OPTIMAL SCHEDULING OF ADJUSTABLE LOADS IN COMMERCIAL BUILDING THROUGH REGIONAL ELECTRICITY MARKET

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ABSTRACT

Currently, with the deployment of renewable generators in the distribution network, end users; called prosumers; can now easily generate electricity. To reduce their electricity cost, each prosumer controls its adjustable loads such as heating, ventilation, and air conditioning (HVAC) loads and battery operation. Furthermore, interconnected prosumers can maximize their performance by trading electricity through the regional electricity market. We propose an optimization framework to minimize the operational cost of the prosumer network while maintaining the prosumers' comfort. A case study shows that the control of adjustable loads and participating in the regional market using the proposed optimization framework succeeds reducing the prosumer's operational cost while keeping their comfort.

Keywords*: energy scheduling, Prosumer, adjustable load, HVAC*

INTRODUCTION

In recent years, due to environmental issues, a new concept for the power system, i.e., 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 exposes consumers to play a more active role in energy markets today [3]. In smart grid, consumers can generate electricity by using DER and can use an energy storage system. In [4], a consumer is called "prosumer" which consumes and supplies energy to the power network. Prosumers in the same region can be interconnected and form a prosumer community. Local energy management systems (EMS) take charge of the management of the prosumer community and control the transaction between prosumers.

Recent works [5]-[10] have studied the efficient coordination in the prosumer community. Sha and Aiello [5] have proposed an energy exchange for prosumers, in which the prosumers energy is transmitted and exchanged between end-users. The motivation for this exchange is energy price. Razzaq et al. [6] have investigated prosumer-based energy management to achieve the demand side management while optimizing the cost for both prosumers and utilities. In [7], an energy management model which helps prosumers to control their energy consumption with respect to controllable and uncontrollable generation has been studied. Liu et al. [8] have used a game theoretical approach to evaluate the benefits of solar PV owned prosumers. In [9], matching the supply and demand has been studied under the Linear Function Submission-Double Auction (LFS-DA) algorithm.

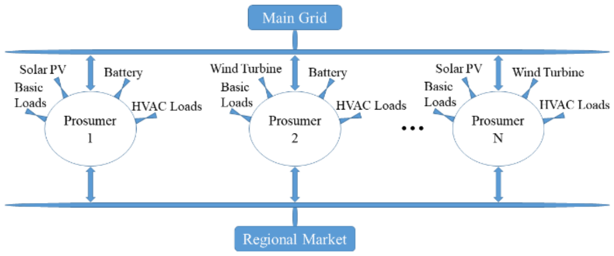


Fig. 1 Regional electricity network. All prosumers are connected on both the main grid and the regional market.

In our previous work [10], we have studied the effects of LFS-DA algorithm on adjustable loads in a network of prosumers, and the HVAC loads have been controlled to a fixed operational point. In this paper, we used more realistic HVAC modelling with different scenarios and analyse the benefit of pre-cooling. We develop an optimization model to control the HVAC load and battery in commercial buildings through the regional electricity network. The proposed optimization model minimizes the prosumers' operational cost while maintaining their indoor temperature between the comfort zone.

The rest of this paper is organized as follows. Section II describes the system model. Problem formulation is presented in Section III. Section IV shows the case study and its results. In Section V, the conclusion is drawn and some research directions are highlighted.

SYSTEM MODEL

Regional Electricity Network

We consider a prosumer community with N prosumers. The regional electricity network is defined as a network of interconnected electricity prosumers. Prosumers are interconnected so that they can trade their electricity between each other, as shown in Fig. 1. The market which promotes transaction between prosumers is called "regional electricity market." Each prosumer in the network is connected both to the main grid and the regional electricity market. Each prosumer may have some DERs such as solar PV and wind turbine, and an energy storage system, i.e. battery. All prosumers have basic and HVAC loads, Fig.1.

Regional Electricity Market

To communicate with other prosumers, each prosumer has a smart meter running an intelligent software as

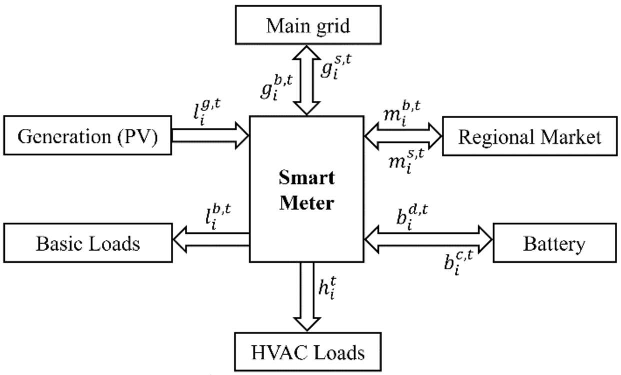


Fig. 2. An example of a prosumer. The prosumer is connected to the main grid and regional market and has a PV generator, battery, basic load, and HVAC load. All the electricity flow is controlled by smart meter equipped in the prosumer.

shown in Fig. 2. This software automatically trades electricity in the regional electricity market and allocates the generated electricity appropriately by referring to the load profile of each customer [9]. A prosumer can sell its surplus of electricity to a neighbouring prosumer through the regional market or to the main grid. On the other hand, a prosumer which has a deficit of electricity can buy electricity from the regional market or the main grid. In this work, we assume that prosumers can sell their surplus only to the regional electricity market. That is, reverse flow to the main grid is not allowed.

Each smart meter receives a set of nine control variables represented by $X_i \equiv \left\{l_i^{b,t}, l_i^{g,t}, h_i^t, b_i^{c,t}, b_i^{d,t}, m_i^{b,t}, m_i^{s,t}, g_i^{b,t}, g_i^{s,t}\right\}$. All variables are measured in kWh and are described in Table I. Each variable varies with time $t \in T$, where T is the set of scheduling time.

The balance equation of prosumer i is expressed as

$$h_i^t + l_i^{b,t} - l_i^{g,t} + b_i^{c,t} - b_i^{d,t} + m_i^{s,t} - m_i^{b,t} + g_i^{s,t} - g_i^{b,t} = 0 \qquad (1)$$

Table 1. Transacting Variables at t

Variable	**Name**
$l_i^{b,t}$	Amount of power for the basic load
$l_i^{g,t}$	Amount of power generated by DER
h_i^t	Amount of power for HVAC load
$b_i^{c,t}$	Amount of power to charge the battery
$b_i^{d,t}$	Amount of power discharged from the battery
$m_i^{b,t}$	Amount of power bought from the regional market
$m_i^{s,t}$	Amount of power sold to the regional market
$g_i^{b,t}$	Amount of power bought from the main grid
$g_i^{s,t}$	Amount of power sold to the main grid

Indoor Temperature

The indoor temperature depends heavily on the ambient temperature and the HVAC load. According to [11], the power consumption of HVAC loads h_i^t is modelled as a linear function. It is

$$h_i^t = A\,Temp_i^t + B \qquad (2)$$

where A, $Temp_i^t$, and B denote power consumption variation of HVAC load according to a unit temperature variation [kW/°C], hourly temperature variation [°C/h], and minimum HVAC operation power, respectively. The values of A and B are selected from the American Society of Heating, Refrigeration, Air Conditioning Engineers (ASHRAE) [12].

The indoor temperature in a building is calculated based on day-ahead forecasting temperature. The indoor temperature is obtained by

$$T_{in}^{t+1} = T_{in}^t + \left(\frac{T_a^t - T_{in}^t}{\tau} - Temp_i^t\right) \qquad (3)$$

where T_{in}^t, T_a^t and τ, denote indoor temperature [°C], ambient temperature [°C], and thermal flywheel factor, respectively. With this model, the indoor temperature is controlled between its extrema and the forecasted ambient temperature.

OPTIMIZATION PROBLEM

This research proposes a cost optimization model to control adjustable loads through the regional electricity market. The prosumer's indoor temperature is maintained in the defined thermal comfort zone in the whole scheduling period.

Optimization Formula for Each Prosumer

We formulate a minimization problem for each prosumer. Let $C_i(X_i, p_t^s, p_t^b, p_t)$ denote the operational cost of each prosumer, where i is a prosumer in $N := \{1,2,...N\}$. The rates of selling and buying electricity with the main grid are represented by p_t^s, and p_t^b, respectively, and p_t denotes the regional electricity market price.

The operation cost of prosumer i is given by

$$C_i(X_i, p_t^s, p_t^b, p_t) = \sum_{t \in T} C_i^t(l_i^{g,t}) - \gamma p_t^s g_i^{s,t} + p_t^b g_i^{b,t} - \gamma p_t m_i^{s,t} + p_t m_i^{b,t} \qquad (4)$$

where γ is the transmission efficiency in the prosumer network. The operational cost consists of the generation cost, the profit of selling electricity and the cost of buying electricity from the main grid and the profit of selling electricity and the cost of buying electricity with the regional market. It is assumed that the generation cost for renewable resources is zero, $C_i^t = 0$.

Optimization problem for Regional Electricity Market

In the prosumer community, we consider the overall cost minimization rather than each prosumer's cost minimization. The goal of this optimization problem is to determine the optimal schedule of adjustable loads by minimizing the prosumers total cost while satisfying their comfort preference. The total cost minimization problem is given by

$$\min \sum_{i \in N} C_i(X_i, p_t^s, p_t^b, p_t) \qquad (5)$$

subject to (1),

$$T_{in}^{min} \le T_{in}^t \le T_{in}^{max}, \qquad (6)$$

$$0 \le l_i^{b,t} \le l_i^{b,max}, \qquad (7)$$

$$0 \le l_i^{g,t} \le l_i^{g,max}, \qquad (8)$$

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

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

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

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

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

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

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

$$0 \le S_i^{init} + \sum\nolimits_{t \in T} (\eta_i b_i^{c,t} - b_i^{d,t}) \le S_i^{max}, \tag{16}$$

where η_i, S_i^{init}, and S_i^{max} represent the battery efficiency, the initial state of charge (SoC), and maximum SoC of battery, respectively. In this optimization problem, all the nine control variables are bounded (7), (8), (9), (10), (11), (12), (13), (14), (15). Eq. (6) shows that the indoor temperature should be kept between the minimum and maximum temperatures, i.e. comfort zone. In (16), the battery status during scheduling period must be between zero and maximum SoC.

To solve the optimization problem, we need to set the electricity price p_t in the regional market. In this paper, we use LFS-DA algorithm [9] to decide p_t.

LFS-DA algorithm

In LFS-DA algorithm, each prosumer participates in the auction by submitting linear demand and supply function to the regional market. When they submit bids, prosumers use linear functions to represent their supply and demand curves. Because each prosumer submits both supply and demand functions, this is a kind of double auction. The details of LFS-DA algorithm are shown in Algorithm 1.

Algorithm 1. The detail of LFS-DA algorithm

```
Initialize the price profile $p^{(k)} = (p_i^{(k)})_{t \in T}$
Repeat
    //Each agent solves its sub-problem (4) and obtains its solution.
    Update all variables in terms of the regional electricity price
    Update $\alpha_i^{*t} \leftarrow \beta_i^t p_t^{(k)} + (m_i^{*b,t} - m_i^{*s,t})$
    //Each agent submits ($\alpha_i^{*t}, \beta_i^t$) to the market.
    Update the market price and find the market clearing
    Update the bidding parameters
    //Reconfiguration by each agent
    Determine the exact value of each variable.
Until the stopping criteria are satisfied.
```

The linear bidding functions can be represented by

$$m_i^s = max(\beta_i^t p_t - \alpha_i^t, 0), \tag{17}$$

$$m_i^b = max(-\beta_i^t p_t + \alpha_i^t, 0), \tag{18}$$

where α_i^t and β_i^t are the bidding parameters for prosumer i. Each prosumer sends α_i^t and β_i^t to the regional market. After bidding function from N prosumers are received, the market-clearing price is determined at the market, and it is sent back to all prosumers. The market-clearing price is calculated as

$$p_t = \frac{\gamma\alpha_i^t(sellers) + \alpha_i^t(buyers)}{\gamma\beta_i^t(sellers) + \beta_i^t(buyers)}, \tag{19}$$

With the updated market-clearing price each prosumer also updates its bidding parameters. These processes repeat until a predefined stopping criterion is satisfied.

CASE STUDY AND SIMULATION RESULTS

In this section, we show the efficiency of the proposed optimization framework in terms of operational cost. The proposed framework is compared with the individual optimization case in which a prosumer transacts only with the main grid.

Simulation Settings

It is assumed that the electricity is sold and bought at the market-clearing prices determined by LFS-DA algorithm. We will discuss details of two scenarios: two and three prosumers. We assume that the basic load and renewable generation are perfectly forecasted.

Figure 3 shows the real PV generation and the basic loads profiles in Korea. We notice that the trading between prosumers is possible due to the surplus of PV generation from 10 AM to 4 PM. Fig. 4 shows the electricity rates of the main grid and regional market. The main grid price is retrieved from the Korean Electric Power Corporation (KEPCO) [13]. We used the ambient

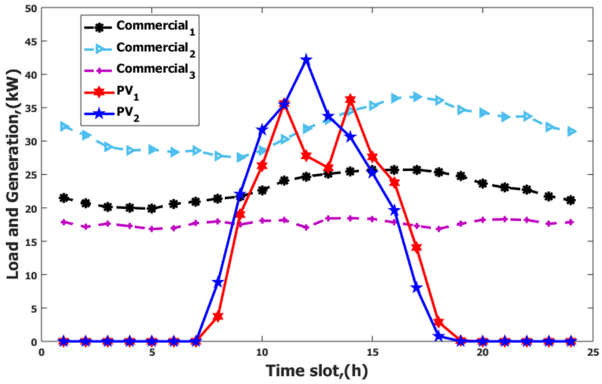


Fig. 3. Basic loads and PV generation profiles in the three-prosumer scenario.

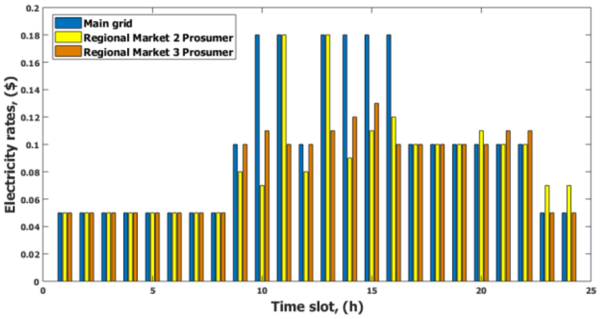


Fig. 4. Comparison between the utility price and regional market price.

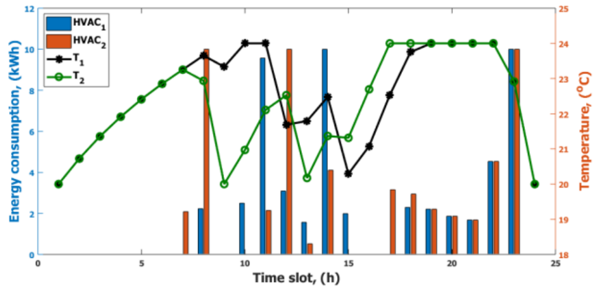
temperature of Geochang in South Korea in summer [14]. Other parameters are given in Table II.

Table II. Parameters used for Simulation

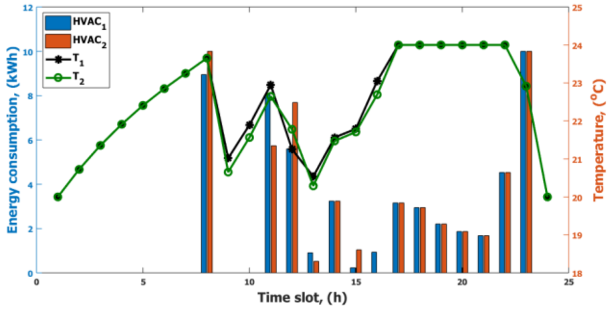
Parameters and Variables for simulation	
Number of prosumers	$N=2,3$ households
Time slots	$T=24$ hrs, with $1h$ for each time slot.
Battery bounds	$b_i^{c,max}=b_i^{d,max}=10kWh$
Regional market bounds	$m_i^{s,max}=m_i^{b,max}=40kWh$
Battery state of charge	$S_i^{init}=0,\ S_i^{max}=40kWh$
Maximum buying from main grid	$g_i^{b,max}=500kWh$
Battery efficiency	$\eta_i=0.85$
Transmission efficiency	$\gamma=0.95$
PV generation cost	$C_i^t=0$
HVAC load bounds	$h_i^{min}=0,\ h_i^{max}=2kWh,\ h_i^{max}=10kWh$
Constants	$A=2.9,\ B=1.1,\ \tau=11$
Indoor temperature bounds	$T_{in}^{min}=20\ [°C],\ T_{in}^{max}=24\ [°C]$ $T_{in}^{1}=T_{in}^{24}=20[°C]$

Two-Prosumer Scenario

In this case, we consider two prosumers equipped with PV generators. Figure 5(a) shows the individual optimization scenario. If the prosumer has a surplus of electricity, it can only consume fully by charging its battery and HVAC load. Otherwise, the surplus is wasted. In this figure, we observe high reductions of indoor temperature at time 9 AM and 1 PM for prosumer 2. The temperature drops at 9 AM is because the prosumer takes advantage of the low price of electricity at the main grid until 8 AM and supply its HVAC loads order to reduce the temperatures during the next time slots, i.e., pre-cooling. In this scenario, the cost reduction by pre-cooling at 8 AM is about 0.5$. The temperature changes around noon because HVAC load consumes the surplus from the PV generation.



(a) Individual optimization



(b) The proposed optimization

Fig. 5. Indoor temperature and electricity consumption for HVAC in two prosumer scenario.

Figure 5(b) illustrates the proposed optimization scenario with two prosumers. Prosumers support each other to maintain the indoor temperature in the preferred interval. Therefore, the indoor temperatures for two prosumers show almost the same profile.

Table III illustrates the total cost of electricity for prosumer 1 and prosumer 2. A cost reduction of 1% is observed by using the regional market compared to individual optimization. Prosumer 2 have higher cost since it has higher demand compared to prosumer 1.

Table III. Daily cost comparison for two prosumers

Cost $	**In Geochang**		
	Prosumer 1	**Prosumer 2**	**Total cost**
Individual	23.82	40.14	**63.96**
R. Market	23.70	39.63	**63.33**

Three-Prosumer Scenario

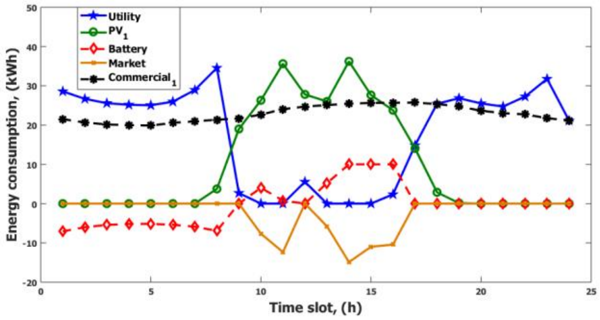
In this scenario, two prosumers out of three are equipped with PV generators, as shown in Fig. 3, and all the three prosumers have batteries, basic loads and HVAC loads. The temperature and HVAC profiles for this scenario are similar to that of two prosumers shown in Fig. 5. The general trend is similar to that of the two-prosumer case. In this case, due to the increase in the number of prosumers, the pre-cooling reduces electricity cost from 21.53$ to 16.45$.

Table IV. shows the operation cost in individual and Regional market scenarios for three prosumers. We observe about 6% reduction of total cost in the regional market compared to individual optimization. Recall that for two-prosumers case, the cost reduction is 1%. The cost reduction in the three-prosumer case is higher than that in the two-prosumer case because the third user has no PV generators. The cost reduction with regional market increases when the prosumers in the local network have different load and generation patterns.

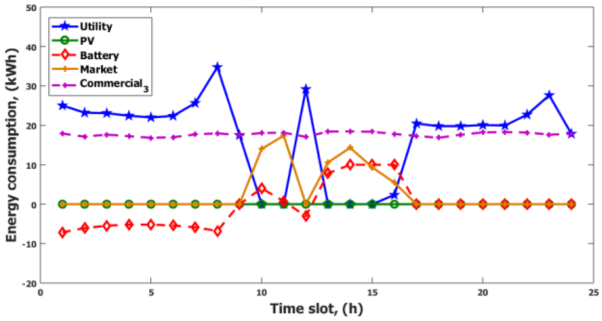
Table IV. Daily comparison for three prosumers

Cost $	**In Geochang**			
	Prosumer 1	**Prosumer 1**	**Prosumer 1**	**Total cost**
Individual	23.82	40.14	41.99	**105.95**
R. Market	22.37	39.08	38.32	**99.77**

Figure 6 shows the power consumptions of the prosumers 1 and 3. Positive and negative values represent power into and out of the prosumer's building, respectively. During night time, the electricity price from the main grid is cheap, so prosumers charge their battery to prepare for peak price period. As shown in Fig. 6(a), prosumer 1 has a surplus at 10 AM and 3 PM, so it can sell the surplus to neighbours. In the individual optimization case, the surplus should be consumed by battery or HVAC load. In the evening, the PV output gradually decreases, so the prosumer uses energy from their battery. Prosumer 3 who has no PV buys much electricity from the regional market since this market has a lower price than the main grid during day time as shown in Fig. 4. All prosumers gain benefits through local transaction since the seller can earn money from its surplus and buyer buy at the lower price and save money. At 12 PM, since surplus from prosumers 1 and 2 is not enough to supply the demand of prosumer 3, he/she buys electricity from the main grid to satisfy the demand.



(a) Prosumer 1



(b) Prosumer 3

Fig. 6. Scheduling for Prosumers 1 and 3 in Regional market in three-prosumer.

CONCLUSION

In this work, we developed an optimization framework for prosumers that enables a transaction between them while keeping their indoor temperatures in the comfortable range. To reduce the operation cost, prosumers can control their batteries and HVAC loads and they can transact in the regional market. Without the regional market, each prosumer can only use pre-cooling to reduce the operation cost. However, with the regional market, they can share the surplus within the local network as well as pre-cooling. The case study shows that electricity network with the regional market has an advantage than that without the regional market. Also, it is shown that the benefit from regional market depends on each prosumers load and generation patterns. Studying the performance of this optimization model with uncertainties is one possible future research work.

Acknowledgments

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