residential building sector is provided, in which methodologies and procedures for assessing building energy flexibility and DR programs are described.

The VPP and its relevant concepts have been reviewed by several researchers. The operation and components of VPPs are reviewed in [18], with a focus on the reviewing the modeling of essential components of VPPs. In [19], the scheduling problem of DER in the microgrid and VPP frameworks is studied, in which different aspects such as modeling techniques, solving methods, and DR are considered. Authors of [20] reviewed structures, architecture and the optimization algorithms used with each type of VPPs. A review of structures, operation, and participation of VPPs in electricity markets is provided in [21]. In [22], a comprehensive review of VPPs is presented, including their applicability for different purposes, their structural and operational optimizations and uncertainty modeling techniques for VPP operation.

In recent years, a few number of works have been performed in the literature to review different aspects of P2P markets. Tushar *et al.* [23] presented an overview of the research in P2P trading, in which the challenges related to P2P trading implementation are discussed. An overview of projects on P2P energy trading is provided in [24], where a comparison of their similarities and differences is presented. A comprehensive review of different types of community-based and P2P trading is given in [25]. The works in [26] and [27] focused on different approaches for P2P trading, where in [26] the focus is on the market clearing approaches in the local P2P trading, and [27] discusses the application of game-theoretic approaches for energy trading.

Given that TE is a new concept, the literature in this field is thin, and the first review article was published in 2017 [28]. Chen *et al.* [28] discussed the transition from DR to TE by reviewing the state of the art of research and industry practice on DR and TE. Recent discussions on TE and distribution marginal pricing, and market decentralization are provided in [29]. A taxonomy for the classification of the TE concepts related to the latest advances in TE technology has been provided in [30]. Extensive review of architectures, distributed ledger technologies, and local energy markets for TE-based microgrids is presented in [31]. The work presented in [32] reviewed distributed ledger technology and its application for TE systems. The cyber-physical infrastructure of a TE systems, and its characteristics, as well as scheduling methods of transactive agents are discussed in [33]. In [34], a bibliographical review on the researches and implementation of the TE concepts in power systems is provided. Authors of [35] presented a review of DER integration approaches in the context of TE systems including home energy management, distributed optimal power flow, and P2P energy trading.

Each of these studies made a notable contribution toward the market reformation in energy sector and provides researchers with a good understanding of the relevant concepts. However, the requirements for transition to a two-sided market and the way these approaches facilities this transition are not discussed in a unified work. Hence, in this paper, we provide a comprehensive study of different concepts related to two-sided energy markets.

III. MOTIVATIONS AND BENEFITS

A. MOTIVATIONS

Influenced by the increasing penetration of "behind-the-meter" DER, power systems are experiencing a paradigm shift from a centralized structure to a decentralized one. DER encompasses a range of consumer level technologies used by households and businesses, such as inverter connected solar PV, electrical energy storage (EES) systems, energy management systems, and electric vehicles (EVs) [36]. An increasing number of customers in electricity markets are seeking to mitigate rising electricity prices and reduce their greenhouse gas emissions by deploying their own on-site renewable generation and storage.

The flexibility of DER is a valuable feature, which can be employed to provide flexibility services such as frequency control and network support ancillary services [37]. Through employing an energy management system, customers are able to appropriately respond to grid signals to mitigate network issues such as voltage and thermal loading problems, and network congestion [38]. However, the high penetration level of DER raises technical, commercial, and regulatory challenges, since the grid infrastructure is designed to deliver large-scale centralized generation to consumers rather than to integrate millions of consumers owned generators [39]. Given the opportunities and challenges associated with DER integration, there is a need for flexible market and regulatory frameworks that can adapt swiftly and effectively as the power system evolves. The concept of the two-sided market is an auspicious option for effectively integrating both demand and supply sides in the market to manage system reliability and security issues while also improving market efficiency.

The other driver to move toward a two-sided market is the digitization of the energy systems. Grid digitization, enabled by recent advances in technology, is changing the way the market participants engage in market activities. Technological advances including smart meters, home automation technologies, and integrated energy management components enable customers to manage their electricity consumption and match it with their electricity generation and storage preferences, while saving money or energy in a simple way [40]. Being equipped with these smart devices, energy customers will no longer need to monitor electricity prices and decide how or when to participate as these decisions could be set up to happen autonomously [41]. Grid digitization paves the path to redesign the market structure such that it efficiently utilizes digital technologies to empower customers to optimize their energy, while demand and supply are balanced across the grid. Indeed, these technologies enable the active participation of demand-side in the market, which in turn improves energy efficiency. Hence, there is a need to reform the market to a two-sided model to appropriately deliver benefits of improved efficiency to energy customers.

B. BENEFITS FOR END-USERS

A two-sided market can provide several benefits for end-users regardless of what assets they own. The first benefit is providing access to localized clean energy. Through a two-sided market, end-users can use locally generated energy by renewable energy resources. In a two-sided market, network tariff structure is less complicated, and energy price can be adjusted based on what end-users consume. Hence, end-users can automate their electricity consumption based on their preferences to reduce their costs. Also, active participation of end-users in a two-sided market enables aggregators and retailers to reduce their costs by knowing their customers' demand profiles and preferences, which in turn reduces the energy costs for end-users.

Besides the benefits that a two-sided market provides for all end-users, there are some benefits specifically for those with DER. Without having a two-sided market, DER owners can utilize their DER to optimize local generation and load, and reduce their electricity bill. Also, they can benefit from selling their surplus energy to the retailers in feed-in tariffs. However, in a two-sided market these end-users can establish bilateral agreements to sell DER services such as network support services (e.g. for voltage control), or participate in P2P trading.

C. BENEFITS FOR THE NETWORK AND THE MARKET OPERATOR

The introduction of high levels of DER connected to distribution networks has led to several system issues related to maintaining the operation of the network within its technical limits. Some of these challenges include increase in bidirectional power flows, the lack of visibility of DER, difficulty in operational forecasting, demand and supply management, and maintaining the system security [42]. A two-sided market can help to address some of these issues. The most important benefit of the two-sided market for the network operators is that they can determine more accurate demand forecasts for their network. Through active participation in the two-sided market, end-users will provide information about their intention to consume or supply energy and this information would help network operators in the optimization of network assets with increasing levels of DER. Also, a two-sided market helps the network operators in managing demand and supply by providing incentives to end-users to increase consumption or shift load to times of peak PV output, or to decrease their demand during peak demand periods. Furthermore, active participation of end-users assists the market operator to maintain the safe, secure and reliable operation of the power system with less operational interventions [41].

IV. INFRASTRUCTURAL REQUIREMENTS

In this section, the enabelment layers and the general infrastructural requirements for a two-sided market are presented

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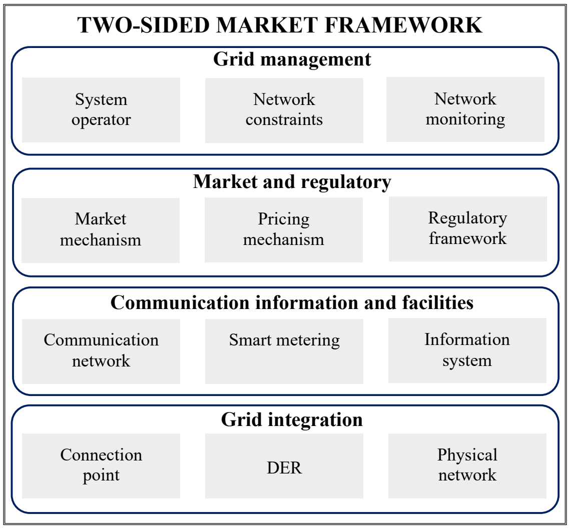

FIGURE 2. Core elements of a two-sided market.

and discussed.

A. CORE ELEMENTS

Fig. 2 illustrates the enabling layers and key elements of a two-sided market. These layers include grid integration, communication and information, grid management, and market and regulatory. Each layer embraces several core elements, which are discussed in the rest of this section.

1) Grid integration layer

This layer consists of key entities participating in the market and connection points through which end-users are connected to the grid. In a two-sided market, active end-users providing or receiving services at the connection points are the key participants. An end-user can be an inflexible energy consumer, a flexible demand resource, or a DER with energy producing capability. In its most complete form, the end-user can be a prosumer who can consume and provide energy services [43]. End-users include residential, commercial, and industrial electricity customers such as battery owners, EV owners, PV owners, small and large customers, and smart buildings connected to distribution networks.

End-users are connected to the network through a connection point. The connection point is a physical connection to the electricity network, through which end-users access to the market to provide or receive energy services [41]. Measurements should be performed at the connection points to be used for the network monitoring and market settlement. Each end-users should have appropriate metering infrastructure to be able to participate in the two-sided market. The metering system provides information about their demand/generation and the market price, which assists end-users to decide whether to participate in the market or not.

2) Communication and information layer

One of the main requirements of a two-sided market is the deployment of ICT enabled systems at different levels. In order to participate in a two-sided market, end-users should be able to measure their real time consumption and generation, and respond to price signals based on these measurements. ICT systems enable the end-users to exchange data and control/monitor their devices. The network providers collect this information to determine more accurate demand forecasts for their network, which is a valuable input into the optimization of network assets with increasing levels of DER.

3) Market and regulatory layer

The current regulatory frameworks, which are based on centralized and hierarchical structures, need to evolve to accommodate the emerging active end-users. Under the deregulated and competitive environment created by a two-sided market, economics and profitability would be the major concerns of every market participant [44]. The regulatory frameworks for the two-sided market need to be flexible to incorporate different business models to encourage market participants to engage in market activities and help them to achieve their desired objectives. End-user decisions in the market are influenced by the way they are charged for energy services. Therefore, an important step in designing a two-sided market is to design an appropriate pricing mechanism which provides the right price signals to the market participants to achieve their desired operational goals in the market. Pricing reform is critical to the efficient evolution of the energy market and ensuring that end-users are being charged for what they actually use. For example, end-users who curtail their PV generation is response to the network request should be paid for the service that they provide and be compensated for the cost of energy they have to buy for their load requirements, since they are not able to use their self-generated energy.

A two-sided market can support a range of different services related to energy, ancillary services, and reserve services. These services include frequency control ancillary services (FCAS), network support control ancillary services (NSCAS), system restart ancillary services, and the reliability and emergency reserve trader (RERT). End-users can provide these services through their direct participation in the market, or indirectly through an aggregator or a retailer.

4) Grid management layer

There are several technical constraints associated with the electricity network that restrict the ability of end-users in providing or receiving energy services. Participation of end-users in a two-sided market requires an operational framework that applies these constraints and optimizes flow of electricity across the network. The network provider grants users safe and reliable access to the electricity system. The energy services are provided through the electricity network, and the network operator is responsible for resolving operational problems, such as grid congestion and voltage violations in the system.

B. ENABLING TECHNOLOGIES

Recent technological developments facilitate the transition to a two-sided market. In this section, we study three leading technologies that are important to move toward two-sided markets namely, the IoT, Blockchain, and ML.

1) Internet of Things

The IoT is a network that connects millions of every *things* that have sensing and communication ability and thus found applications in multiple domains including smart cities [45] and smart grids [46]. The IoT devices in the energy sector, which include smart meters and smart appliances e.g., smart washing machines, collect information about the energy consumption/generation patterns of the end-users and can be controlled by the end-user or energy companies to balance the load in the grid which in turn reduces energy management cost [47]. As an example, Reposit [48] is an IoT device that monitors the customer's energy usage pattern to optimize battery charging and discharging.

2) Blockchain

In recent years, blockchain has received a tremendous attention as a communication framework for smart grid [49], [50]. Blockchain is an immutable database, shared across all participants, that stores the history of communications. In case a communication involves transferring data, the hash of the data is recorded in the blockchain while the raw data is stored off-chain, e.g., in a local or cloud storage, that in turn ensures blockchain scalability and reduces the associated overheads [51]. The data owner authorizes the nodes to access data stored either in cloud or local storage. Any data modification or access is recorded in the blockchain that enables the data owner to monitor their data.

Incorporating blockchain in two-sided markets introduces a number of advantages which are: *i) decentralization:* as blockchain establishes a trusted network over untrusted participants without relying on TTP using distributed consensus algorithm, *ii) security:* transactions are sealed using asymmetric encryption and contain the hash of the transaction content which in turn ensure data confidentiality and integrity. The consensus algorithm ensures that malicious nodes cannot control the network which in turn enhances the security of the blockchain, *iii) anonymity:* the users are known by a changeable Public Key (PK) which in turn introduces a level of anonymity, *iv) auditability:* the transactions are stored in the public ledger permanently that facilitates auditability.

3) Machine learning

Wide range of devices in the smart grid generate a huge volume of data that can help the network operators to balance the demand and supply in the grid and preserve system reliability and security. ML algorithms enhance the energy demand/generation prediction accuracy which in turn increases the grid stability and prevents grid power fluctuation in real-time [52]. Conventionally, the ML algorithm is run by a central server. Due to the large volume of collected data, centralized learning increases the computational overhead on running ML algorithm, bandwidth consumption for transferring raw data, and latency in processing the data. Additionally, the entity running ML algorithm can build a virtual profile about the users compromising their privacy. To address this challenge, federated learning [53] is introduced that pushes the learning task to the edge of the network where the devices run the learning algorithm based on their own data. The outcome of the learning algorithm at the edge may also be transferred to a central server to provide a global view.

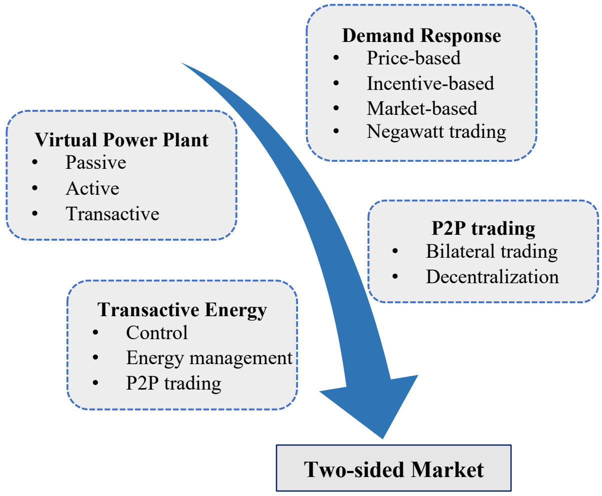

FIGURE 3. Different approaches facilitating transition to two-sided markets.

V. TRADING ARRANGEMENTS IN TWO-SIDED MARKETS

The transition toward a two-sided market needs innovative approaches that engage end-users in the market activities. These approaches are focused on the distribution side of the network, in which end-users are the key players. In this section, four main approaches that lay the groundwork for a two-sided market are reviewed, and a classification of existing methods, along with examples of academic and industrial works related to these concepts, are provided. Fig. 3 illustrates the concepts related to different trading arrangements.

A. DEMAND RESPONSE AND NEGAWATT TRADING

1) Overview

DR is a subset of demand-side participation, in which customers can participate in the market in different ways. DR programs are established to motivate changes in electric consumption by end-user in response to changes in the price of electricity [55]. Active participation of the demand-side in the market allows to achieve the supply-demand balance by the lowest combination of resources, and to prevent the congestion problem [56].

There are many types of DR programs that can be classified according to various criteria. DR can be provided by giv-

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TABLE 1. Classification of DR Programs Based on the Financial Scheme and the Behavioral Approach Followed by End-Users [8], [17], [54].

DR program	Description	Financial Scheme	End-user behavior
Time of use tariffs	Adjusting the price based on the time of the day	Price-based	Passive
Critical peak pricing	Significantly higher prices for the times that the power system is under high pressure	Price-based	Passive
Extreme day pricing	Applying critical peak pricing within a daily time resolution	Price-based	Passive
Real time pricing	Adjusting the price continuously in response to wholesale market prices	Price-based	Passive
Direct load control	Direct control of some equipment of end-users by the system operator	Incentive-based	Active
Interruptible/Curtailable	Curtailing/interrupting specific loads in response to the operator request	Incentive-based	Active
Emergency services	Load reduction during reserve shortfalls periods	Incentive-based	Active
Demand bidding	Participating in the energy market by offering a bid for load reduction	Market-based	Active
Capacity market	Participating in the capacity market by offering a bid for load reduction	Market-based	Active
Ancillary services	Participating in the ancillary services market by offering a bid for load reduction	Market-based	Active
Negawatt trading	Trading the right to buy energy with other end-users or the grid	Market-based	Transactive

ing permission to direct load control of end-users appliances to a third party. Alternatively, end-users can provide DR by cutting their electricity use at high price times by signing a contract with a retailer or an aggregator. DR can also be provided by reducing or shifting the load of controllable devices of end-users. For example, by exploiting building thermal inertia, heating, ventilating, and air-conditioning systems can be utilized for different DR programs [57]. Also, some DR programs allow end-users to bid demand reductions into different markets directly or through a third party. Moreover, DR programs can be integrated with multi-energy systems to manage both electrical and thermal energy of thermal-electric coupling systems [58].

Table 1 provides a classification of DR programs based on the employed financial scheme and the type of behavioral approach followed by the end-user. End-users behavioral approach in DR programs can be classified as passive, active, and transactive. Passive end-users adjust their demand based on predefined prices to minimize their operational costs, while active end-users decide on their responses following specific request from the grid. Transactive end-users are able to decide on when and in which price they want to reduce their demands, or to sell their right to buy energy.

Based on the employed financial scheme, DR programs can be classified in different categories namely, price-based, incentive-based, and market-based. Price-based programs utilize approved utility tariffs or contractual appointments to adjust demand of end-users. End-users receive varying prices that are defined based on the cost of electricity in different time periods, and adjust their consumption based on these prices. Time of use tariffs, critical peak pricing, extreme peak pricing, and real time pricing are examples of tariffs which can be utilized to encourage end-users to change their consumption based on the price. Incentive-based programs provide financial incentives to participating end-users for reducing/shifting their electric loads or for giving some level of control to the system operator over some of their electrical assets. Incentive-based programs include direct load control, interruptible/curtaiable, and emergency services.

Market-based programs allow end-users to participate in different markets and offer a demand reduction. In these programs, end-users can offer the available demand reduction capacity and the requested price. Demand bidding, capacity market and ancillary services market are examples of market-based programs. A specific type of market-based programs is negawatt trading. The term negawatt (negative watt) was first introduced in 1989 as a technique for energy management [59]. In the negawatt trading, end-users are considered as a kind of energy resource, in which the difference between the baseline demand and the demand after responding to the market signal is provided by the consumers. Unlike other DR programs which are mainly based on rules, established by the grid, negawatt trading enables end-users to independently decide on when and in which price they want to reduce their demands, or to sell their right to buy energy [60].

Different methodologies for DR based on these programs have been proposed in the literature. A price-based approach for demand response is proposed in [61], in which the load profile attributes of responsive loads are taken into account. In [62], price-based approach is utilized to adjust the loads to adapt the uncertainties in renewable generation resources. In [63], an incentive mechanism is proposed, which uses differentiated revenue price that is influenced by the response of each end-user. An online privacy-preserving incentive-based approach is proposed in [64], in which a recommender system is used to select the optimal customers for demand reduction offer. A blockchain-based negawatt trading platform is proposed in [65], in which buildings can offer their demand reduction to a DR aggregator. In [66], incentive prices are employed to procure negawatt from consumers to manage demand and supply optimally.

2) Pilot projects

The Yokohama Smart City Project, is an example of DR demonstration for buildings that can reduce their electricity demand, in order to provide the stable amount of negawatt for the power utility as a negawatt aggregator [67]. Another example is the pilot projects funded by the Australian government [68] to provide 200 MW of emergency reserves for extreme peaks. These projects engage large scale industrial and commercial businesses who participate in DR by reducing their power consumption, switch to backup generation or dispatch their energy storage for short periods when electricity reserves reach critically low levels. In [69], wholesale DR participation in six different wholesale markets is studied including, Singapore, Alberta, Ontario, Electric Reliability Council of Texas, PJM interconnection, and New England Independent System Operator (ISO).

B. VIRTUAL POWER PLANT

1) Overview

The VPP is an approach which supports the transition to a two-sided market by aggregating and coordinating DER across the network to exploit their flexibility [6]. A VPP can be considered as an alternative version of DR programs, which includes DR aggregation by focusing on flexible loads [70]. VPP enables demand-side participation in the market, either by direct control of their flexibility [71], or influencing their energy consumption pattern by sending indirect control signals, such as price signals [72]. A VPP involves the collaboration of a number of stakeholders including consumers and prosumers, aggregators, system operators, network providers, and regulatory bodies to form a kind of collaborative business ecosystem with high degree of interactions and interdependences. The role of an aggregator or coordinator in the VPP is crucial as it schedules, coordinates and controls participating end-users by providing control instructions or price signals to deliver specific services to the network [73]. The emergence of VPP concept is supported by different principles from different fields of study including ICT, electrical and electronics engineering, social sciences, and economics [74].

A VPP is similar to the microgrid in several aspects. However, it differs from a microgrid as it is not limited by geography and can be easily incorporated into the existing regulatory frameworks. A microgrid can operate in either the connected to the grid or in the isolated modes, while a VPP can only work in connection with the grid [19]. A microgrid has a focus on local resource optimization at the low and medium voltage level, which may or may not participate in wholesale markets. It can operate its own local market to manage local resources. A microgrid can participate in wholesale markets through contracting with a VPP, or if it can operate at wholesale market scale, it may present itself as a VPP to the market, depending on its business model and broader ambitions.

TABLE 2. Classification of VPPs Based on the Operator's Objective and the Behavioral Approach Followed by End-Users

Type	Operator's objective	End-users	
		Preferences	Behavior
Passive VPP	Provide grid services	Not included	Passive
Active VPP	Minimize system costs	Included	Active
Transactive VPP	Minimize system and end-users costs	Included	Transactive

The VPP frameworks can be segregated into three types based on the VPP operator's objective and the behavioral approach followed by end-users. The first type of VPPs is the passive VPP (utility VPP), in which the VPP operator controls end-users' flexible resources (e.g. batteries). In this model, which can be viewed as the aggregation of direct load control model, end-users are passive players who have no control over their controllable assets. The VPP operator aim is to manage end-users flexibility to support the grid by providing different services, and in turn, rewards end-users. The proposed VPP in [75] is an example of passive VPP that manages a large number of customers with thermostatically controlled appliances through direct load control. The second type of VPPs is called an active VPP, in which the VPP operator performs an optimization problem to minimize the system costs taking into account end-users preferences. This model also requires end-users to give control of their flexible assets to the VPP operator. The proposed model in [76] is an example of active VPP which considers customers comfort in the optimization problem. The third type of VPPs is the transactive VPP, in which the VPP operator's objective is to minimize system and end-users costs, while end-users preferences are taken into account. In this model, price signals will be used to coordinate end-users, and to achieve the system objectives. Different from passive and active VPPs, in this model, end-users are able to control their assets and decide on their actions by responding to price signals [77]. Table 2 summarizes different VPP models and their features.

2) Pilot projects

A pilot project implemented in Adelaide, South Australia employs solar battery storage systems across 1,000 residential and business premises to form a VPP capable of dispatching up to 12 MWh of stored energy [78]. This VPP is a centrally-managed network of battery systems installed "behind-the-meter" that can be controlled to deliver multiple benefits to the household, the retailer, and the local network. A VPP is being formed in the United States, by aggregating output from 5,000 home battery and solar systems to provide 20 MW of power capacity to the New England ISO [79]. A project in Japan anticipates to from a large-scale VPP by aggregating more than 10,000 behind the meter assets using control and customer engagement software [80]. Other examples of pilot VPP projects include, advanced VPP grid integration [81], Simply VPP [82], and Advanced Microgrid Solutions (AMS) VPP [83]. A comparison of VPPs business models in different projects is presented in [84].

C. P2P TRADING

1) Overview

P2P trading is another approach for the integration of small-scale producers and consumers to energy markets, enabling bilateral energy transactions between them [23]. It provides a decentralized environment, in which small-scale prosumers and consumers can exchange electricity and other services among themselves, instead of interacting with third parties like utilities, and aggregator. Built upon the concept of sharing economy, P2P trading facilitates the arrangement of transactions between numerous individual agents [40]. The P2P energy trading offers several advantages to both end-users and grid operators such as increasing welfare by preference satisfaction, competition in a transparent market, lowering operational costs, and improving system reliability [85]. P2P energy trading can be performed at local markets between end-users. It can be used to coordinate DR of end-users, which enables them to fully utilize the DR capabilities for reducing their energy costs [86]. Also, P2P trading can be employed at higher levels for energy trading between microgrids, energy communities, or VPPs [87]. P2P trading and VPP can co-exist in a unified platform as a federated power plant, a VPP formed through P2P transactions between self-organizing prosumers [88]. Through forming a federated power plant, participating parties in P2P trading can be involved in transactions for grid services like a VPP, which in turn improves the allocation of their flexible resources.

The P2P trading frameworks in the literature can be classified from different perspectives. In [35], P2P frameworks are classified in four groups, based on the technical approach adopted in the market mechanism. These approaches include distributed methods, game-theory, matching theory, and auction-based mechanisms. In another classification, Tushar *et. al* [23] consider game theory, auction theory, constrained optimization, and blockchain as four main technical approaches applicable for P2P trading. Also, P2P frameworks can be classified based the market structure as full P2P, community-based, and hybrid P2P markets [25]. Another aspect which can be considered for the classification of P2P frameworks is the extent to which network technical constraints are considered in the model. In this regard, a P2P model is network-oblivious if it does not consider network technical constraints, and is a network-aware model when the network constraints are included in the P2P trading formulation [35]. Network-oblivious models aim to minimize cost [89] or maximize social welfare [86], [90], [91] without considering network constraints. These models generally assume that the grid operator is in charge to monitor network constraints and rejects transactions that violate network constraints. On the other side, network-aware P2P models incorporate network constraints in the optimization problem either implicitly through optimal power flow [92], [93], or explicitly through defining grid service charges based on sensitivity analysis [94], line congestion [95], locational marginal pricing [96], load flow analysis [97], or based on the electrical distance between agents [98], [99].

2) Pilot projects

Pilot projects in P2P trading are already underway in several countries. Vandebron is a platform established in 2014, which provides an online P2P energy marketplace platform for renewable energy [101]. An Australian start-up, PowerLedger, has developed a blockchain-based platform for P2P energy trading that empowers consumers to trade energy with each other in a trustless environment [102]. NRGcoin is another blockchain-based platform, which develops virtual currency based on smart contracts for small prosumers trading in P2P markets [103]. Another example platform is Piclo, which provides a match-making service for P2P trading [104]. It matches prosumers for energy trading and at the same time enables network operators to participate in the market by placing bids for demand flexibility in congested parts of the network. The Energy Collective [105], and P2P-SmartTest [106] are other examples of pilot P2P projects. A comparison of P2P projects is provided in [24].

D. TRANSACTIVE ENERGY

1) Overview

TE is a market-based approach for energy management, which uses price signals to coordinate demand and supply across the network and among all users and entities [7]. TE approach facilitates the integration of DER in the grid, while maintaining the system reliability. It provides a transformative solution to technological and socioeconomic challenges of the power grid modernization [107]. TE systems bridge the gap between the wholesale and retail markets by expanding the current concepts of wholesale transactive power systems into retail markets by enabling small-scale consumers to actively participate in the markets [108]. The TE can be considered as a smart paradigm that sets market rules to manage the system with high reliability, while enabling active participation of end-users in the energy management process [29]. A TE system has the following attributes [100], [109]:

- It enables end-users to specify their preferences through active participation in energy management process.
- It provides a decentralized system, in which end-users are decision makers.
- Coordination signals are used to coordinate end-users to achieve system-level objectives while respecting power system constraints.
- TE exploits the flexibility of both demand and supply sides in energy management and coordinates them through market interactions.

Designing a TE-based two-sided market entails consideration of a set of requirements and key elements. In the literature, several frameworks have been proposed for TE

TABLE 3. Mapping Elements of Proposed TE Frameworks in the Literature to the Two-sided Market Framework

	Elements of the TE Framework				
Layer name	[31]	[32]	[35]	[85]	[100]
Grid integration	Users and network	Users	Users and network	Network setup and connection point	DER integration
Communication and Information	Communication and distributed ledger	Communication	Communication and computation	Information system	ICT layer
Market and regulatory	Market and regulation	Aggregation	Regulatory and financial	Market and pricing mechanisms, Regulation	Smart energy management
Grid management	System operator		Physical and technical constraints	Energy management system	Active grid management

systems, which each of those includes a few fundamental elements. A seven-layer architecture for designing TE systems is proposed in [31], in which users, network, system operator, market, distributed ledger, communication, and regulation are considered as the key functional layers of the system. The proposed architecture in [32] has three main layers, namely, user layer, communication layer and the aggregator owned data center. In [35], four elements are considered as the fundamental elements of a TE system; users and entities, electricity network, regulatory and financial environment, and computation and communication requirements. Authors of [85] introduced seven components for the efficient operation of TE-based microgrid markets. These components include network setup, grid connection, information system, regulation, market mechanism, pricing mechanism, and energy management system. In [100], DER integration, active grid management, and smart energy management are considered as three enablement layers for a TE market. Though the proposed frameworks in the literature consider various elements for a TE system, all of these elements can be mapped to the presented framework for a two-sided market in Section IV, as shown in Table 3.

2) Pilot projects

The Monash microgrid TE market is a pilot project in Monash University, Australia, aiming to achieve net zero emissions by 2030 [100]. Through participating in a competitive market, a combination of DER including PVs, battery, EV chargers, and flexible buildings are managed to provide services for internal and external stakeholders. Another example of a transactive microgrid is the Brooklyn microgrid, which aims to create a P2P energy market for locally generated renewable energy [85]. It uses a private blockchain to create a virtual community energy market platform. The Clean Energy and Transactive Campus (CETC) project is another example of campus-based TE framework, in which Pacific Northwest National Laboratory (PNNL), Washington State University, and the University of Washington have teamed to form a multi-campus TE framework to employ TE control for the economic dispatch of DER and real-time grid management [110]. Another pilot project, implemented by TeMix, provides a cloud-based platform for Retail Automated Transactive Energy System (RATES) [111]. The platform provides a standards based approach to TE on the smart grid, and enables end-users to enhance profitability by having access to real-time market data. Transactive Energy Colombia Initiative (TECI), is a small-scale pilot project implemented by University College London and Universidad EIA, aiming to set up a P2P pilot in Medellin, Colombia [112]. The project groups 14 residential users and allows them to buy energy from other users, considering energy attributes. A comprehensive list of implemented TE projects and their main outcomes can be found in [30], in which projects have been classified based on the main purposes and the scope of each project.

VI. DISCUSSION

Different approaches explained in Section V are compared and discussed here in relation to the way they facilitate a two-sided market implementation. The efficient integration of end-users in a two-sided market allows to exploit their capabilities and provides value streams for them and the power network. Though DR programs enable exploiting flexibility of demand-side for providing different services, there are many barriers which prevent the full potential of DR being realized, including economic, social, technological, and regulatory issues. These programs are usually concentrated on the consumption part of the network and neglect the importance of active participation of the supply-side. DR programs rely on scheduling flexible demands of end-users, and hence, they would affect the comfort level of energy consumers. Though negawatt trading enables end-users to participate in a two-sided market taking into account their preferences, uncoordinated operation of flexible end-users hinders to unlock their potential values for the network. More details on challenges and barriers in implementing DR programs and negawatt trading can be found in [15], and [60].

Alternatively, coordinated operation of flexible end-users in VPPs can unlock potential values for both end-users and the network by increasing network efficiency, reducing pollution, and increasing energy security [6]. VPPs can coordinate and orchestrate responsive demands to integrate them in the two-sided market, and provide new value streams to customers and other stakeholders. By being aggregated

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TABLE 4. Summary of Main Features of the Studied Approaches.

	Participation in markets	Focused side	Exchanged signals	Main challenges	Pilot projects	Relevant academic references
DR	Uncoordinated	Demand	Price/ Control	Incorporating comfort level of end-users Privacy concerns in direct control methods Network issues due to uncoordinated operation	Yokohama Smart City [67] Australia DR program [68]	[8], [9], [10], [11], [12], [13], [14], [15] , [16], [17], [55], [57], [60], [61], [62], [63], [64], [65], [66]
VPP	Coordinated	Demand	Price/ Control	Incorporating preferences of end-users Autonomy and privacy of end-users Scalability due to top-down structure	AGL VPP [78], Sunrun [79], AutoGrid [80], Advance VPP [81], Simply VPP [82], AMS VPP [83]	[6], [18], [19], [20], [21], [22], [70], [71], [72], [74], [75], [76], [77]
P2P	Uncoordinated/ Coordinated	Demand	Price	Secure operation of power network Decentralized balancing of demand and supply Coordination of trading at different levels	Vandebron [101], PowerLedger [102], NRGcoin [103], Piclo [104], Energy collective [105], P2P SmartTest [106]	[23], [24], [25], [26], [27], [40], [85], [86], [88], [89], [90], [91], [92], [93] , [94], [95], [96], [97], [98], [99]
TE	Coordinated	Demand/ supply	Price/ Control	Implementation costs Data privacy and cybersecurity threat Assessment and valuation of TE systems	Monash Microgrid [100], Brooklyn Microgrid [85], CETC [110], TeMix [111], TECI [112]	[7], [28], [29], [30], [31], [32] , [33] , [34], [35], [85], [100], [107], [108], [109]

in a VPP, the assets in the demand-side can be forecasted, optimized, and traded like a single power plant. However, due to the top-down coordination scheme of VPPs, there are some challenges with regard to end-users autonomy and preference consideration. End-users may have various preferences in terms of environmental and social concerns and energy security. To effectively integrate end-users in a VPP, the VPP operator needs to know their preferences. However, it endangers the privacy of end-users as they need to reveal their private information with a third party. Also, VPPs that use direct control strategies threaten autonomy of end-users and hinder exploiting their flexibility efficiently (see [88] for more details on challenges in VPP).

Some of these challenges can be alleviated through a P2P trading structure, that enables direct interaction between end-users, while each end-user is in control of its assets [90]. Compared to a VPP, P2P trading can offer additional source of values such as energy matching, uncertainty reduction, and preference satisfaction [88]. However, lack of a central operator in P2P approaches makes it difficult to have an accurate assessment of the network state, which may endangers the security of the system [95]. Besides, P2P trading needs decentralized algorithms to match demand and supply, without the intervention of a third-party. Furthermore, there are some other challenges in implementing P2P trading as reviewed in [23], including the definition of a unified model, the coordination of trading at different levels, and the interaction with the grid.

Given this context, TE can be used as an approach for integrating end-users in the grid while operating the system safely and efficiently. Unlike direct load control DR programs, TE systems respect end-users preferences by integrating their individual decision model into the market-based coordination. Also, different from price-based programs that do not consider the potential load response resulted from the broadcasted price signals, TE uses internal price, designed according to specific control objectives and preferences of the end-users [113]. TE approaches can also be employed in VPPs to from a transactive VPP. This type of VPP is the best fit for two-sided markets as it allows to aggregate and coordinate resources in VPP through a market-based coordination scheme. The P2P trading is fully related to the TE concept as it presents a market-based energy management approach to coordinate peers in the market. Indeed, TE systems can include P2P trading to make the small-scale producers and consumers capable for trading energy directly and locally. However, TE represents a broad set of activities that includes much more than P2P trading. The application for TE approaches include network management, transactive control, and P2P trading [30]. In TE, all customers can participate in the market, either in the demand or supply side, exploiting their local resources, such as PV and storage systems, to create benefit by responding to price signals. Despite extensive attention in recent years, the research on TE systems is relatively new. In order to employ TE approaches in two-sided markets, different challenges should be addressed by future research activities and industrial projects. The implementation of TE approaches is costly as they need a set of automation, and communication infrastructures. Data are a substantial asset of TE systems without that generating value-based signals for coordination is not possible. Hence, the privacy and security of end-users' data are of utmost importance. The other challenge with TE approaches is related to physical or cyber-attack issues, which may affect the resiliency of the system (see [30] and [32] for more details on challenges in TE systems). A summary of main features and challenges of different trading arrangements is provided in Table 4.

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VII. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

A two-sided market paves the path toward energy democratization by creating a marketplace, in which different end-users can trade energy and different services. In this paper, we survey requirements for transition to a two-sided market. As such, at first the initiatives for this transition have been introduced, followed by a discussion on the benefits that can be provided for different stakeholders. This paper identifies different elements of a two-sided market, and the enabling technologies for it. A comparative study on different approaches that can be used in two-sided markets is provided, including DR, VPP, P2P, and TE. The main findings of this study can be summarized as follows:

- The requirements and elements of a two-sided market are presented. It is worth pointing out that they are mainly generic requirements and that there some specific requirements exist which need to be considered for each trading arrangement.
- As summarized in Table 4, DR, VPP, P2P, and TE have unique features and challenges, and hence, their implementation in a two-sided market leads to different outcomes.
- TE maximizes the participation of both demand and supply sides in the bidding and scheduling process, and hence, employing TE approaches for different programs supports the move to a two-sided market.

Some future research trends about two-sided markets are as follows:

1) Interaction of different markets with the two-sided markets

In the context of the two-sided market, several markets can be considered that promote energy trading at different levels. The local market is a promising option to manage energy locally and to handle local problems associated with the integration of DER. A local market can provide market services such as DR, dynamic pricing, aggregation, and P2P trading, which can help to overcome system balancing issues at the local level. However, in order to develop a coherent market design, these local markets should work with other markets in an integrated way.

2) Network charging

The current network charging is defined assuming one-sided market. Under a two-sided market platform, the way end-users utilize the network would be changed. Hence, new network charging schemes need to be developed to reflect this change in the billing of energy consumers.

3) Scalability

Unlike conventional markets that have limited participants, the emergence of IoT technology and DER increased the number of participants in markets which reduces the scalability of the traditional centralized communication methods. A scalable communication method is demanded for two-sided markets that can also handle the ever increasing number of devices introduced in the market. As centralization will no longer scale, moving toward decentralization is the key in future research directions.

4) Data security and privacy

Data exchanged in two-sided markets are highly confidential and privacy-sensitive, which highlights the demand for secure and private communication frameworks. Traditional markets enable a central controller to be able to monitor all interactions while this, in turn, risks the privacy of the users.

The enabling technologies for two-sided markets studied in Section IV-B can play a role in addressing the outlined challenges in future research. Blockchain has the potential to function as a big umbrella connecting various markets while ensuring security of the communications and preserving the privacy of the participants. ML algorithms can reduce the volume of raw data exchanged in the network and thus enhance scalability and reduce the resources consumed from participants. IoT devices can provide accurate data regarding the actual energy consumption/generation of the participants, which in turn can facilitate calculating and billing network charge.

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