Studies on consumers' benefits from transformation of electricity markets

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Abstract

Structural transformation in electricity markets has emerged in many countries to ameliorate the services in electricity markets. To realize lower electricity charges for consumers, many countries have deregulated their electricity retail markets. Furthermore, renewable energy resources have been utilized worldwide because of their environmentally friendly nature. Although novel types of trading will be available in the transformation of electricity markets, liberalization might pose issues regarding consumers' viewpoints. The objective of studies presented in this thesis is to analyze consumers' benefits in electricity markets to consider successful market mechanisms. Four problems are set to examine the benefits of consumers, and market models are proposed using mathematical modeling techniques based on graph theory. Results of the studies demonstrated the characteristics of the consumers and suggested several insights to improve situations with issues in electricity markets. Advanced understanding of consumers' benefits obtained by these models is expected to contribute to providing insights for considering successful market mechanisms that will be developed in the transformation of electricity markets.

Keywords: Graph theory, Network flow, Evolutionary game, Electricity market, Switching cost, Envy-freeness

1 Introduction

1.1 Backgrounds

For a long time, many countries have vertically integrated electricity markets for ensuring a stable supply of electricity. In the vertically integrated electricity markets, a limited number of power companies have conducted generation, transmission, and retail of electricity. Nevertheless, those electricity markets with centralized structure mainly have issues on electricity charges and services offered by the suppliers [1]. For instance, consumers cannot recognize whether current electricity charges are appropriate or not since they do not have any suppliers for the comparison.

The structural transformation of electricity markets has emerged in many countries to ameliorate the services in electricity markets. As the first step of the transformation, traditionally centralized electricity markets have been deregulated and divided into several sectors. The deregulation aims at the participation of various electricity suppliers in the markets. One of the examples is the deregulation of electricity retail for providing consumers with choices among suppliers and realizing relatively lower charges than ever. For instance, the Japanese government has gradually deregulated their electricity markets, and electricity retail for all consumers in Japan was liberalized in 2016.

As modernization of power grids, smart grids have been considered by utilizing advanced metering and communication technologies [2]. The anticipated advantages of smart grids are accommodating distributed power sources, improving resilience to natural disasters, etc. In terms of consumers, it is expected to (i) increase consumers' choices and (ii) enable new products, services, and markets [2].

From the consumers' viewpoints, the roles of consumers in electricity markets have been greatly changed with the transformation. In the centralized electricity markets, consumers do not have any alternatives to their suppliers. After the deregulation of centralized electricity markets, consumers will have alternatives for their suppliers. Moreover, consumers will possibly have chances to provide surplus electricity to its neighbors in future smart grids. Thus, consumers' choices are not only purchasing electricity from suppliers but also providing surplus electricity to others in the future. These kinds of consumers are called prosumers since they both produce and consume electricity.

1.2 Research objective

Although new types of trading will be available in the transformation of electricity markets, liberalization might pose issues regarding consumers' viewpoints. Many consumers have not switched their suppliers in many countries though consumers can choose suppliers after the deregulation of electricity retail. Besides, if consumers will not actively participate in electricity sharing markets in smart grids as well as electricity retail, mechanisms for electricity sharing might also fail. Characteristics of electricity markets must be examined carefully to avoid large impacts on society such as California electricity crisis in 2001 [3].

The objective of studies in this thesis is to analyze consumers' benefits in electricity markets for realizing successful market mechanisms. These studies provide opportunities to understand consumers' benefits and provide insights for mechanism design. These studies clarify the benefits of consumers about their decision making for electricity trading. One of the applications of these studies is a tool for the "proof of concept" of operations regarding electricity markets. For electricity suppliers, the tool can be used to check the effects on the settings of their electricity services. Besides, for policymakers such as governments or public offices, the tool gives insights to understand the characteristics of consumers such as their benefits, behaviors, etc.

1.3 Related works

Electricity markets have transformed into a more complex style than ever. Hence, many kinds of problems must be addressed in consideration of mechanisms for electricity markets to provide desirable benefits for consumers.

The most fundamental study to realize electricity markets is matching production and demand for electricity in a particular time interval for a stable supply of electricity. Utilizing renewable energy makes it difficult to manage production and demand due to uncertain conditions of wind, solar, etc. Energy storage might facilitate this problem by offsetting the gap between production and demand. Babrowski *et al.* introduce a model to analyze the allocation and amount of energy storage systems [4].

In addition to the methods to determine electricity distribution, studies on economic perspectives are crucial for market mechanisms. An example of mechanism is the auction to determine trading by adjusting electricity prices. Karaca *et al.* introduce a game theoretic approach to examine auction mechanisms for electricity markets to realize truthful bids and prevent strategic manipulations by participants [5]. Another example is a mechanism of Demand Response (DR), which aims at reducing peak demand [6].

Forecasting technologies for electricity have gained increasing attention. Demand forecasting will become more complex after the deregulation. For instance, DR might increase difficulty in forecasting demand [7]. Furthermore, forecasting is inevitable to utilize renewable energy since production from renewable energy is considered to be uncontrollable. In [8], Bacher *et al.* present a method for online forecasting of production from PV systems.

Characteristics of participants is a key research topic to design mechanisms for electricity markets. Regarding supply-side, technologies to forecast production are considered for a stable supply of electricity. Similarly, mechanism design must address the characteristics of consumers at demand-side. The insights of the characteristics of consumers will improve the quality of mechanisms to induce desirable actions from demand-side. Ruiz *et al.* [9] present a game theoretical model to examine the effects of electricity consumers' switching costs on suppliers' competition.

1.4 Problem statement

This thesis focuses on problems in modeling techniques for analyzing consumers' benefits in liberalized electricity markets. Behavior and decision of demand-side are equally or even more important than supply-side to deploy new technology even though many related studies have mainly focused on technology and cost-effectiveness of supply-side. Methods to analyze the benefits of consumers can be applied for both improving current situations and examining future novel mechanisms of electricity markets. This thesis deals with the following four problems.

1. **Constructing a modeling framework for electricity trading**
   The structure of electricity markets has become complex after liberalization. Especially, the networked structure will become an important aspect since deregulation increases the number of participants in electricity networks. For the analysis of the characteristics of participants, this thesis proposes mathematical modeling concepts. This approach is applied to electricity market models for Problem 2, Problem 3, and Problem 4.
2. **Representing electricity trading in deregulated electricity markets**
   This problem is to model participants in deregulated electricity markets and examine the benefits of them. Since there are multiple types of participants in the deregulated markets, combinations of electricity trading among participants increase than ever. This thesis focuses on representing the deregulation of electricity retail since this kind of deregulation is closely related to electricity consumers. This problem is the first application of the model considered in Problem 1 for modeling benefits, prices, and trading of market participants.
3. **Examining switching behavior of consumers in electricity retail**
   As the third problem, this thesis proposes a market model focusing on switching costs to analyze the behavior of consumers in electricity retail markets. Electricity retail markets in many countries see inactive switching behavior, which means the action of consumers to change their supplier. This topic aims at providing insights for promoting the switching behavior of consumers by modeling consumers' decision making. This approach is different from that in Problem 2 since the model in Problem 2 does not focus on the behavior of each participant.
4. **Describing fairness among prosumers in electricity sharing**
   The fourth problem is to examine the fairness of benefits of prosumers in a model for electricity sharing. This study examines electricity trading among prosumers, which has roles varying between suppliers or consumers from time to time. Electricity consumers do not necessarily act to maximize their benefits as considered in Problem 3. This problem focuses on envy-freeness, which is one of the fairness measures for resource allocation. This measure is selected since it is considered to be important even for irrational consumers. Since this problem deals with time-varying roles of prosumers, this problem is considered to be a successor for Problem 2.

2 Constructing a modeling framework for electricity trading

As a solution for Problem 1, this thesis introduces a mathematical modeling framework to represent trading in electricity markets. Mathematical modeling is a fundamental concept to describe a real-world problem and acquire a solution for the problem [10]. One of the key objectives of the modeling is to understand the crucial characteristics of real-world problem with mathematical models that simplifies the real-world. Electricity market models presented in this thesis are composed of several approaches used in Operations Research (OR), which is a research field to support decision making by using techniques such as combinatorial optimization, graph theory, game theory, economics, etc.

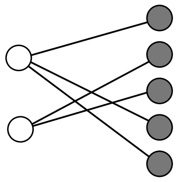

Fig. 1: Example of matching between market participants.

Trading between market participants can be represented as *matching market*, which only deals with a single unit of commodities [11]. To extend matching market to the modeling framework for electricity markets, the characteristics of electricity trading are integrated into matching market. This thesis focuses on the following three characteristics.

1. *Representing network structure among participants*
   The networked structure of electricity markets can be represented as matching in graph theory. For instance, Fig. 1 shows an example of matching between two types of market participants (e.g. suppliers and consumers).
2. *Satisfying constraints on production and demand*
   Production and demand of electricity must be balanced in electricity trading to realize a stable supply of electricity. This thesis utilizes network flow to determine the production and demand of electricity in trading.
3. *Describing benefits for consumers in markets*
   After deregulation, consumers will face different benefits of electricity trading since choices about suppliers increase than ever. In proposed market models, utility function represents the benefit of consumers from trading in matching. The utility function uses electricity charges as main factor since the charges are considered to be a more common aspect compared to other factors such as environmental impacts, reliability of supply, etc.

3 Representing electricity trading in deregulated electricity markets

Regarding Problem 2, the relationships between participants in electricity retail markets are modeled as a tripartite graph containing suppliers, retailers, and consumers. Consumers purchase electricity from retailers, and suppliers provide electricity to retailers. The market model is an extension of a market model proposed in [12]. Although the model in [12] can deal with only single-unit commodities, the model proposed in this thesis can represent electricity as a multi-unit commodity by the modeling framework.

A sequential solution method is proposed to determine prices and electricity trading in a deregulated electricity market model. To determine electricity trades satisfying constraints on supply and demand on the model, a matching problem among participants is formulated by utilizing integer programming and network flow. The integer programming is formulated as the maximization of social welfare, which is a total of benefits of all participants.

Social welfare and payoff allocation on the model were investigated by conducting simulation experiments. As a result, our sequential solution method determined efficient electricity trades though the efficiency depends on the structure of the markets and capacity of participants. Furthermore, the results also indicated that the payoff allocation for each market participant was affected by the period that has elapsed since the start of the deregulation.

4 Examining switching behavior of consumers in electricity retail

To express the irrational behavior of consumers for Problem 3, consumers' decision making is modeled to obtain matching in a bipartite graph of consumers and suppliers. This thesis focuses on two types of switching costs of consumers: (i) effort at switching suppliers and (ii) searching costs. The preference of consumers over suppliers involving an effort at switching is modeled as preference relation with *interval order* [13]. The proposed model can describe a situation where consumers do not switch suppliers unless the benefit of switching is more significant than the effort. This kind of situation cannot be represented by using general matching market models such as [10].

For describing interaction among consumers, we propose an evolutionary game on a network among consumers. Consumers are connected through a social network in the model, and they are possible to share information with neighbors. The game expresses the dynamics of the share of two strategies of consumers: searching alternatives actively (cooperators) and waiting for suggestions from the other consumers (defectors). To promote cooperation, this thesis also focuses on giving rewards to consumers as compensation for searching costs by referring to [14].

We examined the conditions to promote cooperation to search for alternatives and switching suppliers in the computational experiment of the evolutionary game. Electricity charges offered by suppliers were also modeled based on Japanese electricity retail markets to determine the preference relation of consumers. The results demonstrated that the share of cooperators and the switching rate were not improved by simply giving rewards for cooperators. These results suggest that the degree of cooperators in a network among consumers demonstrates a vital role to increase the share of cooperators and the switching rate.

5 Describing fairness among prosumers in electricity sharing

This thesis introduces a resource sharing model among prosumers in a social network for Problem 4. To consider electricity sharing among prosumers, it is needed to represent time-varying production and demand in a model. This thesis extends our previous study [15] based on Time-Varying Graph (TVG) [16], which denotes changes of network structure through a time span. Prosumers change their role to either seller or buyer according to its production and demand every time. As an extension for [15], prosumers share resources with their neighbors in a social network of prosumers in time-varying matching.

The extended concepts of envy are introduced since resource sharing is conducted on a social network in the proposed model. The envy in resource sharing discussed in related works is defined in the situation where all agents share the same resources each other over time. To evaluate envy-freeness for resource sharing among agents in a social network, we proposed two indices that indicate normalized envy through a time span of trading in a TVG. To discover matching that satisfies supply and demand of prosumers, we formulate a minimum-cost circulation problem.

Experimental results indicated that appropriate weight settings on arcs can decrease envy among prosumers over time. The results demonstrated the envy among agents is reduced by using the minimum cost circulation problem and the condition of weight on arcs in a flow network. Although the concept of envy-freeness for resource sharing among prosumers was proposed, more realistic datasets of electricity should be used in future simulation experiments to obtain practical insights about the benefits of prosumers.

6 Conclusion and future works

6.1 Conclusion

The results of studies on four problems contextualize the objective of this thesis, which is to analyze consumers' benefits to consider successful market mechanisms. Regarding Problem 1, concepts of graph theory were utilized to construct a modeling framework for electricity markets, which represent both consumers' benefits and constraints on supply and demand. A market model to represent deregulated electricity markets was presented for Problem 2, and this study explained the relationship between the benefits of participants and prices in electricity trading. About Problem 3, the results about consumers' switching behavior demonstrated both the network structure and the existence of consumers active to switch suppliers become important factors to promote switching behavior. In the resource sharing model for Problem 4, envy-freeness was utilized as one of the metrics of electricity sharing among prosumers.

The market models presented in this thesis demonstrated several insights about consumers' benefits in electricity markets. Considering these insights, these models are expected to contribute to market mechanisms that will be developed in the transformation of electricity markets from now on. The advanced understanding of the benefits of consumers will produce fine effects for decision making by both the supply-side and demand-side of the markets.

6.2 Limitations and future works

To enhance the models' applicability and obtain sophisticated insights, the following topics are left as future works.

1. Using realistic datasets about production and demand
   To construct more realistic electricity market models and validate the models, experiments should use realistic datasets of production and consumption of electricity. Though the data about electricity have traditionally been restricted in general, there has been the movement toward opening up energy-related data to improve reproducibility and transparency of energy modeling recently. For instance, *Renewable.ninja* provides simulation data about hourly worldwide solar and wind generation [17].
2. Integrating multiple factors of the utility of consumers
   In addition to electricity charges, the other factors of the utility function for consumers should be considered according to the future transformation of electricity markets. Especially, it is inevitable to address environmental concerns regarding electricity generation and consumption worldwide for sustainable development.
3. Extending parameter conditions in simulation
   Simulation experiments with additional parameter conditions should be conducted to obtain more realistic insights about consumers. The conditions include increasing the number of nodes in graphs, integrating heterogeneous switching costs of consumers, adding dynamical transitions of prices, etc. For this purpose, the efficiency of algorithms to determine trading should be improved.

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