Analysis of the Value of Distributed Energy Resources through the Regional Electricity Market

Leon Fidele Nishimwe H.
Department of Electrical Engineering
Soongsil University
Seoul, Republic of Korea
gashukaleon@gmail.com

Taehyung Park
Department of Industrial and Information Systems Engineering
Soongsil University
Seoul, Republic of Korea
tpark@ssu.ac.kr

Sung-Guk Yoon
Department of Electrical Engineering
Soongsil University
Seoul, Republic of Korea
sgyoon@ssu.ac.kr

***Abstract*—The development of the smart grid has enabled end-users of electricity to use efficiently distributed energy resources (DERs). End-users can sell as well as purchase electricity, and they are called Prosumers. A Prosumer can manage its daily consumption pattern by controlling the heat, ventilation and air conditioning (HVAC) load, deferrable load, and energy storage system (ESS) therefore minimizing its electricity cost and discomfort. Prosumers can share the electricity surplus with the main grid and or with their neighboring Prosumers to maximize their profit. The main objective of this paper is to analyze the value of renewable energy and controllable loads such as HVAC, deferrable load, and ESS in the Prosumers network through the electricity price in the regional market. Diverse case studies show that the value of the regional market heavily depends on the surplus and deficit of electricity from renewable energy of Prosumers, and the main grid electricity price.**

Keywords: HVAC loads, deferrable load, Prosumer, electric market

NOMENCLATURE

Index

a Index of ambient temperature.
i Index of Prosumers.
in Index of Indoor Temperature.
N Number of PV Prosumers.
t Index of the time slot.
i, def Index for i^{th} Prosumers' deferrable load.

Variables

$b_i^{c,t}$ Amount of energy charged by the energy storage system (ESS).
$b_i^{d,t}$ Amount of energy discharged by the energy storage system (ESS).
d_i^t Amount of energy consumed by the deferrable load.
$g_i^{b,t}$ Amount of energy purchased from the main grid.
$g_i^{s,t}$ Amount of energy sold to the main grid.
h_i^t Amount of energy consumed by the HVAC load.
$l_i^{b,t}$ Amount of energy consumed by the basic load.
$l_i^{g,t}$ Amount of energy generated by DER.
$m_i^{b,t}$ Amount of energy purchased from the regional electricity market.
$m_i^{s,t}$ Amount of energy sold to the regional electricity market.
T_{in}^t Indoor Temperature at time t.

Parameters

A Power consumption variation of HVAC load according to a unit temperature variation.
B Minimum HVAC operation power.
$b_i^{c,max}$ Maximum energy charging rate for the ESS.
$b_t^{d,max}$ Maximum energy discharging rate for the ESS.
d_i^{max} Maximum energy consumption rate by the deferrable load.
D_i Total required energy for the deferrable load.
$g_i^{b,max}$ Maximum energy that can be bought from the main grid.
h_i^{min} Minimum energy consumption rate by the HVAC load.
h_i^{max} Maximum energy consumption rate by the HVAC load.
$m_i^{b,max}$ Maximum energy purchased from the regional electricity market.
$m_i^{s,max}$ Maximum energy sold to the regional electricity market.
S_i^{init} Initial state of charge of the ESS.
S_i^{max} Maximum state of charge of the ESS.
T_{in}^{min} Minimum indoor temperature.
T_{in}^{max} Maximum indoor temperature.
T_a^t Ambient temperature at time t.
$Temp_i^t$ The hourly temperature variation.
η_i Battery efficiency.
γ Transmission efficiency in the Prosumers' network.
τ The thermal flywheel factor.

I. INTRODUCTION

Due to the increasing environmental issues, the population growth and the expansion of housing all along with the deployment of controllable loads, demand for high quality and reliable energy increase day by day. Therefore, a new concept for the power system, i.e., the smart grid, becomes important [1]. Generally, traditional power grids are used to distribute power from central generators to many consumers. In contrast, the smart grid takes advantage of distributed energy resources (DERs) based on renewable energy resources and provides a higher efficiency [2].

The integration of DERs enables consumers to play a more active role in energy markets today [3]. In the smart grid, consumers can generate electricity by using DERs, such as PV generators or Wind Turbine, and they can use the energy storage system. In [4], the end users that both consume and produce energy are called Prosumers; which can both consume, and supply energy to the power network. Prosumers are able to use smart controls, and communication technologies to improve their efficiency by scheduling the pattern of their loads according to the electric power price [5]. For optimal performance of Prosumers, distributed energy resources (DERs) will need further attention.

Recently, many researchers provided details on the energy sharing management for interconnected microgrids and an efficient coordination in the Prosumer community. In [6], the energy sharing problem inside the microgrid of P2P PV Prosumers was studied. An internal pricing model is proposed for the operation of the energy sharing zone, which was defines based on the supply and demand ration of shared PV energy. In [7], the authors studied an energy exchange for Prosumers, in which the Prosumers' energy is transmitted and exchanged between end-users. The motivation of the energy exchange is the energy price. Furthermore, [8] proposed a Prosumer-based energy sharing and management scheme to achieve the demand side management while optimizing the cost for both Prosumers and utilities. In [9], the authors propose an energy management model which helps Prosumers to control their energy consumption with respect to the controllable and uncontrollable generation and consumption as well as the Prosumers ability. Authors in [10], have used a game theoretical approach to evaluate the benefits of solar PV owned Prosumers. In [11], the authors studied the matching of the electricity supply and demand under the Linear Function Submission-Double Auction (LFS-DA) algorithm. An exact balance of electricity supply and demand was achieved.

In our previous work [12] and [13], we have studied the effects of LFS-DA algorithm on adjustable loads in a network of Prosumers. In [12], Rugira performed an optimization framework to minimize the Prosumers energy cost and dissatisfaction by controlling the HVAC Load. In [13], we focused on developing a model to minimize the operation cost of the Prosumers network while maintaining the Prosumers comfort. Until now, to the best of our knowledge, with the development of Prosumer, the value of DERs, Controllable loads and ESS on the regional market is not known. Therefore, this paper, propose a study to analyze the value of renewable energy, HVAC load, deferrable load, and ESS through the regional electricity market. The novelty of our work is to identify the significant tool on the operation cost of a Prosumer through the regional market by controlling the HVAC load, deferrable load and ESS in commercial buildings into the regional Prosumers network. The value of DERs was evaluated by considering the operation cost of a Prosumer through the regional electricity market.

The rest of this paper is organized as follows. Section II describes the structure of the Prosumers' network and the regional electricity market. The cost optimization model used to analyze the value of DERs is presented in Section III. Section IV shows the case study and simulation results. In Section V, the conclusion is drawn.

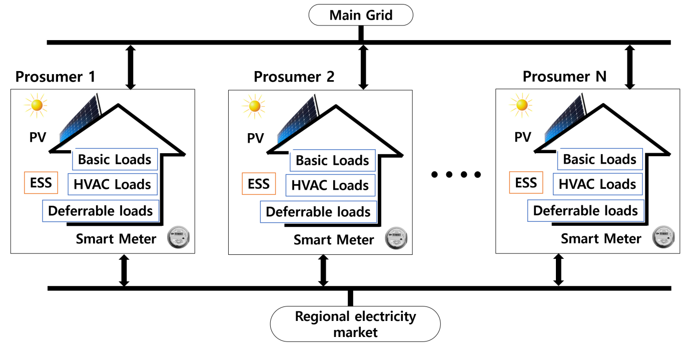

Fig. 1. Structure of the Prosumers' Network

II. Regional Electricity Market

A. Structure of the Prosumers' Network

The regional Prosumers network is a network that consists of interconnected electricity Prosumers. Prosumers are interconnected so that they can trade their electricity surplus between each other. The importance of regional electricity network is to motivate the energy sharing among Prosumers and reduce their dependence on the main grid. The structure of the Prosumers network is illustrated in Fig. 1. We consider a network of N Prosumers, in which each Prosumer is connected on both the main grid and on the regional electricity market. Each Prosumer is equipped with a smart meter which trades the electricity in the regional market and distributes the electricity generated by DERs appropriately by referring to the load profile of each Prosumer [11].

All Prosumers are equipped with some DERs such as solar PV and wind turbine, and an ESS. In this paper, the ESS can be any battery-type plug-in electric vehicle by considering the Vehicle to Grid (V2G) technology. The electric vehicle (EV) can be charged during the day time from PV energy or during the nighttime when the main grid electricity is cheap. Also, each Prosumer has basic loads, HVAC loads and deferrable loads, Fig. 2. To know the value of DERs, the operational cost of the regional market is optimized. The operational cost can be affected by renewable energy surplus and the controllable loads. HVAC loads are controlled by setting the preferred temperature range. The deferrable loads are modeled in such a way that their power consumption is adjusted within a range of their fixed operational time. A Prosumer can sell its surplus of electricity to a neighboring Prosumer through the regional market or can sell to the main grid. On the other hand, a Prosumer which has a deficit of electricity can buy electricity from the regional market or from the main grid. In this work, to motivate the on-site consumption while simplifying calculations, we assume that Prosumers can sell their surplus only to the regional electricity market.

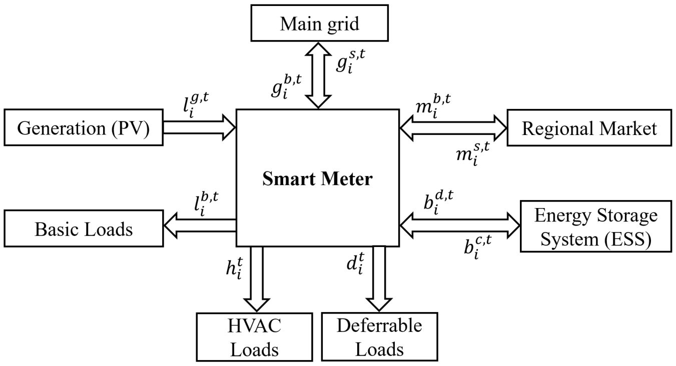

Fig. 2. An example of a Prosumer. The Prosumer is connected to the main grid on one hand and to the regional market on the other hand. Each Prosumer has an installed PV generator, an ESS, basic loads, HVAC and deferrable loads. The electricity flow is controlled by a smart meter.

III. Regional Market Cost Optimization Model

The main goal of this paper is to analyze the value of DERs through the regional electricity market. In order to evaluate the value of the considered DER in this paper, we compared a cost optimization model to control the HVAC load and deferrable loads through the regional electricity market to a case when the Prosumers do not participate in the regional market. We assumed that all Prosumers are connected to the regional electricity market. The price of electricity in the regional market is determined by using LFS-DA algorithm [13].

A. Cost Model for Each Prosumer

In this section, we scheduled the HVAC and deferrable loads with a goal of minimizing the operation cost for each Prosumer. For the Prosumers cost optimization, there are ten decision variables which varies daily within $t \in T$ time periods, where $T := \{1, 2, ...T\}$ is the set of the scheduling time. Each Prosumer receives a set of ten decision variables represented by $X_i \equiv \{l_i^{b,t}, l_i^{g,t}, h_i^t, d_i^t, b_i^{c,t}, b_i^{d,t}, m_i^{b,t}, m_i^{s,t}, g_i^{b,t}, g_i^{s,t}\}$.

The operation cost for Prosumer $i \in N := \{1, 2, ...N\}$, consists of the renewable energy generation cost, the profit of selling the electricity and the cost of purchasing electricity from the main grid and the profit of selling and the cost of buying electricity with the regional electricity market.

The total operation cost is given by

$$C_i(X_i, p_t^s, p_t^b, p_t) = \sum_{t \in T} C_i^t(l_i^{g,t}) - \gamma p_t^s g_i^{s,t} + p_t^b g_i^{b,t} - \gamma p_t m_i^{s,t} + p_t m_i^{b,t}, \tag{1}$$

where p_t^s, and p_t^b represent the rates of selling and buying electricity with the main grid respectively. While p_t denotes the regional electricity market price. γ is the transmission efficiency in the Prosumers network.

B. Cost Optimization for the Regional Electricity Market

In the Prosumers network, neighboring Prosumers can share their surplus of generation at a reduced price compared to the main grid price, this is to motivate the on-site consumption of renewable energy generation. The goal of the regional market cost optimization is to determine the optimal schedule for the HVAC and deferrable loads. This scheduling problem is formulated in terms of minimizing the Prosumers total cost.

The regional electricity market cost minimization problem is given by

$$min \sum_{i \in N} C_i(X_i, p_t^s, p^b{}_t, p_t), \tag{2}$$

Subject to

$$h_i^t + d_i^t + l_i^{b,t} - l_i^{g,t} + b_i^{c,t} - b_i^{d,t} + m_i^{s,t} - m_i^{b,t} + g_i^{s,t} - g_i^{b,t} = 0 \tag{3}$$

$$T_{in}^{min} \leq T_{in}^t \leq T_{in}^{max}, \tag{4}$$

$$0 \leq l_i^{b,t} \leq l_i^{b,max}, \tag{5}$$

$$0 \leq l_i^{g,t} \leq l_i^{g,max}, \tag{6}$$

$$h_i^t = A \cdot Temp_i^t + B, \tag{7}$$

$$T_{in}^{t+1} = T_{in}^t + (\frac{T_a^t - T_{in}^t}{\tau} - Temp_i^t), \tag{8}$$

$$h_i^{min} \leq h_i^t \leq h_i^{max}, \tag{9}$$

$$0 \leq m_i^{s,t} \leq m_i^{s,max}, \tag{10}$$

$$0 \leq m_i^{b,t} \leq m_i^{b,max}, \tag{11}$$

$$0 \leq b_i^{c,t} \leq b_i^{c,max}, \tag{12}$$

$$0 \leq b_i^{d,t} \leq b_i^{d,max}, \tag{13}$$

$$g_i^{s,t} \geq 0, \tag{14}$$

$$0 \leq g_i^{b,t} \leq g_i^{b,max}, \tag{15}$$

$$\sum_{t=t_{i,s}}^{t_{i,e}} d_i^t = D_i, \tag{16}$$

$$0 < d_i^t \leq d_i^{max}, \tag{17}$$

$$d_i^t = 0, \quad if \quad t \in T \setminus T_{i,def}, \tag{18}$$

$$0 \leq S_i^{init} + \sum_{t \in T}(\eta_i b_i^{c,t} - b_i^{d,t}) \leq S_i^{max}, \tag{19}$$

In this optimization problem, all the ten control variables are bounded (4), (5), (6), (9), (10), (11), (12), (13), (15), (17). As discussed in [13], equation (7), shows the HVAC load model. Equation (8) describe the indoor temperature model. The indoor temperature is maintained in the preferred comfort zone for each Prosumer. Equations (16), (17), and (18) introduce the model of deferrable load. In this paper we considered the scheduling to shift the operational period of the deferrable load. Each Prosumer needs to pre-set the start time $t_{i,s}$ and the end of time $t_{i,e}$ that the deferrable load can be scheduled. The set of time in which the deferrable load can be shifted is given by $T_{i,def} = [t_{i,s}, t_{i,e}] \in T$. The model of deferrable load used in this paper was retrieved from [14]. Moreover, in equation (19), we described the ESS status during the scheduling period.

To solve this optimization problem, the regional electricity market price is needed. In this paper we used the LFS-DA algorithm, detailed in [11], to decide the regional electricity market price.

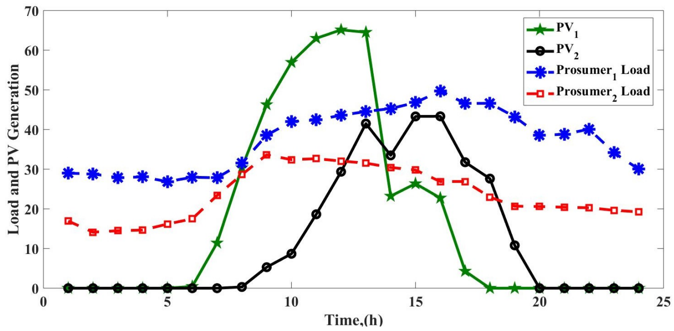

Fig. 3. PV_1 is the PV generation of $Prosumer_1$. PV_2 is the PV generation for $Prosumer_2$. The basic loads' curves for two Prosumers within the Prosumers' network are illustrated.

IV. The Case Study and Simulation Results

In this section, we analyzed the value of DERs through the regional electricity market. We considered two cases. In the first case, the Prosumers network consists of two Prosumers. In the second case, we consider a complex scenario in which the network of Prosumers consists of ten Prosumers with different PV generation capacity and different load cures. The value of DERs is discussed in terms of the gain of regional electricity market which is obtained by comparing the cost optimization when a Prosumer transacts only with the main grid and the cost optimization when the Prosumer participates in the regional electricity market. We also investigate the value of DERs when they are generating electricity compared to when they are not generating electricity.

A. General Settings

In this paper, we set the scheduling period as 24 hours of a day, divided into equal time slots of time interval $t \in T$ which is 1 hour. All parameters of the Prosumers used in this paper are detailed in Table I. In the first case, all Prosumers have PV generators, ESS, basic loads, HVAC, and deferrable loads. In the second case, eight Prosumers have PV generators, but two among them do not have a surplus. We analyzed various scenarios with different load pattern and PV generation profile. The daily basic load and PV generation curve for the first case is shown in Fig. 3. The PV generation and basic loads are considered to be known beforehand.

From Fig. 3, we observe that the transaction of electricity between Prosumers is possible from 9 AM to 5 PM due to the surplus of PV generation in those hours. During the night hours, Prosumers can use the power from the main grid. Aforementioned is confirmed with Fig. 4, which illustrates the price of electricity of both the main grid and the regional electricity market. As shown in Fig. 4, the main grid power is cheap during the night hours. In the day time, the main grid price is very high compared to the regional market electricity price. It is the cheap electricity that motivates Prosumers to participate in the regional electricity market. The transaction is possible because during the day time Prosumers have PV electricity surplus that they can share in the regional market. In the case of ten Prosumers' network, there is no significant

TABLE I
Parameters and Basic Variables Used For Simulation

Parameters and variables used in this paper	
Number of Prosumers	$N = 2$ and $N = 10$ buildings
Scheduling period	$T = 24h$ divided into 24 equal time slots
Deferrable load's operation period	$T_{i,def} = [t_{i,s} = 3PM, t_{i,e} = 9PM]$
Battery bounds	$b_i^{c,max} = b_i^{d,max} = 10kWh$
Regional market bounds	$m_i^{s,max} = m_i^{b,max} = 40kWh$
Battery state of charge	$S_i^{init} = 0$, $S_i^{max} = 40kWh$
Maximum purchase from the main grid	$g_i^{b,max} = 500kWh$
Battery efficiency	$\eta_i = 0.85$
Transmission efficiency	$\gamma = 0.95$
PV generation cost	$C_i^t = 0$
PV generator capacity	$72.55kW$ and $55.6kW$
HVAC load bounds	$h_i^{min} = 0$, $h_i^{max} = 10kWh$
Constants	$A = 2.9$, $B = 1.1$, $\tau = 11$, $D_i = 10.2kWh$, $d_i^{max} = 3.3kWh$
Indoor temperature bounds (comfort zone)	$T_{in}^{min} = 20^oC$, $T_{in}^{max} = 24^oC$, $T_{in}^1 = T_{in}^{24} = 20^oC$

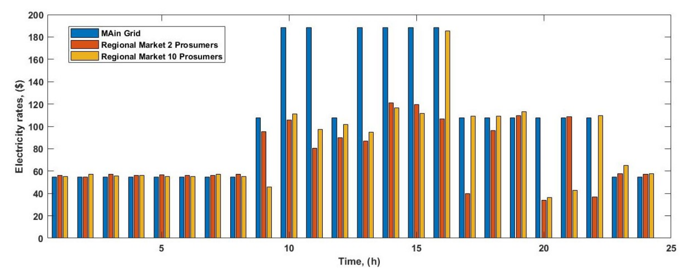

Fig. 4. Comparison between the main grid utility price and the regional market price in two Prosumers network and in a ten Prosumers network.

transaction at 4 PM because the electricity price in the regional market is almost equal to the main grid price. Furthermore, there is also a transaction in the regional market at time 8 PM and 10 PM for the two Prosumers case. In addition to this, the transaction is possible at 8 PM and 9 PM, in the ten Prosumers case. The transaction is possible due to the available surplus of electricity that can be shared among Prosumers, and additionally, the amount of power stored in the ESS can be shared in the regional electricity market. The main grid price used in this paper was retrieved from the Korean Electric Power Corporation (KEPCO) [15].

B. Effectiveness of Controllable Loads in the Regional Market

Prosumers can manage their daily consumption pattern by controlling the ESS and flexible loads such as HVAC and deferrable loads, therefore minimizing their electricity cost and their discomfort. Controlling the ESS, HVAC load, and deferrable results in a reduction of the Prosumers' total operation cost in the regional market. However, compared to the total cost of Prosumers who transact only with the main grid, the regional market has a marginal gain through controlling ESS and controllable loads. In Table II, we observe the value of ESS, HVAC, and deferrable loads through the

TABLE II
EFFECTIVENESS OF CONTROLLABLE LOADS AND ESS IN THE REGIONAL MARKET

HVAC Load	Deferrable Load	ESS	Without Regional Market [$]	With Regional Market [$]	Gain [%]
X	X	X	80.9	72.0	**11.01**
O	X	X	76.8	68.1	**11.32**
X	X	O	69.7	61.8	**11.24**
X	O	X	81.0	73.9	**8.78**

regional market. This results for each HVAC, deferrable load, and ESS is obtained by assuming that all the other loads are fixed. It is assumed that Prosumers are generating electricity from their PV generators. In the Table II, X denotes that the load is fixed or simply that the load is not controlled while O denotes that the load is controlled.

We compare the Prosumer's total cost in the regional electricity market to their total cost when a Prosumer with installed PV transacts only with the main grid. Numerical results in Table II, show that the Prosumer's total cost is high when the HVAC and ESS are fixed and when the deferrable loads is used in the peak time hours. The price of electricity can be minimized by controlling the operation time and setting of the HVAC, deferrable load and ESS. However, the gain of the regional market is still marginal by only relying on managing the daily consumption. For simplicity, we assumed that all Prosumers have the same initial characteristics excepts for basic loads and PV generation capacity.

In this case study, deferrable were controlled by shifting their operation period. We consider two cases, first, the deferrable load is considered as a fixed load when they operate during the nighttime from 1 AM to 6 AM, therefore, using the cheap electricity from the main grid. Second, the deferrable load is considered controlled loads when their operation time is in the afternoon from 3 PM to 9 PM.

C. Value of PV Generation in the Regional Electricity Market

In this subsection, our objective is to check the efficacy of PV generation in the regional electricity market. We analyzed the value of PV generator by checking their generation-time performance in the regional market optimization problem and the time during which they are not producing electricity. We assumed that the HVAC load, Deferrable load, and ESS are fixed. As shown in Fig. 3, all Prosumers have the surplus of electricity, we observe that the transaction of electric power between Prosumers is possible from 9 AM to 6 PM and at 8 PM, and 10 PM.

Numerical results in Table III show that the gain of the regional electricity market is 11.01% when both Prosumer's PV generators are generating the electricity. The regional electricity market gain decreased to 5.91% and 3.28% when either PV_2 for $Prosumer_2$ or when PV_1 for $Prosumer_1$ is shut down, respectively. This means thatPV_1 for $Prosumer_1$ has much value in the regional electricity market compared to PV_2 for $Prosumer_2$. The reduction of the regional market

TABLE III
THE VALUE OF PV GENERATOR THROUGH THE REGIONAL ELECTRICITY MARKET

PV_1	PV_2	Without Regional Market [$]	With Regional Market [$]	Gain [%]
X	X	163	163	**0.00**
X	O	127	123	**3.28**
O	X	117	110	**5.91**
O	O	80.9	72.0	**11.01**

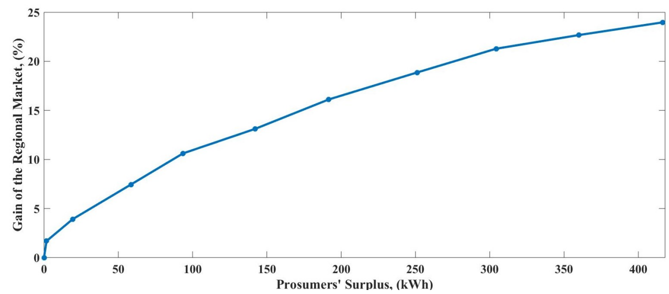

Fig. 5. The gain of regional electricity market depends highly on the PV generation surplus.

gain is related to the generation capacity and surplus of Prosumers. Furthermore, as observed in Table III, in the first line, without PV surplus there is no gain of participating in the regional electricity market. It means that the gain of the regional electricity market depends highly on the electricity surplus. Generally, from Table III, it is shown that the gain increase with the increase in the electricity surplus that can be shared in the regional market. The result is confirmed in Fig. 5. In this figure, it is illustrated that the gain of the regional electricity market increases to a significant value until a certain threshold. Therefore, without a surplus, there is no gain for the regional electricity market. However, with more surplus, the gain of the Regional electricity market become significant.

D. Complex Prosumers' Network Case

To confirm the significance of PV generation in the regional market, we solved our optimization problem by considering a complex Prosumers' network consisting of ten Prosumers with different characteristics. Among ten Prosumers 8 have installed PV generators, and two Prosumers do not have PV generator. Among Prosumers with installed PV generators, two Prosumers do not have a surplus of electricity. Numerical results in Table. IV, shows that the optimal cost of the regional market is $ 393.15 when Prosumers have PV generator with the electricity surplus but does not have controllable loads. Due to the fact that Prosumers have enough electricity to share with each other the transaction in the regional electricity market is possible. The total operation cost without the PV generator is $ 832.03. The operation cost is very high when the PV generators are shut down compared to when there is an amount of surplus to share in the regional electricity market. Therefore, it is shown that the PV generation is very important for the regional electricity market to be successful. According

TABLE IV
THE VALUE OF PV GENERATOR THROUGH THE REGIONAL ELECTRICITY MARKET

CASE with 10 Prosumers	**Without Regional Market [$]**	**With Regional Market [$]**	**Gain [%]**
Without PV and controllable loads	832.03	832.03	**0.00**
With PV without controllable load	448.61	393.15	**12.36**
With PV and Deferrable loads	451.07	400.71	**11.16**
With PV and ESS	399.28	343.10	**14.08**
With PV and HVAC	430.83	362.40	**15.88**

to Table IV, with the PV generator installed with a certain amount of surplus and assuming that the both the ESS and controllable loads are fixed, the gain of the regional electricity market is 12.36%. Furthermore, both the PV generation surplus and ESS increase the gain of the regional electricity market to 14.08%. The regional electricity has a significant value with a gain of 15.8% when Prosumers can control their HVAC loads, and they have PV generators installed with sufficient amount of surplus.

V. CONCLUSION

The objective of our paper is to evaluate the value of DERs through the regional electricity market. We considered a network of Prosumers where each Prosumer has a PV generator, ESS, basic loads, HVAC load, and deferrable load. In order to support the Vehicle to Grid technology (V2G), the ESS can be replaced by an electric vehicle (EV) with a plug-in function. We adapted an optimization framework for Prosumers that enables a transaction between them while keeping their indoor temperatures in the comfortable range and the operation of their deferrable load in the pre-set operation time. To reduce the operation cost, Prosumers can control their ESS, HVAC loads, deferrable loads, and they can transact in the regional market. Without the regional market, each Prosumer can only use pre-cooling and ESS to reduce the operation cost. However, with the regional market, Prosumers can share the surplus within the local network as well as controllable load. With a sufficient electricity surplus, the gain of the regional market is significant until a certain threshold. Case studies show that the regional market depends highly on the PV surplus of Prosumers in the Prosumers network. With the PV surplus and control of the ESS, the gain of the regional electricity market is 14.08%. Moreover, through our considered case studies, the value of the regional market is more significant when Prosumers have the PV generation surplus, and they can control their HVAC loads. With the PV generator surplus and HVAC load control, the gain of the regional market is 11.32% and 15.88% in the two Prosumers network case and in the ten Prosumers network case, respectively. The control of the ESS and HVAC loads increase the benefits of a Prosumer in the regional market, however, they have a marginal impact on the gain of the regional market.

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