Peak Load Shifting in the Internet of Energy with Energy Trading among End-users

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***Abstract*—Recent advances in renewable energy generation and the Internet of things (IoT) has urged energy management to enter the era of the Internet of energy (IoE). The IoE adopts a huge number of distributed energy-generating facilities, distributed energy storage facilities, and IoT technologies to implement energy sharing, promote utilization of electrical grids, and maintain safety of electrical grids. Rapid economic and social development makes energy shortage tend to be increasingly serious. Most cases of energy shortage occur during the peak energy load, and hence the previous works focused on shifting peak load to address energy shortage. However, few of these works took the IoE framework into account. Consequently, this work aims to consider the IoE framework to investigate the peak load shifting problem in which end-users in the energy market can adopt their respective energy storage facilities to charge and discharge energy to minimize the total operating costs. In such a problem setting, each end-user can not only be a demander but also be a supplier in the energy market, so that operating costs are concerned; the energies from both conventional electrical grids and distributed renewable energy sources can be stored in energy storage facilities; real-time price of energy will be applied adequately to affect energy distribution of supply and demand. Simulation results on a case study show that the proposed model can obtain the optimal result, and achieve peak load shifting.**

***Index Terms*—Internet of energy, distributed energy storage system, peak load shifting**

I. INTRODUCTION

WITH advance in development of renewable energy generation and the Internet of things (IoT), the world has entered the era of the Internet of energy (IoE) [1]. In the IoE, all energy sources (including renewable energy sources) are connected together through the Internet, so that energy production, storage, and distribution can be controlled smartly. The IoE aims to increase the utilization rate of energy, remarkably promote the ratio of supplying renewable energy sources, and introduce diversified distributed energy sources to supply the demand of the whole energy market. Owing to development of IoT technologies, the information of energy suppliers and demanders can be obtained immediately and precisely to adjust energy allocation. The framework of the IoE emerges so that the energy market increasingly relies on renewable and distributed power-generating facilities in the electrical grid. End-users can not only consume the energy from conventional electrical grids, but also switch to consume other distributed renewable energies in the same network, to lessen the power-generating pressure of original energy suppliers.

The main reasons of the energy shortage problem during peak load are as follows: firstly, the total used energy exceeds the maximal energy amount that can be supplied by the energy market, or leads to malfunction of some power-generating facilities; secondly, shortage of power-generating fuels in conventional power stations remarkably affects reliability of power supply. Shifting peak load in electrical grids can effectively address energy shortage, and hence has attracted a lot of attention from a variety of fields. In general, peak load shifting is to shift the energy usage demand during the peak load period to the off-peak load period with low energy demand. For instance, the work in [2] in 1990s applied the energy load management to reduce energy consumption and to arrange appropriate power-generating schedules to achieve the goal of peak load shifting. Note that adjusting load is a popular strategy to improve the performance in other fields, e.g., load reduction multimedia data [3].

Residential electric demand-side management (DSM) has received much attention recently. The work in [4] conducted electric DSM in houses with solar power-generating facilities to reduce grid electricity power consumption. The work in [5] introduced smart meters in houses to acquire the electricity consumption data of residential users, and introduced small-scale energy storage facilities for their own use, to decrease energy transmission and to encourage users to manage their own electricity usage. The work in [6] applied a control system of electric DSM in houses that additionally considers the neural network controllers to make scheduling plans coordinated for power generation of home appliances of users in the system. With this system, users' power production and demand can be satisfied, and the utilization rate of local energy can be promoted. The work in [7] analyzed electricity demand of grids using a mathematical model for the home energy management system to save the energy consumption of home appliances as well as various energy storage facilities and to avoid any peak load of grids.

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Some works adopted battery energy storage systems (BESS) to shift the peak load of grids. By including BESSs in various electric control systems, various mathematical programming models have been established to achieve the optimal shifting results of peak loads. The work in [8] devised a BESS in which the remaining energy that is not used in the grid can be stored during the off-peak load to supply the later potential energy shortage and to promote the reliability of energy supply of grids. The work in [9] showed that BESS can improve the peak load, in which energy are stored at a lower market price and are sold out at a higher market price to maximize the benefit. The work in [10] showed the functionality of BESS and proposed a mathematical model with BESSs. Then, they adopted interior points to address this model and obtained the optimal plan of charging and discharging energy. Their proposed method can smooth the energy load cure, and show the effects of shifting energy load.

Smart grid includes a huge number of smart meters, and provides a system to automatically change energy consumption of users according to the real-time price (RTP) of energy as well as the energy demand of users [11], [12]. The work in [13] considered a system that integrates smart grids and electric cars, and makes an energy-charging plan for electric cars in smart grids to minimize the cost of operating the grids. The work in [14] considered a BESS in which energy can be traded with the grid (rather than trading among BESS owners), so that BESS owners can charge energy when the energy price is low, and sell redundant energy when the price is high, to maximize the profit and the utilization rate of electrical grids. Note that the work in [14] did not consider shifting the peak load.

Smart grid increases smart functions in conventional electrical grids through using smart measures and technologies; and the IoE transforms centralized and unidirectional conventional electrical grids into an electrical grid and allows more interaction among end-users. A lot of previous works regarded these two technologies as the same technology. However, in reality, smart grids are still established on conventional electrical grids through using smart devices to promote the safety and reliability of electrical grids and the quality of electricity supply, and introduce new energy sources. Different from smart grids, the IoE introduces the concept of Internet and new energy technologies to achieve the transformation of energy infrastructures, so that it forms a novel network that integrates information and energies. With the IoE, energies can transmit bidirectionally in the network, and the supply and demand of energy can be balanced dynamically, while new energy sources are introduced adaptively to the maximal degree.

As for conventional electrical grids and smart grids, a lot of previous works considered electric DSM, RTP-based adjustment, and BESS to improve the peak load shifting of electrical grids. To improve conventional electrical grids, both the IoE and smart grids introduce various facilities of charging and discharging distributed renewable energies. However, most smart grids only add smart facilities to conventional electrical grids, but do not provide a trading platform, so that redundant renewable energy and the energy stored in BESSs in smart grids can only be consumed by their respective owners. Different from smart grids, the electrical grids in the IoE allows users to share the information and interact with each other. Like e-commerce, the IoE provides a C2C trading platform. Therefore, through the IoE, the trading for the energy from electrical grids and distributed renewable energy are considered to shift the peak load.

This work proposes a peak load shifting problem in the IoE that provides a C2C energy trading platform to end-users to trade the energy stored in their respective distributed energy storage facilities. This work establishes a mathematical programming model for a scheduling plan of charging and discharging the energy from electrical grids as well as distributed renewable energy, to reduce the energy consumption of end-users as well as the energy waste of grids. Then, the model is solved by an optimization solver. This model has the following features: each end-user can not only be a demander but also be a supplier in the energy market, so that operating costs are concerned; the energies from both conventional energy grids and distributed renewable energy generations can be charged in energy storage systems; the RTP of energy is applied adequately to affect distribution of energy supply and demand. Finally, the simulation on a case study is conducted for evaluating performance of the proposed model.

The organization of this work is as follows: Section II introduces the related works and preliminary knowledge of this work. Section III describes the concerned problem for shifting peak load in the IoE with energy trading among end-users. Section IV creates a mathematical programming model for the problem. Section V gives the simulation results. Section IV concludes this work.

II. Preliminaries

This section first introduces peak load shifting. Then, we review the works on the peak load shifting in conventional and smart grids, and the peak load shifting using energy storage systems. Finally, the preliminary knowledge on the IoE is introduced.

A. *Peak load shifting*

Peak load shifting is defined as shifting the energy usage demand during peak load to the off-peak load period with low energy demand. Note that even if a strategy of shifting the peak load is applied, the total energy consumption in this market is kept unchanged, and only the energy utilization time of users is redistributed. In addition, peak load shifting can reduce the influence of energy load changes on power-generating systems, and reduce the energy cost at the same time [15].

A lot of the related works on peak load shifting applied the dynamic energy pricing to indirectly affect the energy utilization of users. The dynamic energy pricing system is to determine the energy price according to the real-time change of the energy price in the energy market. The work in [16] developed a dynamic energy pricing system to affect the decision of DSM, so that electric generators and appliances in the system can make dynamic responses and apply energy-saving strategies. The work in [17] mentioned that in most electricity markets, end-users just purchase electricity from distributed electricity suppliers but are not involved with the market. And, the market pricing strategy is to determine the price according to the total electricity consumption amount of a month or season, or to let users pay different prices for peak and off-peak load time periods, respectively. However, such a strategy does not allow users to respond to the market RTP change. Therefore, they created a day-ahead RTP model for electricity usage scheduling that makes use of characteristics of RTP and applies smart meters to collect the information of electricity usage, to optimize the capacity of electricity production.

B. Peak load shifting in conventional and smart grids

In conventional electrical grids, if the electric power generated by power stations is not consumed nor stored, the power is wasted. This problem is called power loss. The electric load demand from end-users changes with time change, in which the peak load could be multiple times of off-peak load. To satisfy the peak load demand in grids, power stations must generate electric power according to this peak load, so that the utilization efficiency of grids is lower during off-peak loads and there is more power loss.

To solve the peak load problem in conventional electrical grids, most previous approaches indirectly controlled energy consumption of end-users by adjusting the electricity price according to their energy consumption amount. The higher the monthly energy consumption is, the higher the energy payment is; contrarily, the lower the monthly energy consumption is, the lower the energy payment is [2]. However, such approaches may not solve the problem exactly. This approach indeed shifts the energy demand during peak load in grids. However, in overall, the total energy consumption does not change, and the shifted load could generate another peak load during the original off-peak load periods [18].

Smart grid is a modernized electrical grid, and it applies information and communications technologies to collect the information of operating grids to promote the efficiency of generation, transmission, and distribution of energy [19]. Compared with conventional grids, smart grids have the following features on energy distribution:

- Smart grids apply advanced energy measuring technologies and facilities (e.g., smart meters) to monitor energy consumption conditions of users and power generation of power suppliers.
- Smart grids set a control center between power suppliers and end-users, which can monitor energy demand of the concerned region in real time, based on which the decisions of distributing energy are made
- Smart grids can adopt energy distribution technologies and facilities to establish an energy distribution network. Through this network, the control center can immediately distribute energy reasonably according to real-time energy demand of grids as well as end-users, to reduce any energy waste.

However, smart grids only cope with energy allocation according to energy demand of users, but do not address the power loss problem owing to energy demand [11].

To avoid power loss, redundant energy needs to be stored. Most smart grid frameworks adopt energy storage facilities to store redundant energy. With advances in related technologies, energy storage facilities become diversified. Storage facilities in grids include not only large-size electric storage facilities of power companies, but also more and more mass and mobile storage facilities (e.g., electric cars) for personal daily use or temporary urgent use. However, because personal energy storage facilities are not controlled by smart grids, smart grids cannot control their time of charging and discharging energy, so that these personal energy storage facilities could charge energy during peak load to enlarge the energy peak load, and too much energy charging could damage the grid. On the other hand, if storage facilities discharge energy at improper times, too much energy could be discharged and wasted.

C. Peak load shifting using energy storage systems

Most power-generating stations are located closely to their connected markets. To avoid energy waste, energy power is generated only when it is required. To respond to the power shortage during peak load and to ensure the reliability of energy supply, most energy suppliers must increase their power-generating scale to satisfy the peak load. However, during the period of off-peak load, a large number of energy usage devices are not utilized fully, so that the operating cost increases and the utilization efficiency decreases.

Energy storage systems in grids are in charge of shifting the peak load, and bring a lot of advantages, including increasing the utilization rate of power-generating facilities, decreasing the pressure of shifting peak load in grids, and increasing reliability of energy supply [10]. The work in [20] experimentally showed that the BESS has the merits of generality, modularity, and extensibility when solving the peak load shifting problem, and the approach of purchasing energy at a low price can assist users in saving the cost of using electricity. The work in [14] followed the above work to show the practical feasibility of BESS from the perspective of cost analysis.

The above works have applied the strategies of electric DSM, RTP control, and BESS to solve peak load shifting problems, as classified in Table I. Most of recent works have focused on RTP control and BESS to solve this problem. Development of RTP and BESS becomes better with advances in smart grids.

Most previous works applied only one of the above three strategies to address the peak load shifting problem, but few of them integrated two of the three strategies, because such integration complicates the original mathematical model. The works of [11], [13], [16] adopted the strategies of RTP control to plan the schedules of energy usage. Although the strategy of RTP control performs well in simulation, it is hard to attract users to apply the strategy in practice. Although the work in [14] incorporated two of the three strategies, it was based on improving conventional electrical grids, but did not consider other renewable energy sources except for conventional electric energy. Therefore, their proposed framework is impractical in the IoE.

TABLE I
Classification of previous works.

Ref.	Electric DSM	RTP control	BESS
[4]	v		
[5]	v		
[6]	v		v
[7]	v		v
[8]			v
[9]			v
[11]		v	
[13]		v	
[14]		v	v
[16]		v	

D. *IoE*

The IoE is an Internet-based smart grid that integrates technologies of new energies and Internet on the basis of the existing infrastructures of energy supply systems and energy distribution networks. In the IoE, a large number of distributed energy-harvesting devices (including home-scale wind farms, solar energy harvesting, and so on) and energy storage facilities (including personal storage facilities) are inter-connected. Development of the IoE has the following challenges [14]. Firstly, new types of relations in the energy market are complicated, and hence it is challenging to investigate how members in this market collaborate. The IoE establishes an energy market of free competition, and breaks the original energy supply chain (i.e., power is generated, then distributed, and then utilized). In the IoE, end-users in the market are not only customers but also suppliers, and hence need to face such a new role change. Secondly, design of embedded systems needs to consider the market demand. Both embedded smart meters and energy storage facilities of embedded energy systems need to be redesigned to respond to user requirements. Lastly, integrated operations and security risk problems of electrical grids are concerned. Because such a new type of energy market will connect not only centralized power-generating facilities, but also a large number of distributed power-generating facilities as well as distributed energy storage facilities (mostly for renewable energies). Therefore, the schemes of ensuring normal operating of this grid and the safety problem of electricity production information are concerned.

III. Problem Setting

This section first introduces energy storage systems in the IoE, and then describes the concerned problem.

A. *Energy storage systems in the IoE*

As illustrated in Fig. 1, the energy storage systems in the IoE concerned in this work consists of the following components:

- Power generation: Power generation includes centralized and distributed power-generating facilities. Centralized power-generating facilities are large-scale power-generating facilities of large power plants, and distributed power-generating facilities include renewable energy systems (e.g., photovoltaics (PV) and wind farms) of end-users.
- Control center: Control center is like the one in smart grids, which is used for handling end-users' energy demand, and when to inform end-users of proceeding the energy charging and discharging operations of their own energy storage facilities.
- Distribution grid: Distribution grid connects all end-users in the IoE. Through the distribution grid, end-users can use the energy from all power-generating facilities in the IoE and energy storage facilities of other end-users.
- End-user: Each end-user has respective distributed power-generating and power storage facilities, and play the role of electricity producers and customers in the IoE.
- Energy storage: Energy storage includes energy storage facilities of both large energy plants and end-users. Based on the information of energy usage of end-users provided by the control center, energy storage facilities charge and discharge energy at appropriate times.

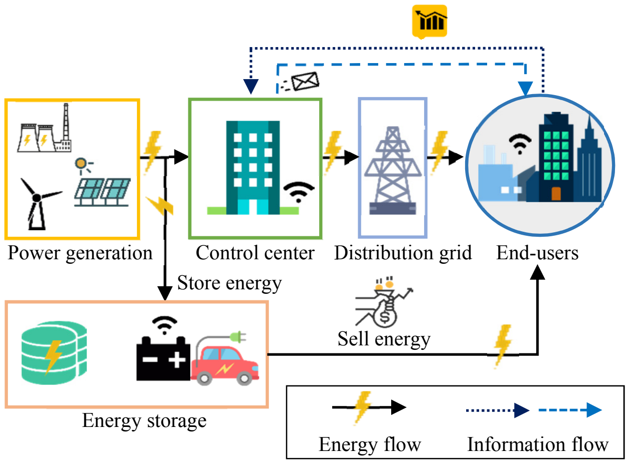

Fig. 1. Illustration of the concerned IoE framework.

The conventional electrical grid provides centralized power generation, and is a network with a unidirectional electricity flow (from power generation to power distribution, and then to end-users). The power generation suppliers adopts centralized power generation according to the estimated energy demand peak value of the whole market. Then, the power distribution includes the control center and distribution grids, in which the control center determines how to distribute energy in the concerned region, and then the distribution grids deliver energy to end-users. End-users are only customers, and consume energy according to their own demands.

Different from conventional electrical grids, the IoE considers energy storage facilities, as explained as follows. The IoE integrates the concept of the Internet into the field of energy, i.e., each end-user in the energy market in the IoE possesses respective power-generating and storage facilities, and can not only play the role of an energy producer but also sell the energy discharged from own storage facilities to other end-users.

B. *Problem description*

This work investigates the problem of peak load shifting in the IoE with an energy market among end-users, which were never considered before. This work plays the role of the whole system (including all power-generating plants and end-users) to minimize the total energy expenditure cost of end-users.

Consider the IoE framework in Fig. 1. In the framework, energy becomes a commodity, and the energy price changes with the market demand. The higher the demand is, the higher the electricity price is. Contrarily, the lower the demand is, the lower the electricity price is. Energy demand of end-users can be realized by smart meters, and this information is transmitted to the control center through the IoE network. The control center will base the energy demand to distribute energy.

If the control center is aware of that the grid is during the off-peak load period, it will transmit the information of charging energy to end-users. End-users can proceed the operation of charging energy according to the information (as shown in Fig. 2(a)), and choose the lower-cost energy in the market to be stored, i.e., the energy to be stored may be purchased from other power-generating suppliers or be generated by the end-user self.

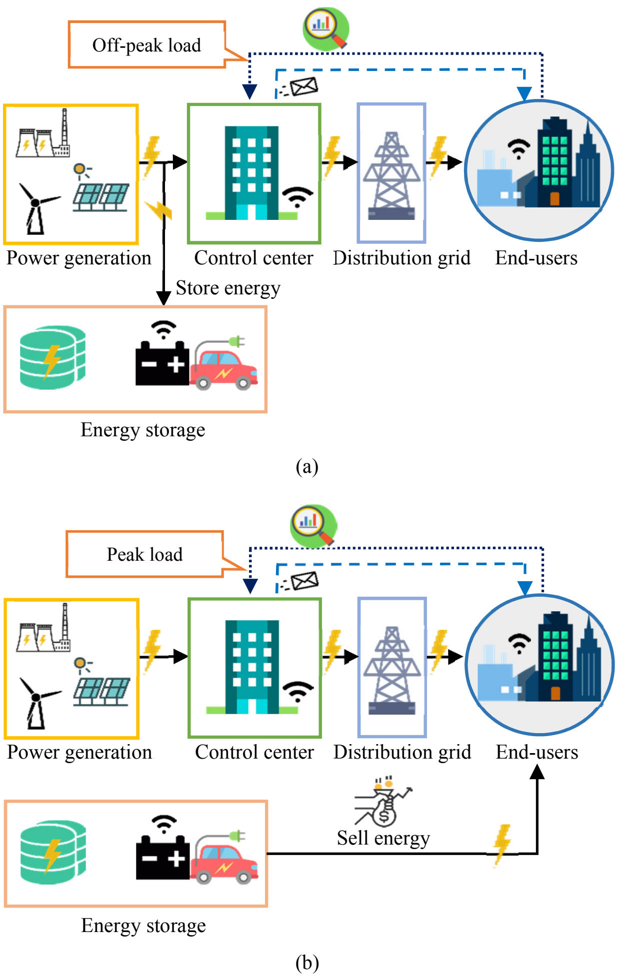

Fig. 2. (a) Charging energy during the off-peak load period; (b) discharging energy during the peak load period.

The system flowchart of discharging energy is illustrated in Fig. 2(b), which is similar to Fig. 2(a). However, different from Fig. 2(a), if the control center is aware of that the grid is during the peak load period, it will transmit the information of discharging energy to inform end-users. End-users can proceed the operation of discharging energy according to the information, and sell the energy in their storage facilities to other end-users.

IV. Mathematical Model

This section establishes a mathematical model for the problem described in the previous section. This model extends the models in [13], [14] with the energy-charging model of renewable energy power-generating facilities. The notations used in this model are given in Table II.

TABLE II
PARAMETER DEFINITION

Parameter	Definition
C_{grid}	Total grid energy usage cost of all end-users.
C_m	Maintenance cost of energy storage facilities of all end-users.
C_{res}	Cost of all end-users' charging their generated renewable energies.
B_{store}	Income of all users' selling the energy in their own energy storage facilities.
i	Index of the concerned day.
t	Index of hour, $t \in \{1, 2, \ldots, 24\}$.
$RTP_i(t)$	Real-time price at the t-th hour on day i.
$RTP_{\min}^{i-1}$	Lowest RTP on the previous day $i-1$.
$RTP_{\max}^{i-1}$	Highest RTP on the previous day $i-1$.
Δ_{i-1}	The maximal difference of RTPs on the previous day $i-1$.
γ	A parameter that determines the ratio of peak load and off-peak load periods.
$E_{store}^{\max}$	Maximal capacity of energy storage facilities.
P_{PCS}^{u}	Unit prices of PCS ($/kWh).
P_{store}^{u}	Unit prices of energy storage ($/kWh).
P_{BOP}^{u}	Unit price of BOP ($/kWh).
P	Energy amount of PCS and BOP (kw).
C_{wind}	Cost of generating wind energy.
C_{PV}	Cost of generating PV energy.
E_{store}	Total energy amount stored in energy storage facilities.
μ	The charging and discharging efficiency of energy storage facilities.
$E_{wind,t}$	The total wind energy amount that energy storage facilities charge at the t-th hour.
E_{PV}	The total PV energy amount that energy storage facilities charge.
E_{grid}	The total grid energy amount that energy storage facilities charge.
M_{Wind}	The maintenance cost of a wind turbine generator per day.
M_{PV}	The maintenance cost of each unit area of solar power-generating equipment per day.
$E_L^i(t)$	The amount of gird energy used by end-users at the t-th hour on day i.
$E_{L,Max}$	The maximal amount of the energy used by end-users hourly.
θ	The percent reserve margin of the grid.
$E_{ES,t}$	The amount of the grid energy used by end-users to charge at the t-th hour on day i.
Decision variable	Definition
$\delta_{grid,t}$	A binary parameter that represents whether end-users use the grid energy at the t-th hour to charge electricity

This work supposes an IoE connected with storage facilities for the energy in existing grids (called grid energy), wind energy, and PV energy. The objective of this model is to minimize the energy usage cost of all end-users in one day, which is calculated as follows:

$$\text{Minimize} \quad C_{grid} + C_m + C_{res} - B_{store} \tag{1}$$

where C_{grid} represents the total grid energy usage cost of all end-users; C_m represents the maintenance cost of energy storage facilities of all end-users; C_{res} represents the cost of all end-users' charging their generated renewable energies; B_{store} represents the income of all users' selling the energy in their own energy storage facilities. Note that the electricity generated from the wind energy and PV energy can be either utilized directly by end-users or stored in end-users' respective energy storage facilities.

On constraints in the problem, the constraints used for computing the four terms in Objective (1) are (2), (5), (6), and (9), respectively. The constraint for computing the total grid usage cost of all end-users C_{grid} is as follows:

$$C_{grid} = \sum_{t=1}^{24} RTP_i(t) \cdot E_L^i(t) + \sum_{t=1}^{24} RTP_i(t) \cdot E_{ES,t}^i \cdot \delta_{grid,t} \tag{2}$$

On the right side of the above equation, the first term is to compute the total cost when end-users use grid energy on day i; and the second term is to compute the total cost when end-users use grid energy to charge on day i. In this equation, $RTP_i(t)$ represents the RTP at the t-th hour on day i; $E_L^i(t)$ is the amount of the gird energy used by end-users at the t-th hour on day i; $E_{ES,t}^i$ is the amount of the grid energy used by end-users to charge at the t-th hour on day i; $\delta_{grid,t}$ is a binary decision variable that decides whether end-users use the grid energy at the t-th hour to charge electricity (i.e., $\delta_{grid,t} = 1$ represents power charging; $\delta_{grid,t} = 0$ represents power discharging) as follows:

$$\delta_{grid,t} = \begin{cases} 1, & \text{if } RTP_i(t) \le RTP_{\min}^{i-1} + \gamma \cdot \Delta_{i-1}; \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

where $RTP_{\max}^{i-1}$ and $RTP_{\min}^{i-1}$ represent the highest and lowest RTPs on the previous day $i-1$, respectively; Δ_{i-1} represents the difference of the two RTPs as calculated as follows:

$$\Delta_{i-1} = RTP_{\max}^{i-1} - RTP_{\min}^{i-1}; \tag{4}$$

and γ is a real parameter within a predefined range [0, 1], used for determining the ratio of peak load and off-peak load periods.

Since the energy in the IoE is a commodity, the RTP changes with time. The higher the energy demand is, the higher the RTP is. As shown in Fig. 3, when $RTP_i(t)$ is greater than $RTP_{\min}^{i-1} + \gamma \cdot \Delta$, the grid is during the peak load period, and hence energy storage facilities should not charge the energy. When $RTP_i(t)$ is smaller than $RTP_{\min}^{i-1} + \gamma \cdot \Delta$, the gird is during the off-peak load period, and hence energy storage facilities can charge the energy.

$E_{ES,t}^i$ used in (2) is computed as follows:

$$E_{ES,t}^i = (E_{L,Max}^i - E_L^i) \cdot (1-\theta) \cdot (1-\delta_{grid,t}) \tag{5}$$

where $E_{L,Max}$ represents the maximal amount of the energy used by end-users hourly; and θ represents the percent reserve margin of the grid. The production cost of grid energy is high, and its amount is set according to the maximal grid energy demand. Therefore, if the unused grid energy is wasted, the energy storage facility in this work first charges energy from the electrical grid. $E_{L,Max}^i - E_L^i$ in the above equation is used to compute the remaining energy amount of the grid. In addition, to respond to additional temporary demand in the grid, it is general to set a percent reserve margin. This work applies $(1-\theta)$ to compute the ratio of the remaining energy that can be used, and applies the decision variable $\delta_{grid,t}$ to decide whether the grid energy is used to charge at the t-th hour.

The constraint for computing the maintenance cost of energy storage facilities of all end-users C_m is as follows:

$$C_m = P_{PCS}^u \cdot P + P_{store}^u \cdot E_{store} + P_{BOP}^u \cdot P \tag{6}$$

The right side of the above equation consists of three terms: power-conversion-system (PCS) cost of energy storage facilities, energy storage cost, and balance-of-plants cost (BOP). In this equation, P is the energy amount of PCS and BOP (unit: kw); E_{store} is the total energy amount stored in energy storage facilities (unit: kWh), which will be calculated in later (10); P_{PCS}^u, P_{store}^u, and P_{BOP}^u are the unit prices of PCS, energy storage, and BOP, respectively.

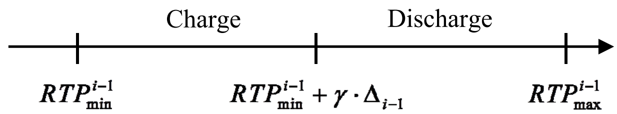

Fig. 3. The thresholds for energy charging and discharging.

The constraint for computing all end-users' charging their generated renewable energies C_{res} is as follows:

$$C_{res} = C_{wind} + C_{PV} \tag{7}$$

where C_{wind} is the cost of generating wind energy; and C_{PV} is the cost of generating PV energy.

Cost C_{wind} in (6) is computed as follows:

$$C_{wind} = M_{wind} \cdot N \tag{8}$$

where M_{wind} is the maintenance cost of a wind turbine generator per day; N is the total number of wind turbine generators.

Cost C_{PV} used in (6) is computed as follows:

$$C_{PV} = M_{PV} \cdot S_{PV} \tag{9}$$

where M_{PV} is the maintenance cost of each unit area of solar power-generating equipment per day; S_{pv} is the total area of solar power-generating equipment. Note that because wind and PV power generations do not need to use additional energy, only their maintenance costs are concerned.

The constraint for computing the income of all users' selling the energy in their own energy storage facilities B_{grid} is as follows:

$$B_{grid} = E_{store} \cdot \mu \cdot RTP^{i}_{\max} \tag{10}$$

where μ is the charging and discharging efficiency of energy storage facilities; E_{store} is the total energy amount stored in energy storage facilities, calculated as follows:

$$E_{store} = E_{grid} + \sum_{t=1}^{24} E_{wind,t} + E_{PV} \tag{11}$$

where E_{grid} is the total grid energy amount that energy storage facilities charge; $E_{wind,t}$ is the total wind energy amount that energy storage facilities charge at the t-th hour; E_{PV} is the total PV energy amount that energy storage facilities charge.

$E_{wind,t}$ in (10) is computed as follows:

$$E_{wind,t} = \sum_{n=1}^{N} f_n(v_t), \quad \text{for } t = 1, 2, \ldots, 24 \tag{12}$$

where v_t is the wind power at the t-th hour; and $f_n(v_t)$ is the amount of the energy generated by the n-th wind turbine generator.

E_{PV} used in (10) is computed as follows:

$$E_{PV} = S_{pv} \cdot \eta_{pv} \cdot p_f \cdot \eta_{pc} \cdot G_t \tag{13}$$

where η_{pv} is the module reference efficiency; p_f is the packing factor; η_{pc} is the power conditioning efficiency; G_t is forecasted hourly irradiance at the t-th hour.

E_{grid} used in (10) is computed as follows:

$$E_{\text{grid}} = \sum_{t=1}^{24} E^{i}_{ES,t} \tag{14}$$

where $E^{i}_{ES,t}$ is the total grid energy amount that end-users use to charge at the t-th hour on day i.

The total energy amount stored in energy storage facilities E_{store} in (10) must be no greater than the maximal capacity of energy storage facilities $E^{\max}_{store}$. That is, the following constraint must be satisfied:

$$E_{store} \le E^{\max}_{store} \tag{15}$$

The differences of the proposed mathematical model from the models in previous works in [13], [14] are as follows:

- This work considers the energy usage cost of all end-users in one day in (1), which were not considered in previous works.
- Since the research goal of [13] was different from ours, the model in [13] did not consider the cost of generating the renewable energy. This work proposes (9) and (10) to compute the costs of generating PV and wind energies.
- The previous work in [14] also considered the energy trading, and the formula of computing the maintenance cost of BESSs in [14] is extended as (6) in this work. However, since the work in [14] did not consider the IoE framework, its mathematical model lacks the equations on generating renewable energies. This work additionally considers (12) and (13) to compute the total amounts of wind and PV energies that energy storage facilities charge, and proposes (11) to include grid energy and renewable energy.
- This work considers the characteristics of the energy market in the IoE framework to propose (3) and (4), and adopts the influence of *RTP* on distribution of electricity supply and demand. The proposed model adopts parameter γ and the energy market data of the former day to determine the peak load and off-peak load values of the energy demand of the current day, to further plan the charging scheduling of energy storage facilities.

V. Implementation and Experimental Results

Based on the proposed mathematical model detailed in the previous section, this section implements this model and conduct a comprehensive experimental analysis. We first show how to generate the experimental data and describe the experimental environment. Then, experimental results are analyzed.

A. Experimental Data and Environment

The experimental data used in this work is generated by extending the data of the Savona Campus case study [13] with the IoE framework with energy trading detailed in the previous sections. The case study in [13] considered two energy sources: smart energy building (SEM) and smart polygeneration microgrid (SPM), equipped with wind energy, PV energy, and national grid energy sources. It considers charging stations of electric cars, facilities of using energy in the campus, and two types of energy storage facilities (i.e., long-term Na-Ni and short-term Li-Ion). Experimental parameter settings are detailed in Table III.

In the IoE framework, both the facilities of using and generating energies transmit in-time information to the control center to make decisions on energy distribution. Energy storage facilities collect the information on energy demand and distributed renewable energy generation in the electrical grid. Therefore, we consider the energy demand of end-users in 24 hours of one day (Fig. 4), daily renewable energy generations (Fig. 5), and the RTPs of 24 hours of one day in the energy trading market (Fig. 6).

TABLE III
EXPERIMENTAL PARAMETER SETTING

Parameter	Value
Charging and discharging efficiency of energy storage facilities μ	85%
Unit price of PCS P^u_{PCS} (€/kWh)	0.256
Unit price of energy storage P^u_{store} (€/kWh)	0.171
Unit price of BOP P^u_{BOP} (€/kWh)	0.533
Highest RTPs on the previous day $RTP^{i-1}_{\max}$ (€/mWh)	141
Highest RTPs on the previous day $RTP^{i-1}_{\min}$ (€/mWh)	67
Maximal energy demand amount $E_{L,Max}$ (kw)	1312
Percent reserve margin of the grid θ	0.3

The objective function and constraints in the concerned problem is a mixed-integer programming model. We adopt the mathematical programming optimization solver Aimms 4.3 to solve the model.

Fig. 4 shows the energy demand of end-users in the 24 hours of one day in the experiment, in which the energy demand during hours 6-17 is obviously higher than that during hours 0-3 and hours 18-24. The peak load of the energy demand (1768kwh) is at hour 11, and the off-peak load of the energy demand (392kwh) is at hour 3. Therefore, the original electrical grid in the concerned area sets the capacity of generating the energy based on the energy demand at hour 11, so that the maximal energy loss of 1376kwh could be generated.

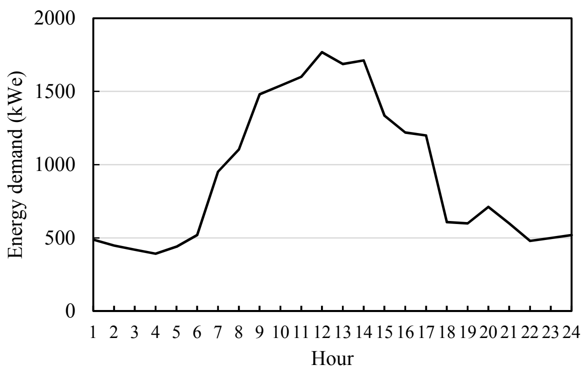

Fig. 4. The energy demand of end-users in 24 hours of one day.

Fig. 5 shows the daily renewable energy generations for two energy sources (i.e., SPM and SEM) in the experiment. Because the two energy sources are from wind and PV energies, the efficiency of generating the renewable energy changes with strength of the wind and light intensity in the environment. The generated renewable energy will serve as the energy source stored in energy storage facilities. However, because the experiments in [13] did not consider the cost of generating the renewable energy, this work supposes that the cost of generating the energy in both SPM and SEB in one day is €1640 according to the information of the facilities of generating the renewable energy in [13].

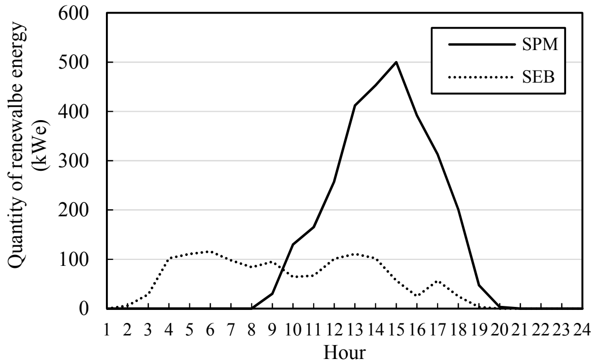

Fig. 5. Daily renewable energy generations for SPM and SEM.

Fig. 6 shows the RTPs of 24 hours of one day in the energy trading market. Because the energy is a commodity that can be traded among end-users in the IoE framework, the RTP changes with the real-time energy demand and supply in the energy market. In the concerned experiment, the RTP achieves the peak value at hour 11, and the off-peak value at hour 3.

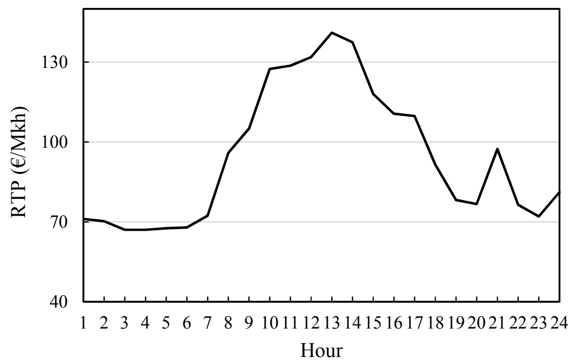

Fig. 6. The RTPs of 24 hours of one day in the energy trading market.

B. Experimental results

The experimental results with different values for the parameter of determining the ratio of peak load and off-peak load periods (γ) are given in Table IV. From Table IV, the optimization solver can obtain the optimal solutions for all values of γ, and with increase of γ value, the optimal result decreases. This is because different values of γ lead to different charging scheduling plans and energy amount stored in energy storage facilities, so as to influence additional energy amount provided in discharging operations during peak load demand.

TABLE IV
The optimal results under different parameter values of γ

γ	0.65	0.7	0.75
Optimal result	€3943.832	€3935.286	€3913.037

Fig. 7 shows the charging plans of energy storage facilities in 24 hours when γ = 0.65, 0.70, and 0.75, respectively), in which the vertical value 0 represents that the energy storage facilities are discharging the energy; and the vertical value 1 represents that the energy storage facilities are charging the energy. From Fig. 7, if parameter γ is larger, the charging period is shorter. Remind that γ is a parameter that determines the ratio of peak load and off-peak load periods. Therefore, if a larger γ value leads to a smaller range for being classified into the peak load period, the charging period becomes longer, and the discharging period becomes shorter. And, end-users have a longer period to charge the energy the energy during off-peak load for later energy demand during peak load.

Fig. 8 shows the effect of peak load shifting of energy storage facilities when $\gamma = 0.65$, in which the 'Original load' curve represents the original energy load demand; and the 'Our load' curves represents the resultant energy load improved by the proposed model with energy trading of end-users.

From Fig. 7(a), when $\gamma = 0.65$, energy storage facilities discharge energy during hours 10-15, and charge energy in the remaining hours. Hence, in Fig. 8, energy storage facilities also discharge energy during hours 10-15 so that the peak load changes from 1768 kWh to 1406 kWh. From the visualization in Fig. 8, the peak value of our load curve is shifted to 1687kWh. In addition, because energy storage facilities charge energy during off-peak period, the lowest value of our load curve is improved from 392 kWh to 819 kWh. The total energy loss is improved from 1376 kWh to 868 kWh.

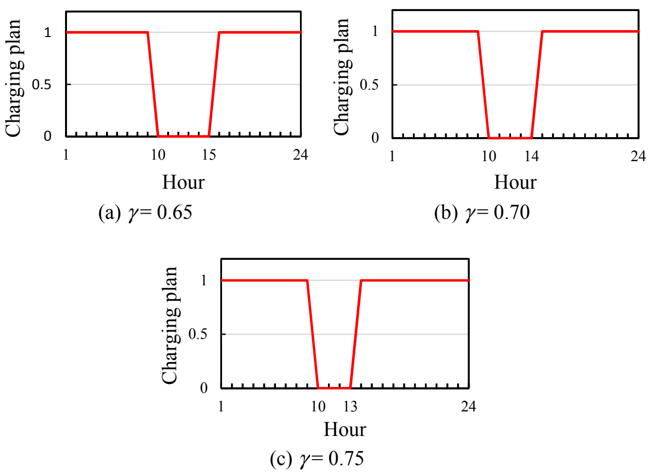

Fig. 7. The charging plans of energy storage facilities in 24 hours when $\gamma = 0.65$, 0.70, and 0.75, respectively.

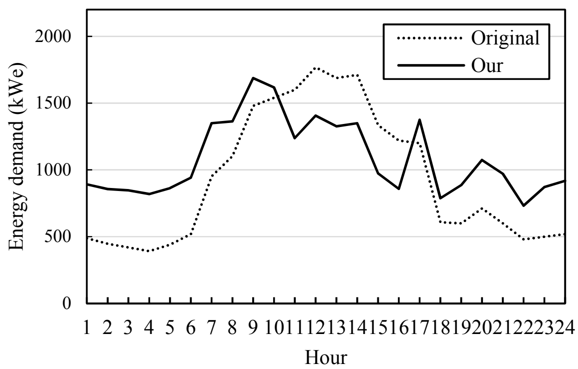

Fig. 8. The effect of peak load shifting of energy storage facilities when $\gamma = 0.65$.

VI. Conclusion

This work has proposed an IoE framework with an energy market among end-users through distributed storage systems to address the problem of shift peak load. This work first proposes a mathematical programming model for this problem, and then uses an optimization solver to conduct simulation analysis on the simulation data from a case provided by previous works. This work is the first to propose peak load shifting in the IoE with energy trading of grid energy and renewable energies. Simulation results show that the proposed model can obtain the optimal result of the concerned problem instance. It is also shown that the energy trading in the IoE can encourage end-users to develop the facilities of generating and storing renewable energies to address peak load shifting.

In the future, more renewable energy sources can be included in the model. In addition, it would be of interest to consider pollution emitted during energy generation, so that the problem may become multiple-objective (minimizing operating costs and pollution).

References

[1] K. Wang, J. Yu, Y. Yu, Y. Qian, D. Zeng, S. Guo, Y. Xiang, and J. Wu, "A survey on energy Internet: architecture, approach and emerging technologies," *IEEE Systems Journal*, in press.

[2] S. Ashok and R. Banerjee, "Load-management applications for the industrial sector," *Applied Energy*, vol. 66, no. 2, pp. 105-111, 2000.

[3] K. Wang, J. Mi, C. Xu, Q. Zhu, L. Shu, and D.-J. Deng, "Real-time load reduction in multimedia big data for mobile Internet," *ACM Transactions on Multimedia Computing, Communications and Applications*, vol. 12, no. 5s, article 76, 2016.

[4] M. Castillo-Cagigal, A. Gutierrez, F. Monasterio-Huelin, E. Caamano-Martin, D. Masa, and J. Jimenez-Leube, "A semi-distributed electric demand-side management system with PV generation for selfconsumption enhancement," *Energy Conversion and Management*, vol. 52, no. 7, pp. 2659-2666, 2011.

[5] M. Castillo-Cagigal, E. Caamano-Martin, E. Matallanas, D. Masa-Bote, A. Gutierrez, F. Monasterio-Huelin, and J. Jimenez-Leube, "PV self-consumption optimization with storage and active DSM for the residential sector," *Solar Energy*, vol. 85, no. 9, pp. 2338-2348, 2011.

[6] E. Matallanas, M. Castillo-Cagigal, A. Gutierrez, F. Monasterio- Huelin, E. Caamano-Martin, D. Masa, and J. Jimenez-Leube, "Neural network controller for active demand-side management with PV energy in the residential sector," *Applied Energy*, vol. 91, no. 1, pp. 90-97, 2012.

[7] R. L. Hu, R. Skorupski, R. Entriken, and Y. Ye, "A mathematical programming formulation for optimal load shifting of electricity demand for the smart grid," *IEEE Transactions on Big Data*, in press.

[8] T. Zhang, S. Cialdea, J. Orr, and A. Emanuel, "Outage avoidance and amelioration using battery energy storage systems," in *Proceedings of 2016 Power and Energy Society General Meeting (PESGM)*, IEEE Press, 2016, pp. 1-6.

[9] A. Rahimi, M. Zarghami, M. Vaziri, and S. Vadhva, "A simple and effective approach for peak load shaving using battery storage systems," in *Proceedings of North American Power Symposium (NAPS)*, IEEE Press, 2013, pp. 1-5.

[10] Y. Ning, X. Li, X. Ma, X. Jia, and D. Hui, "Optimal schedule strategy of battery energy storage systems for peak load shifting based on interior point method," in *Proceedings of 2016 12th World Congress on Intelligent Control and Automation (WCICA)*, IEEE Press, 2016, pp. 2285-2288.

[11] A. Keshtkar, S. Arzanpour, and F. Keshtkar, "Adaptive residential demand-side management using rule-based techniques in smart grid environments," *Energy and Buildings*, vol. 133, pp. 281-294, 2016.

[12] K. Wang, Z. Ouyang, R. Krishnan, L. Shu, and L. He, "A game theory based energy management system using price elasticity for smart grids," *IEEE Transactions on Industrial Informatics*, vol. 11, no. 6, pp. 1607-1616, 2015.

[13] S. Bracco, F. Delfino, F. Pampararo, M, Robba, and M. Rossi, "A dynamic optimization-based architecture for polygeneration microgrids with tri-generation, renewables, storage systems and electrical vehicles," *Energy Conversion and Management*, vol. 96, pp. 511-520, 2015.

[14] M. G. Ippolito, S. Favuzza, and E.R. Sanseverino, Economic feasibility of a customer-side energy storage in the Italian electricity market," in *Proceedings of 2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC)*, 2015, pp. 938-943.

[15] J. Valenzuela, P. R. Thimmapuram, and J. Kim, "Modeling and simulation of consumer response to dynamic pricing with enabled technologies," *Applied Energy*, vol. 96, pp. 122-132, 2012.

[16] A. Pinaa, C. Silvac, and P. Ferrãoa, "The impact of demand side management strategies in the penetration of renewable electricity," *Energy*, vol. 41, no. 1, pp. 128-137, 2012.

[17] E. Telaretti and L. Dusonchet, "Battery storage systems for peak load shaving applications: Part 1: Operating strategy and modification of the power diagram," in *Proceedings of 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, 2016, pp. 1-6.

[18] A. H. Mohsenian-Rad, V. W. Wong, J. Jatskevich, R. Schober, and A. Leon-Garcia, "Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid," *IEEE Transactions on Smart Grid*, vol. 1, no. 3, pp. 320-331, 2010.

[19] X. Cheng, R. Zhang, and L. Yang, "Consumer-centered energy system for electric vehicles and the smart grid," *IEEE Intelligent Systems*, vol. 31, no. 3, pp. 97-101, 2016.

[20] E. Telaretti and L. Dusonchet, "Battery storage systems for peak load shaving applications: Part 2: Economic feasibility and sensitivity analysis," in *Proceedings of 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, 2016, pp. 1-6.