2018 IEEE Conference on Control Technology and Applications (CCTA)
Copenhagen, Denmark, August 21-24, 2018

Strategic Battery Storage Management of Aggregators in Energy Demand Networks*

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Abstract— **This paper considers optimization problems of energy demand networks including aggregators and investigates strategic behavior of the aggregators. The participants of the network are a utility company, who plays a role of energy supply source, aggregators and a large number of consumers. We suppose that the network will be optimized by price response based or, in other words, market based optimization processes. We also suppose that the aggregator has a strategic parameter in its cost function and, by choosing the parameter strategically, the aggregator will try to pursue its own benefit. This general problem formulation will apply to a specific problem setting, where the aggregator possess battery storage with different specifications: The one is high-performance and expensive and the other is low-performance and cheap. The aggregator will choose total capacity of storage to be installed and a ratio of high-performance storage to low-performance storage as the strategic parameters and try to increase its own benefit. By using numerical examples, we show that the strategic decision making by the aggregator could provide useful insights in qualitative analysis of energy demand networks.**

I. Introduction

In recent years, researches on decentralized control architectures based on price responses by the participants of the power supply/demand networks are increasing because of the liberalization of energy market and increasing share of distributed energy sources such as renewable energy [1], [2], [3], [4], [5], [6]. Designing of market based control associated with consumers may include significant challenges because the network includes a large number of consumers and each consumer only has negligible ability to affect the price. One promising approach is to consider a hierarchical market architecture and introduce aggregators, who are new entities in the electricity market which act as mediators between the energy supply sources and consumers [7], [8], [9]. The aggregators are expected to solve the scalability issue of the network and make the negotiation power of demand side large.

There seems to be a few works that try to clarify the fundamental role the aggregators play in the market from economic point of view or quantitatively evaluate the impact of the aggregators. For example, in economics literature [10], [11], impact or power of a market participant might be evaluated by market power. Market power indicates the ability to alter profitably price away from competitive levels [10].

Motivated by the concept of market power, in [12], the authors have formulated the three-layered, including the utility company, multiple aggregators and many consumers, price response based optimization problem and proposed a specific market power index for the aggregators. In this problem, the aggregator is supposed to be a strategic agent and will try to pursue the benefit as well as market power. Specifically, the aggregator has a design or, in other words, strategic parameter in its cost function and, by strategically choosing the parameter, will try to increase its own benefit. The strategic decision making by the aggregator may provide useful insights in qualitative analysis of the large energy demand network.

In the present paper, the three-layered price response based optimization problem formulated in [12] will apply to the specific setting. We suppose that the aggregator possesses battery storage with different specifications: The one is high-performance and expensive and the other is low-performance and cheap. The aggregator will strategically decide the total capacity of storage to be installed and the ratio of high-performance storage to low-performance storage and try to increase its own benefit. The strategic decision making by the aggregator may provide useful insights in qualitative analysis of energy demand networks as we will see in the numerical example.

The remainder of the paper is organized as follows. Section II formulates the three-layered price response based optimization problem in which the aggregator possess battery storage. Section III briefly reviews the price response based optimization processes proposed in [12], where the aggregators can contribute to mitigate a scalability issue in solving a large size optimization problem. A numerical example in Section IV considers strategic decision making of the aggregator, and the aggregator will try to pursue the additional benefit by choosing a design parameter in its cost function. Section V gives concluding remarks.

II. Energy Demand Network with Aggregators

Fig. 1 illustrates a concept of future energy market where several generation companies and aggregators are connected to each other, and many consumers are associated with each aggregator. The utility company may play a coordination role for energy transactions between the multiple generation companies and aggregators. Although the energy demand

*This material is based upon work supported by the Japan Science and Technology Agency, CREST under Grant No. JPMJCR15K2, and the Japan Society for the Promotion of Science under Grant No. 17K06490.

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market depicted in Fig. 1 may be realistic enough, a simplified setting as shown in Fig. 2 is still enough for the main purpose of this paper such as analyze and clarify an impact of strategic behavior of the aggregators who have batteries.

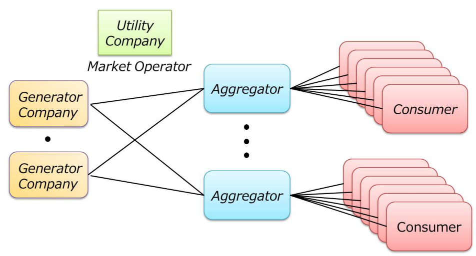

Fig. 1: A conceptual model of energy market.

Fig. 2 illustrates a model of energy demand network including aggregators. In Fig. 2, a single utility company play a role of energy supply source. The utility company is connected to the wholesale market, and multiple aggregators are connected to the utility company. Consumers are connected to the utility company through the aggregators. This paper considers the energy demand network depicted in Fig. 2 and investigates market based optimization through pricing with the supply/demand balancing constraints. Under this optimization process, our main interest is on strategic behavior of the aggregators.

We suppose that the time horizon for optimization is divided into P time-slots. If one considers a day-ahead market, the time horizon may be 24 hours and P could be 48 that corresponds to 30 minutes time-slot. If one is interested in a short term energy scheduling and considers minute-by-minute optimization horizon, each time-slot could be a few seconds.

A. The utility company

The utility company purchases electricity from the wholesale market directly and sells it to the aggregators on price $p_0 \in \mathbb{R}^P$. The generation cost generally follows a convex function [13]. In this paper, we consider the following quadratic cost function:

$$J_0^\sharp(u_0) = u_0^{\mathrm{T}} Q_0 u_0 + R_0 u_0 + C_0,$$

where $u_0 \in \mathbb{R}^P$ is the amount of electricity purchased by the utility company. For a given price p_0, the benefit-maximization problem of the utility company is formulated

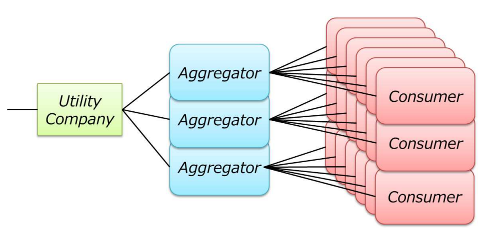

Fig. 2: A model of energy demand network.

as:

$$\max_{u_0} \quad J_0^\sharp(u_0) + p_0^{\mathrm{T}} u_0. \tag{1}$$

B. Aggregators

Aggregators A_i, $i \in N = \{1, \ldots, n\}$ purchase electricity on price p_0 from the utility company and sell it to the consumers on price $p_i \in \mathbb{R}^P$. We assume that the operational cost of the aggregator is also a convex function with respect to the purchased amount of electricity. Especially, we suppose that the cost function of aggregator A_i can be expressed as:

$$J_i(u_i) = u_i^{\mathrm{T}} Q_i u_i + R_i u_i + C_i, \tag{2}$$

where $u_i \in \mathbb{R}^P$ is the amount of electricity purchased by aggregator A_i.

In addition to aggregating the consumers' demands, an aggregator has batteries and operates them strategically. The impacts of having batteries by a strategical aggregator are discussed later. We assume that an aggregator can choose from two types of batteries: Expensive ones that have high performance and cheap ones that have low performance. Both types of batteries have similar dynamics, but parameters are different. The dynamics of the expensive batteries are follows:

$$x_{ibH}[t+1] = \eta_{iH} x_{ibH}[t] + \frac{u_{ibH}[t]}{H_{iH}}, \tag{3}$$

where $x_{ibH}[t]$ is state of charge of the high-performance battery at time t, η_{iH} is the value which indicates the volatility of the battery, H_{iH} is the capacity of the battery, and $u_{ibH}[t]$ is the energy charged into the battery at time t. Likewise, the dynamics of the low-performance batteries are follows:

$$x_{ibL}[t+1] = \eta_{iL} x_{ibL}[t] + \frac{u_{ibL}[t]}{H_{iL}}, \tag{4}$$

where the parameters are analogous to the high-performance battery. In this research, we assume that an aggregator has these two batteries, and tries to find the optimal ratio of having these two types of batteries. In reality, batteries have physical constraints, but for simplicity, we do not consider inequality constraints in this research.

The cost functions of the high-performance and low-performance battery are as follows:

$$\begin{aligned} J_{ibH}^\sharp(u_{ibH}) = &\sum_{t=1}^{P} \{-\frac{z_{i1}}{H_{iH}^2} u_{ibH}^2[t] - z_{i2}(x_{ibH}[t] - x_{ibH}^{ref})^2\} \\ &- H_{iH} \eta_{iH}^2 z_{i3}, \end{aligned} \tag{5}$$

$$\begin{aligned} J_{ibL}^\sharp(u_{ibL}) = &\sum_{t=1}^{P} \{-\frac{z_{i1}}{H_{iL}^2} u_{ibL}^2[t] - z_{i2}(x_{ibL}[t] - x_{ibL}^{ref})^2\} \\ &- H_{iL} \eta_{iL}^2 z_{i3}, \end{aligned} \tag{6}$$

where

$$H_{iH} = \alpha_i H_{iT}, \quad H_{iL} = (1 - \alpha_i) H_{iT}. \tag{7}$$

x_{ibH}^{ref} and x_{ibL}^{ref} is the desired set-point of state of charge and $z_{i1},\ z_{i2},\ z_{i3}$ are weighting coefficients, respectively. The first term of right-hand side represents the cost of fast charging and discharging. This is proportional to quadratic of charging/discharging amount. In order to normalize the scale with respect to battery capacity, the penalty is divided by quadratic of the capacity. The second term is the penalty to the deviation from the desired set-point. The penalty is proportional to quadratic of the deviation. The third term represents the initial cost of installing a battery. We assume that the price of battery is proportional to its capacity and quadratic of its quality, which is represented by the volatility.

Strategic aggregators choose the total capacity of batteries H_{iT} and ratio of high-quality batteries α_i when they install the batteries. We define these parameters as strategic parameter:

$$r_i = \{H_{iT},\ \alpha_i\}. \tag{8}$$

For given prices p_0 and p_i, the benefit-maximization problem of aggregator A_i is formulated as:

$$\begin{aligned}\max_{u_i,u_{ibH},u_{ibL}} \quad & J_i(u_i) + J_{ibH}^{\sharp}(r_i;u_{ibH}) + J_{ibL}^{\sharp}(r_i;u_{ibL}) \\ & + p_i^{\mathrm{T}}(u_i - u_{ibH} - u_{ibL}) - p_0^{\mathrm{T}} u_i. \end{aligned} \tag{9}$$

By defining the total utility function of aggregator A_i as

$$\begin{aligned} & J_i^{\sharp}(r_i;u_i,u_{ibH},u_{ibL}) \\ & \quad = J_i(u_i) + J_{ibH}^{\sharp}(r_i;u_{ibH}) + J_{ibL}^{\sharp}(r_i;u_{ibL}), \end{aligned} \tag{10}$$

the benefit-maximiztion problem (9) is written as

$$\begin{aligned}\max_{u_i,u_{ibH},u_{ibL}} \quad & J_i^{\sharp}(r_i;u_i,u_{ibH},u_{ibL}) \\ & + p_i^{\mathrm{T}}(u_i - u_{ibH} - u_{ibL}) - p_0^{\mathrm{T}} u_i. \end{aligned} \tag{11}$$

C. Consumers

Consumers $A_{ij},\ i \in N,\ j \in N_i = \{1,\ldots,n_i\}$ purchase electricity from aggregator A_i on price p_i and consume it by using appliances. The cost function of consumer A_{ij} is convex and can be expressed in a quadratic form [4], [14]. Examples of the explicit representation of the cost function including both of the dynamic and static appliances can be found in [15]. We use

$$J_{ij}^{\sharp}(u_{ij}) = u_{ij}^{\mathrm{T}} Q_{ij} u_{ij} + R_{ij} u_{ij} + C_{ij},$$

as the cost function of consumer A_{ij}, where $u_{ij} \in \mathbb{R}^P$ is the amount of electricity purchased and consumed by consumer A_{ij}. For a given price p_i, the benefit-maximization problem of consumer A_{ij} is formulated as:

$$\max_{u_{ij}} \quad J_{ij}^{\sharp}(u_{ij}) - p_i^{\mathrm{T}} u_{ij}. \tag{12}$$

D. Social Welfare Maximization

The market is designed so that the social welfare will be maximized through pricing. Specific optimization processes will be considered in the next Section III. We define the social welfare as the sum of the cost functions of the utility company, aggregators and consumers. We also consider the linear constraints which represent the supply/demand balance.

The social welfare maximization problem is expressed as:

$$\begin{aligned}\max_{\substack{u_0 \\ u_i,u_{ibH},u_{ibL}\ i\in N \\ u_{ij}\ j\in N_i}} \quad & J_0^{\sharp}(u_0) + \sum_{i\in N} J_i^{\sharp}(r_i;u_i,u_{ibH},u_{ibL}) \\ & + \sum_{\substack{i\in N \\ j\in N_i}} J_{ij}^{\sharp}(u_{ij}) \qquad (13a) \\ \text{subject to} \quad & u_0 = \sum_{i\in N} u_i \qquad (13b) \\ & u_i = u_{ibH} + u_{ibL} + \sum_{j\in N_i} u_{ij} \quad i \in N. \qquad (13c) \end{aligned}$$

We denote by u_0^*, u_i^*, u_{ibH}^*, u_{ibL}^* and u_{ij}^* the optimal solution to (13).

We note that the cost function (13a) of the social welfare maximization problem can also be recognized as the sum of the cost functions of the benefit maximization problems in (1), (9) and (12), since the terms depend on the prices will be cancelled-out under the supply/demand balance constraints in (13b) and (13c). The benefit-maximization problems in (1), (9) and (12) are selfish and do not concern supply/demand balancing. Supply/demand balance should be enforced by an appropriate pricing.

III. Optimization of Energy Demand Networks

This section considers market based welfare maximization through pricing. The aggregators are expected to moderate difficulties arisen in a large scale energy demand network optimization. Optimization can be utilized in a decentralized way by using dual decomposition. We propose an optimization process unitizing information exchange or aggregation by the aggregators, which is based on the well-known method of supply function bidding.

A. Dual Decomposition

Let us consider the dual problem of (13) given as:

$$\begin{aligned}\min_{\substack{\lambda_0 \\ \lambda_i\ i\in N}} \max_{\substack{u_0 \\ u_i,u_{ibH},u_{ibL}\ i\in N \\ u_{ij}\ j\in N_i}} \quad & J_0^{\sharp}(u_0) \\ & + \sum_{\substack{i\in N \\ j\in N_i}} J_{ij}^{\sharp}(u_{ij}) + \lambda_0^{\mathrm{T}}(u_0 - \sum_{i\in N} u_i) \\ & + \sum_{i\in N} J_i^{\sharp}(r_i;u_i,u_{ibH},u_{ibL}) \\ & + \sum_{i\in N}\{\lambda_i^{\mathrm{T}}(u_i - u_{ibH} - u_{ibL} - \sum_{j\in N_i} u_{ij})\}, \end{aligned} \tag{14}$$

where $\lambda_0 \in \mathbb{R}^P$ and $\lambda_i \in \mathbb{R}^P$ denote Lagrange multipliers.

It is known in optimization literature [16] that Lagrange multipliers can be interpreted as the shadow prices. Let λ_0^* and λ_i^* denote the dual optimal. By using λ_0^* and λ_i^*, the social welfare maximization problem (13) can be decomposed into the sub-problems of the utility company, aggregators and consumers. The utility company can maximize the benefit by solving (1) with $p_0 = \lambda_0^*$ and obtain u_0^*. Similarly, the aggregator A_i can maximize the benefit by solving (9) with $p_0 = \lambda_0^*$ and $p_i = \lambda_i^*$ and obtain u_i^*, u_{ibH}^*, u_{ibL}^* and consumer A_{ij} can maximize the benefit by solving (12) with $p_i = \lambda_i^*$ and obtain u_{ij}^*.

Then the dual problem (14) can be decomposed to the benefit of each market participant as follows:

$$\text{Utility company } A_0: \max_{u_0} J_0^\sharp(u_0) + p_0^{\mathrm{T}} u_0 \tag{15}$$

$$\begin{aligned}\text{Aggregator } A_i: \max_{u_i, u_{ibH}, u_{ibL}} \; & J_i^\sharp(r_i; u_i, u_{ibH}, u_{ibL}) \\ & - p_0 u_i \\ & + p_i^{\mathrm{T}}(u_i - u_{ibH} - u_{ibL})\end{aligned} \tag{16}$$

$$\text{Consumer } A_{ij}: \max_{u_{ij}} J_{ij}^\sharp(u_{ij}) - p_i^{\mathrm{T}} u_{ij} \tag{17}$$

B. Information Exchange via Aggregators

We propose an information exchange or aggregation procedure by the aggregators which moderate the amount of information exchange as well as computational burden. In this procedure, the aggregators will define the cost function of their own local sub-network and submit it to the utility company.

Consumer A_{ij} submits the cost function $J_{ij}^\sharp$ to aggregator A_i. When aggregator A_i gathered the cost functions of all the consumer $A_{ij},\ j \in N_i$, the aggregator determines the utility function of the sub-network associated with aggregator A_i. We define the cost function $J_i^{\sharp\sharp}(\cdot)$ of the sub-network as:

$$\begin{aligned}J_i^{\sharp\sharp}(r_i; u_i) = J_i(u_i) & \\ + \max_{\substack{u_{ibH}, u_{ibL} \\ u_{ij}\ j \in N_i}} & J_{ibH}^\sharp(r_i; u_{ibH}) + J_{ibL}^\sharp(r_i; u_{ibL}) \\ & + \sum_{j \in N_i} J_{ij}^\sharp(u_{ij})\end{aligned} \tag{18a}$$

$$\text{subject to} \quad u_i = u_{ibH} + u_{ibL} + \sum_{j \in N_i} u_{ij}. \tag{18b}$$

The function $J_i^{\sharp\sharp}(r_i; u_i)$ decides the optimal allocation of energy when the purchased amount u_i by aggregator A_i is specified. For general convex functions J_i and $J_{ij}^\sharp$, it may not be easy to obtain an explicit representation of $J_i^{\sharp\sharp}$. However, in our problem settings, the cost function of the sub-network is also given in a quadratic form as:

$$J_i^{\sharp\sharp}(r_i; u_i) = u_i^{\mathrm{T}} Q_i^{\sharp\sharp} u_i + R_i^{\sharp\sharp} u_i + C_i^{\sharp\sharp},$$

and the coefficients $Q_i^{\sharp\sharp}$, $R_i^{\sharp\sharp}$ and $C_i^{\sharp\sharp}$ will be determined by algebraic manipulations considering the Karush-Kuhn-Tucker (KKT) conditions for (18).

The cost function $J_i^{\sharp\sharp}(\cdot)$ of the sub-network will be submitted by aggregator A_i to the utility company. The utility company determines the optimal price $p_0 = \lambda_0^*$ by using the submitted cost functions. The social welfare maximization problem (13) can be rewritten as:

$$\max_{\substack{u_0 \\ u_i\ i \in N}} \quad J_0^\sharp(u_0) + \sum_{i \in N} J_i^{\sharp\sharp}(r_i; u_i) \tag{19a}$$

$$\text{subject to} \quad u_0 = \sum_{i \in N} u_i. \tag{19b}$$

The dual problem of (19) can be expressed as:

$$\min_{\lambda_0} \max_{\substack{u_0 \\ u_i\ i \in N}} J_0^\sharp(u_0) + \sum_{i \in N} J_i^\sharp(u_i) - \lambda_0^{\mathrm{T}}(-u_0 + \sum_{i \in N} u_i). \tag{20}$$

By solving this problem, the utility company decides the optimal price $p_0 = \lambda_0^*$ and broadcast it to the aggregators. The utility company can maximize the benefit by solving (1) with $p_0 = \lambda_0^*$ and obtain u_0^*. The aggregator A_i can maximize the benefit by solving

$$\max_{u_i\ i \in N} \quad J_i^{\sharp\sharp}(r_i; u_i) - p_0^{\mathrm{T}} u_i, \tag{21}$$

with $p_0 = \lambda_0^*$ and obtain u_i^*.

Another task of aggregator A_i is to determine the price p_i for the sub-network. Once u_i^* is obtained as a solution to (21), aggregator A_i can determine the optimal price $p_i = \lambda_i^*$ by solving the dual problem of

$$\max_{u_{ij}\ j \in N_i} \quad J_{ibH}^\sharp(u_{ibH}) + J_{ibL}^\sharp(u_{ibL}) + \sum_{j \in N_i} J_{ij}^\sharp(u_{ij})$$

$$\text{subject to} \quad u_i^* = u_{ibH} + u_{ibL} + \sum_{j \in N_i} u_{ij},$$

that is

$$\begin{aligned}\min_{\substack{\lambda_i \\ i \in N}} \max_{\substack{u_{ij} \\ j \in N_i}} \; & J_{ibH}^\sharp(u_{ibH}) + J_{ibL}^\sharp(u_{ibL}) + \sum_{j \in N_i} J_{ij}^\sharp(u_{ij}) \\ & - \lambda_i^{\mathrm{T}}(-u_i^* + u_{ibH} + u_{ibL} + \sum_{j \in N_i} u_{ij}).\end{aligned} \tag{22}$$

This process also determines the amount of charge/discharge of batteries owned by aggregator A_i.

Finally, aggregator A_i broadcasts the optimal price $p_i = \lambda_i^*$ to the consumers, and consumer A_{ij} can maximize the benefit by solving (12) with $p_i = \lambda_i^*$ and obtain u_{ij}^*.

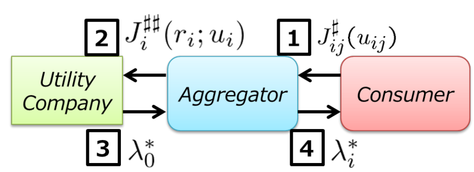

Fig. 3: Exchanges of information.

Fig. 3 illustrates the information exchange according to the proposed optimization process. By comparing (14) and (20), it can be seen that: the number of cost functions which should be gathered to the utility company is reduced to $1+n$ from $1 + n + \sum_{i \in N} n_i$; the dimension of dual variable is also reduced to P from $(1+n)P$. The remaining tasks are equitably shared by n aggregators and solved in (18) and (22) in a decentralized manner. In addition, the proposed optimization process does not require any communications between the utility company and aggregators/consumers due to iterative computations, thus it may be applicable to a short term energy scheduling problem. Other optimization processes in which the aggregators moderate the tasks of the utility company has been considered [8], [9]. In [8], a hierarchical optimization structure combines supply function bidding and tâtonnement process. In [9], a bidding of parameters which locally approximate the supply function was used to apply the Newton method for price updating rule, which accelerates the convergence of tâtonnement process.

IV. Numerical Examples

We suppose that the energy demand network will be optimized through price response based optimization prosess described in Section III, while the aggregator A_i will choose the parameter H_{iT}, the total capacity of the battery storage, and α_i, the ratio of the capacity of the high-performance storage. In this section, we indicate the results of numerical examples and show that at some point there exists the optimal parameter that maximizes the benefit of aggregator.

A. Results

In this example, we have one utility company, three aggregators, and ten consumers for each aggregator. We assume only aggregator A_1 has batteries. A_1 seeks optimal ratio of high-performance battery and low-performance battery, which is represented by α_i, for variety of total battery capacities H_{iT}. Fig. 4 shows the 3D-plot of the benefit of aggregator A_1: $J_i^\sharp(r_i; u_i, u_{ibH}, u_{ibL}) + p_i^{\mathrm{T}}(u_i - u_{ibH} - u_{ibL}) - p_0 u_i$. Since we do not use inequality constraints, we set $z_{i1} = 50000$, $z_{i2} = 50000$ and $z_{i3} = 100$ in order to make x_{ibH} and x_{ibL} in realistic value.

Figs. 5, 6, 7, 8 indicate the benefit when H_{iT} is fixed to 8000, 10000, 13000, 20000, respectively. These figures are the cut-planes of Fig. 4.

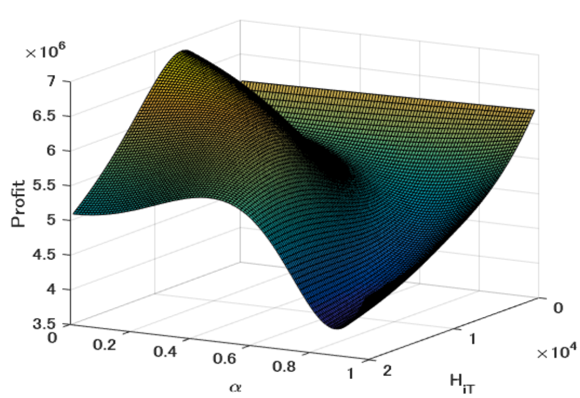

Fig. 4: Profit of aggregator

The results of Figs. 5-8 show that, with the appropriate ratio of high-performance storages, the aggregator can maximize its benefit. We can see that with different H_{iT}s, aggregator has to choose different α_i in order to maximize

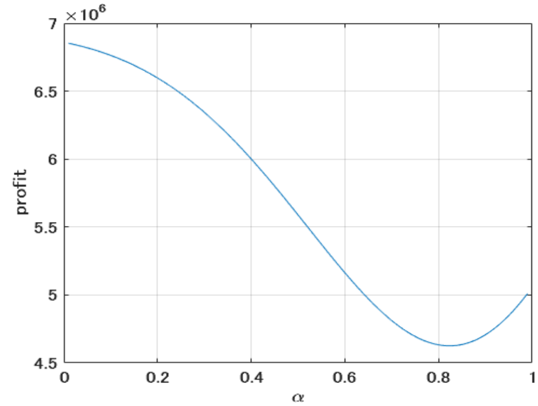

Fig. 5: $H_{iT} = 8000$

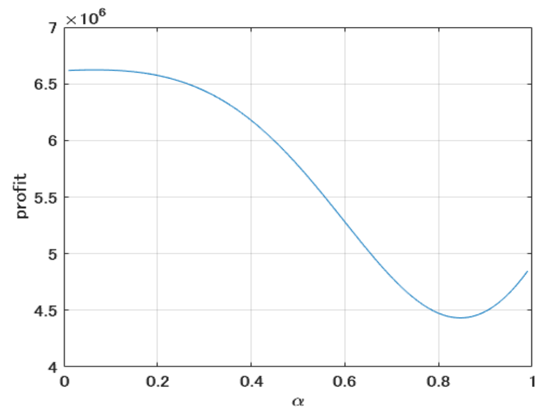

Fig. 6: $H_{iT} = 10000$

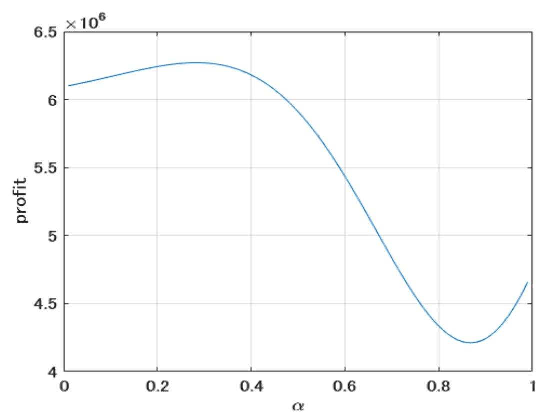

Fig. 7: $H_{iT} = 13000$

benefit. The highest point of the benefit is achieved with the combination of parameters $\alpha_i = 0$, $H_{iT} = 7200$, which is the best strategy of the aggregator in this numerical example.

Fig. 9 shows the 3D-plot of the social welfare of the energy demand network in (13).

From Fig. 9, it can be seen that the some combination of H_{iT} and α_i can actually increase the social welfare of the energy demand network. This means that the network or, in

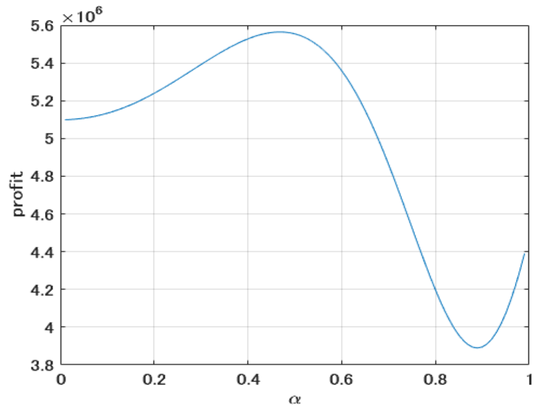

Fig. 8: $H_{iT} = 20000$

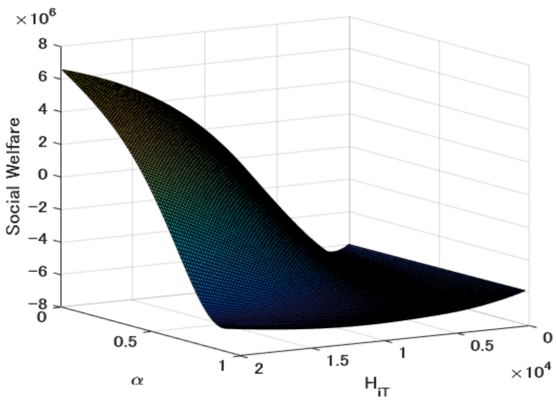

Fig. 9: Social welfare

other word, the society may accept strategic behavior of the aggregator A_i. However, the combination of H_{iT} and α_i that maximize the social welfare may not necessarily maximize aggregator A_i's personal benefit, as we can see in Fig. 4. A strategic aggregator A_i may try to increase its own benefit not the social welfare, and it is not a desired behavior for the other participants in the network. From the market or society design point of view, it may be important to align the maximization of aggregator A_i's personal benefit and the social welfare. If it was realized, the society should accept the strategic behavior of aggregator A_i. This problem, aligning the maximization of the aggregator's personal benefit and the social welfare, may be formulated as the problem of mechanism design [17], [15], [18], where a suitable transfer cost or, in other word, incentive should be designed to alter aggregator's decision making so as to align selfish optimization and social welfare optimization. An extension of the current work in this direction is under investigation.

V. Conclusions

This paper considered optimization problems of the energy demand networks including aggregators and investigated strategic behavior of the aggregators. We formulated the energy demand networks including aggregators and considered optimization process through pricing. The aggregator acts as intermediate between the utility company and a large number of consumers and is expected to moderate tasks of the utility company to solve a large scale optimization problem. We also formulated the model of battery that is possessed by the aggregators. With the numerical example, we showed that the best strategy of aggregators does not maximize the social benefit. Therefore, in this network, the society has to accept the selfish behavior of the aggregator, or design an incentive that makes the aggregator's best strategy maximizes the social welfare.

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