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DOI
10.1109/ISGT-Europe47291.2020.9248838

Publication date
2020

Document Version
Final published version

Published in
Proceedings of 2020 IEEE PES Innovative Smart Grid Technologies Europe, ISGT-Europe 2020

2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)
Virtual, October 26-28, 2020

Modeling the decentralized energy investment and operation in the prosumer era: a systematic review

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***Abstract*—This paper reviews the literature on the modeling approaches on decentralized energy investment and operation in the prosumer era. The study has several contributions. Firstly, it adds investment models into the review which have not been previously reviewed for decentralized energy modeling. Secondly, a modeling framework consisting of four building blocks is proposed that covers model conceptualization and model operationalization. Thirdly, the relationship between trading mechanisms and model methods is revealed using four evaluation criteria. Furthermore, by reviewing the papers, several trends in the literature are found. Operational models and local markets have been extensively studied, while wholesale market integration and investment models lack scientific attention. Among different trading mechanisms, the usage of bilateral contracts is most commonly seen. Lastly, optimization models significantly outnumber other model methods, and then it follows that their pitfalls such as the scalability of the model and the existence of stable outcomes need to be further addressed in future research.**

***Index Terms*—prosumers, market design, modeling, review, investment, operation**

I. Introduction

Under the concern of global warming and energy shortage, the production from Distributed Energy Resources (DER) such as wind turbines and solar PV has grown continuously in recent years. Up to 2019, 697 GW of solar PV have been installed worldwide [1], which is higher than the sum of all other DER capacities. The integration of DER shows that electricity consumers are currently taking a more proactive role compared to the past [2], i.e. they become prosumers.

Trading on the traditional wholesale electricity market is managed through a central market operator [3]. On the one hand, energy producers that participate in the market were, in the past, largely based on centralized fossil-fueled generation. The increase of DER brings more uncertainties in generation ability than in the past, and the traditional wholesale market is not able to react to such intermittent renewable energy generation [4]. On the other hand, the wholesale market was designed initially to accommodate generation companies and retailers, its entry barrier makes it hard for prosumers to join the market. Therefore, new market designs are needed to address and accommodate the prosumer engagement issue (e.g., through peer-to-peer trading [5]). To that end, decentralized market designs have been proposed by e.g., [6].

With the technological advancements in ICT, prosumer energy markets are emerging in practice [7]. In the literature, the modeling of these markets is reviewed by [8], [9] on peer-to-peer markets and [9] on community-based markets. However, the same as the wholesale market, the designs of the prosumer markets have a significant influence on the investment decisions of the market participants. Existing studies on DER investment either assume no actors [10], or multiple actors without interactions [11]. Yet, due to the early stage of the decentralized markets, the investments therein are rarely discussed.

In this study, we conduct a systematic review of the papers on the modeling approaches for the decentralized energy investment and operation with a focus on the prosumers. The contributions of this review are threefold. Firstly, existing studies only look at decentralized market designs (e.g., [6], [8], [9]), the investment decisions of the prosumers have been ignored. Our paper adds investment models into the current review studies, which gives the prosumer integration problem a holistic overview in that the models for investment and operation are both considered. Secondly, we propose a modeling framework that consists of four elements. This framework functions as a guideline on the necessary building blocks of a model towards decentralized decision-making on DER for the prosumers. Thirdly, we use four evaluation criteria to reveal the relationship between the trading mechanisms and the model methods.

The paper is organized as follows. Firstly, Sec. II introduces the review methodology. Then, Sec. III and Sec. IV review the papers based on the proposed framework. At last, conclusions are drawn in Sec. V. Note that in this paper, the term prosumers refers to the actors that produce and consume energy, which may be but are not limited to households.

II. Review Methodology

A. Search strategy

In this section, the search strategy will be briefly introduced. A literature search has been done using the database Scopus. The search featured decentralized decision-makers (such as the prosumers) in the electricity market, using search terms that

This research received funding from the Netherlands Organisation for Scientific Research (NWO) [project number: 647.002.007].

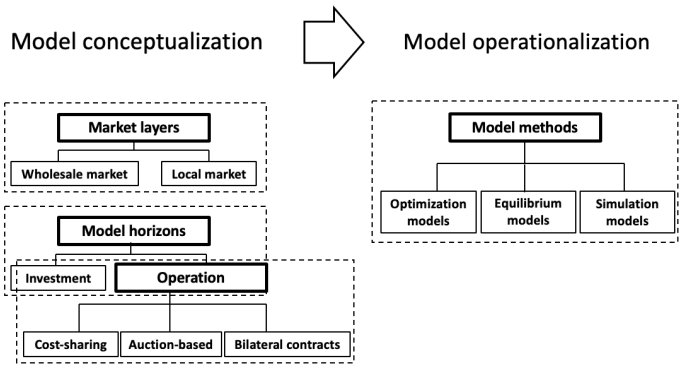

Fig. 1. Review framework.

cover the modeling of investment and/or operation of DER. It turns out that back in the 90s, there is a large body of scientific literature studying the design and the modeling of the restructured wholesale market alone. There, only a limited number of decentralized decision-makers such as large generation companies are included, and thus this set of literature was excluded from this review. Moreover, since this study has the perspective of the prosumers, the literature that focuses on energy networks is excluded as well. The search results were then limited to journal articles, conference proceedings and book chapters in English. The final result is 45 publications.

B. Modeling framework

A modeling framework is proposed in Fig. 1. It starts from the conceptualization of the model and then to the model operationalization. In the conceptualization, first, the layer of the market to be studied and the modeling horizon have to be determined. Then, if the chosen modeling horizon includes operation, the trading mechanisms will have to be further specified. After the conceptualization, a model method will be selected in order to operationalize the model into formulations.

Following the framework, Tab. I gives an overview of the reviewed literature. Note that the reviewed papers in the four building blocks are not always mutually exclusive, instead, those blocks should be deemed as different perspectives to analyze the papers and as minimum considerations to guide the modeling of the decentralized energy systems.

III. Model Conceptualization

A. Market layers

Fig. 2 shows the actors and the corresponding market layers. The actors are divided into wholesale actors, intermediaries and local actors. In this study, the system operator is considered as the only wholesale actor. There are other participants in the wholesale market, such as generation companies. However, as mentioned earlier, these generation companies usually have large-scale power plants and there are often a limited number of such companies in a market. They are not considered as the decentralized decision-makers in this study.

1) Wholesale market layer: A minority of the publications are categorized in the wholesale market layer, which include two types of studies. The first type focuses on the modeling of wholesale market participation. The involvement of an intermediate role between the prosumer and the system operator is often present. For example, [15] designed a market structure that accounts for the distribution system operator to aggregator relationship. The second type of papers mainly considers self-interested intermediaries and their interactions. These intermediaries are modeled as decentralized decision-makers. For instance, [19] studied several DER-based microgrids, and compared the system costs under cooperative and non-cooperative scenarios.

2) Local market layer: Most of the publications belong to the local market layer. They are further divided into three groups. The first type features the modeling of direct interactions between local peers, i.e. via a peer-to-peer market. For instance, [48] formulated a peer-to-peer market based on the consensus between the market participants, and product differentiation was considered in their model. In the second type, the intermediaries are also involved to facilitate the local energy exchange. This is usually done in the form of a local market operator ([37], [53]), a microgrid ([21], [46]) or a community ([29], [40]). Last but not least, there are also publications which are built upon techno-economic models, which usually look for the system optimums. For example, a residential neighborhood is modeled in [21]. The objective is to analyze the economic benefits of DER installation for self-interested households.

B. Model horizons

The reviewed models have different research horizons, i.e. investment models and operational models. Investment decisions are associated with long time spans, while operational decisions take place on the short-term. Note that in an investment model, an operational model is inherently embedded but often in a simplified way. However, the operational models usually take investment decisions as a given without investigating them further.

1) Investment: The studies focusing on the investments of DER compose 16% of the total reviewed papers. Around half of them consider mainly investment ([14], [19], [21], [41]), without detailed studies on the operational aspects. It is observed that all of those studies introduced cooperation among the prosumers. Some papers ([14], [26]) quantified the bargaining power of each player to allocate the investment costs by applying the Shapley value concept. While in [41], the different DER technologies were modeled as players, and then a cooperative model was built. It is also found that some studies investigated investment decisions based on a detailed assessment of the operational aspects ([12], [13], [17]). Those papers took the viewpoints of intermediaries, such as aggregators or virtual power plants, where new designs of the trading mechanisms were proposed.

2) Operation: 84% of the review papers focus on the operational aspects of the prosumer markets, where the investment

TABLE I
CATEGORIZATION OF THE LITERATURE BASED ON THE REVIEW FRAMEWORK.

Building blocks	Sub-blocks	Numbers	Literature
Market layers	Wholesale market	9	[12]–[20]
	Local market	36	[7], [21]–[55]
Model horizons	Investment	7	[12]–[14], [17], [19], [26], [41]
	Operation	38	[7], [15], [16], [18], [20]–[25], [27]–[40], [42]–[55]
Operation: trading mechanisms	Cost-sharing mechanisms	10	[21], [27], [29], [33], [36], [37], [42], [47], [52], [55]
	Auction-based mechanisms	12	[7], [17], [18], [20], [22], [24], [25], [31], [34], [43], [45], [53]
	Bilateral contracts	19	[15], [16], [23], [25], [28]–[30], [32], [35], [36], [38]–[40], [44], [46], [48], [49], [51], [54]
Model methods	Optimization models	31	[12]–[19], [21], [23]–[26], [28], [29], [32]–[36], [38]–[40], [42]–[48], [54]
	Equilibrium models	8	[7], [20], [31], [36], [41], [50]–[52]
	Simulation models	10	[22], [24], [27], [30], [32], [37], [46], [49], [53], [55]

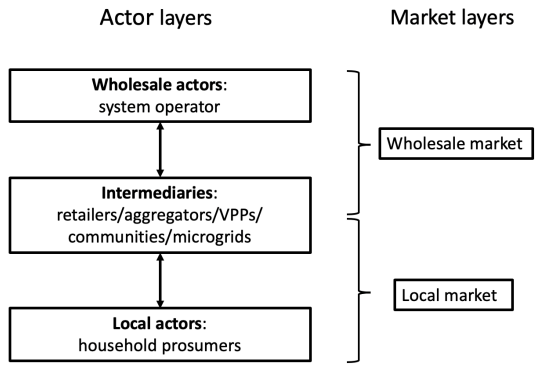

Fig. 2. Vertical layers of actors and markets.

of the DER are taken as given. In those studies, the keywords such as market, trading, sharing and exchange are often used interchangeably. Among others, peer-to-peer markets are the most commonly discussed topic, see e.g., [7], [36], [48]. It has to be noted that all the reviewed papers belong to the virtual layer of the market where mainly the information on price and quantity was studied, the papers on the other layer of the market, i.e. the physical layer of energy exchange and control are considered out of the scope. It then follows that most of the articles aim to design novel trading mechanisms in those prosumer markets (see Sec. III-C for details), meanwhile business models are elaborated only in comprehensive reviews of [6], [9].

C. Operation: trading mechanisms

Energy trading mechanisms between the prosumers are often proposed in operational studies. This section reviews the various trading mechanisms.

1) Cost-sharing mechanisms: In the literature, prosumer energy trading sometimes refers to only the physical energy exchange without the proactive involvement of the prosumers. In such cases, a system optimum is obtained and then the cost of the system is allocated to the prosumers based on cost-sharing mechanisms. One line of research is based on cooperative game theory, where the Shapley value is commonly used for allocating costs [27]. The other line is related to pricing rules in the market, where bill sharing [55], mid-market rate [50], [52], [55] and supply and demand ratio mechanism [55] are frequently mentioned.

2) Auction-based mechanisms: Auction-based mechanisms rely on the coordination by a market operator, who holds auctions in the market. Buyers and sellers are required to submit their price-quantity pairs, and then the market operator matches the supply and the demand. In essence, auction-based mechanisms and cost-sharing mechanisms both determine a price or prices in the market. The main difference is that, in the former, the participants are price-makers while in the latter, they are assumed as price-takers. [31] gave an overview of the different auction-based mechanisms, and compared the performances of Discriminatory and Uniform k-Double Auction. In those studies, the focus is on the design and performances of different mechanisms. The other type of papers focuses on the self-scheduling of the prosumers and the social welfare maximization of an intermediary, given a certain auction-based mechanism. Bilevel optimization is often used. Examples of these studies are [16]–[18], [29], [43], [45].

3) Bilateral contracts: Mutually agreed trading arrangements, i.e. bilateral contracts, can be formed between prosumers [56]. These arrangements indicate direct energy and information exchanges between the prosumers. They can happen without an intermediary (e.g., [38], [44]), which protects the privacy of market participants. However, sometimes, a market operator is present only to provide a trading platform [7], instead of administrating it [56]. Lastly, an intermediary role may be of importance to such a market. It is most commonly seen in community-based markets, for example, a supervisory third-party is introduced to facilitate the local energy exchange in [40].

IV. MODEL OPERATIONALIZATION

After the conceptualization, the models are operationalized into model methods. Note that the models can be categorized into different model methods depending on the chosen criteria. In this study, we propose four evaluation criteria (iterative approach, Nash equilibrium formulation, cooperative game, iteration convergence) to link the used trading mechanisms to the model methods (see Fig. 3).

A. Optimization models

Optimization models are used to obtain the best utility for the actors. In the reviewed studies, there are three types of

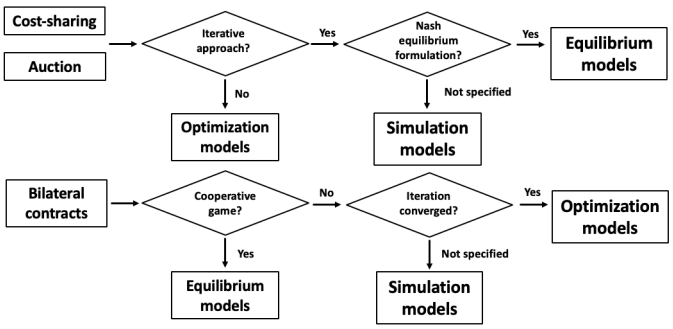

Fig. 3. The categorization of model methods according to the trading mechanisms in this study.

optimization models. The first type concerns the planning of an energy system. The objective is usually to minimize total system cost for energy system expansion [12], [14]. Single-level optimization is commonly used. The second type uses bilevel optimization to obtain the optimum self-scheduling and the bidding strategies of the prosumer groups (see Sec. III-C2). The third type features the negotiation processes between the prosumers, which are often associated with the bilateral contracts discussed in Section III-C3. Note that this type of optimization models may lead to a system equilibrium, and thus it can sometimes be considered as equilibrium models. In this study, we take the perspective of the decentralized decision-makers, i.e. the models that end up with a system equilibrium that is reached by optimizations of individual decision-makers are considered as optimization models, unless the Nash Equilibrium is formulated explicitly. Given the popularity of optimization models, challenges such as the scalability of the model [57] and the existence of stable outcomes [38] need to be further addressed in future research.

B. Equilibrium models

In this review, equilibrium models refer to game-theoretical models. In such models, players seek to maximize their payoff functions until a Nash Equilibrium is formed. For example, [36] formulated a peer-to-peer market as an equilibrium problem and proved that formulation led to the same result as a centralized market design problem. Furthermore, cooperative game theory is often used where coalitions are formed to achieve equilibrium. Examples of these studies are [30], [51], [52].

C. Simulation models

Simulation models in this study indicate the models with iterations or that the result is time-dependent. For example, an agent-based model [49] simulates the agent behavior at each time step. Auction-based models sometimes iterate until certain time steps are reached ([24], [27]).

V. Conclusion

This paper reviews the literature on the modeling approaches for the decentralized energy investment and operation in the prosumer era. Compared to existing reviews, this study 1) added investment models into the review which are yet reviewed, 2) proposed a modeling framework consisting of four necessary building blocks from model conceptualization to model operationalization. In addition, our review identified several modeling trends in the literature. Firstly, existing studies mainly focus on operational models and the local market level. However, the investment models and the wholesale market integration by aggregated prosumer groups need more scientific attention. Secondly, using bilateral contracts is the favorite trading mechanism in the reviewed papers, while cost-sharing and auction-based mechanisms have been deployed equally in terms of the number of papers. Lastly, we proposed four evaluation criteria to reveal the relationship between the trading mechanisms and the model methods. These criteria allow a distinct categorization of the model methods, and it is found that the optimization models are the most deployed method. Given the popularity, future studies in the field should further address their pitfalls such as the scalability of the model and the existence of stable outcomes.

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