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Optimal Energy Scheduling for Data Center With Energy Nets Including CCHP and Demand Response

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ABSTRACT Internet data centers are growing rapidly in recent years and they operate with intensive energy activity. Combined cooling, heating and power (CCHP) brings new opportunities for reducing the electricity cost in internet data centers. The main objective of this study is to optimize the energy resources scheduling in the data center coupled energy nets considering the involvement of CCHP and different demand response techniques. In this paper, internet data center coupled energy nets are proposed, where power grid, solar photovoltaic, CCHP, and battery energy storage systems are the primary energy sources. The adjunct residential buildings and commercial buildings near the internet data centers are also included in the proposed energy nets, where different types of load and demand response characteristics are utilized. A two-stage optimized energy management model considering the coordinated operation of CCHP and demand response technologies is established for internet data center coupled energy nets. In the day-ahead stage, the control objective is to minimize system cost while satisfying various constraints. Consider the electricity tariff chance between day-ahead market and real-time market, real-time control is implemented to minimize the imbalance cost between two electricity markets. Case studies are conducted on a practical internet data center coupled energy nets in Foshan City, China. It is observed that the proposed control framework can optimally schedule the energy resources in the energy network to meet system demand and improve the energy efficiency. The economic evaluation demonstrates that the proposed control scheme reduces system daily cost by 22.01%.

INDEX TERMS Combined cooling, heating and power, data centers, mixed integer linear programming, renewable energy sources, two-stage optimal scheduling.

NOMENCLATURE

ABBREVIATIONS

BESS	Battery energy storage system
CCHP	Combined cooling, heating and power
IT	Information technology
PV	Photovoltaic
SOC	State of charge

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INDICES

i	Index of energy net ($i = 1, 2, \ldots, \mathrm{I}$)
t	Index of time slot ($t = 1, 2, \ldots, \mathrm{T}$)
δ	Index for front-end servers
$(\hat{\cdot})$	Index of variables in a real-time market

PARAMETERS

A^{PV}	The PV panel area exposed to solar irradiation, m^2

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a_1, a_2	The intercept and slope for the linear function, RMB, RMB/kWh
COP^{AC}	The coefficient of performance of absorption chiller
COP^{EC}	The coefficient of performance of electric chiller
$C_i^{BESS\_P}$	Inverter cost for BESS in the i^{th} energy net, RMB/kW
$C_i^{BESS\_E}$	Battery cost for BESS in the i^{th} energy net, RMB/kWh
$C_i^{BESS\_total}$	The investment cost for BESS in the i^{th} energy net, RMB
D	The tolerant service delay allowed in interactive workload, s
E_R^{BE}	Battery rated capacity, kWh
E_{ini}^{BE}	The initial energy of BESS, kWh
H^G	Natural gas heat rate, kWh/m^3
M^n	The total servers number in data center
m_t^n	The number of active servers providing interactive load
n_{Cycle}	The number of cycle for BESS
$\overline{P}^{BE,Dis}$, $\overline{P}^{BE,Chr}$	The upper limits for battery discharging power and charging power, kW
$P_{\max}^{PV}$	Upper limits for the power generation from PV, kW
$P_{\min}^{EC}/P_{\max}^{EC}$	Lower/Upper limits for input power of electric chiller, kW
$P_{\min}^{Gas}/P_{\max}^{Gas}$	Lower/Upper limits for purchased gas from the natural gas grid, kW
$P_{\min}^{GT\_E}/P_{\max}^{GT\_E}$	Lower/Upper limits for the power generation from the gas turbine, kW
$Q_{\min}^{AC\_heating}/Q_{\max}^{AC\_heating}$	Lower/Upper limits for the heating energy consumed by absorption chiller, kWh
$Q_{\min}^{GB}/Q_{\max}^{GB}$	Lower/Upper limits for the heating energy generated by gas boiler at time t, kWh
$r_{i,t}^{Grid}$	The day-ahead electricity price, RMB/kWh
$r_{i,t}^{Grid,RT}$	The real-time electricity price, RMB/kWh
$\underline{SOC}$	The lower limits of SOC, %
$\overline{SOC}$	The upper limits of SOC, %
T_t^{amb}	Temperature in the ambient at time t, °C
T_t^C	The PV module temperature at time t, °C
$T^{C_{ref}}$	The PV module reference standard temperature, °C
T^{rated}	The PV module rated temperature, °C
β_{PV}	Temperature influence coefficient for energy conversion efficiency
η^{GT_E}	The gas turbine efficiency for generating power
η^{GT_Q}	The gas turbine efficiency for generating heat
η^{HE}	The efficiency of heat exchanger
η^{GB}	The gas boiler efficiency for generating heat
$\eta_i^{BE,Dis}$, $\eta_i^{BE,Chr}$	Battery discharging and charging efficiency in the i^{th} energy net
η^{inv}	The PV inverter conversion efficiency
η_t^{PV}	The PV module energy conversion efficiency at time t
η^{ref}	The PV module reference energy conversion efficiency under a standard temperature
$\underline{\varsigma^{CL}}, \overline{\varsigma^{CL}}$	The controllable load minimum and maximum allowable ratio
ξ	Carbon price, RMB/kg
$\lambda_t^{\delta n}$	The amount of interactive workload allocated from front-end server δ to IDC n at time t, request/s
μ	Natural gas emission coefficient, g/kWh
μ_n	The servers average service rate in data center, request/s
Δt	Time interval

VARIABLES

$C_{i,t}^{Degradation}$	The BESS degradation cost in the i^{th} energy net at time t in the day-ahead market, RMB
$C_{i,t}^{CCHP}$	The CCHP operating cost in the i^{th} energy net at time t in the day-ahead market, RMB
$C_{i,t}^{CL}$	The controllable load cost in the i^{th} energy net at time t in the day-ahead market, RMB
$C_{i,t}^{DR}$	the demand response cost in the i^{th} energy net at time t in the day-ahead market, RMB
$C_{i,t}^{Emission}$	the natural gas emission cost in the i^{th} energy net at time t in the day-ahead market, RMB
$C_{i,t}^{Grid}$	The net power purchase cost in the i^{th} energy net at time t in the day-ahead market, RMB
$C_{i,t}^{DR,IDC}$	the internet data center demand response cost in the i^{th} energy net at time t in the day-ahead market, RMB
$\hat{C}_{i,t}^{Degradation}$	The BESS degradation cost in the i^{th} energy net at time t in the real-time market, RMB
$\hat{C}_{i,t}^{CCHP}$	the CCHP operating cost of the i^{th} energy net at time t in the real-time market, RMB
$\hat{C}_{i,t}^{CL}$	The controllable load cost in the i^{th} energy net at time t in the real-time market, RMB
$\hat{C}_{i,t}^{DR}$	the demand response cost of the i^{th} energy net at time t in the real-time market, RMB
$\hat{C}_{i,t}^{Emission}$	the natural gas emission cost of the i^{th} energy net at time t in the real-time market, RMB
$\hat{C}_{i,t}^{Grid}$	the net power purchase cost of the i^{th} energy net at time t in the real-time market, RMB

$\hat{C}_{i,t}^{DR,IDC}$	the internet data center demand response cost in the i^{th} energy net at time t in the real-time market, RMB
E_t^{BE}	Battery storage energy at time t, kWh
G_t	The solar irradiation forecast at time t, W/m^2
L_t^{δ}	The amount of arrival interactive workload at the front-end server δ at time t, request/s
$P_{i,t}^{BE,Dis}$, $P_{i,t}^{BE,Chr}$	Battery discharging power and charging power in the i^{th} energy net at time t, kW
P_t^{CL}	The controllable load amount at time t, kW
$P_{i,t}^{Cooling}$	The cooling energy demand of the i^{th} energy net at time t, kW
P_t^{EC}	The electric power of electric chiller at time t, kW
$P_t^{GT\_E}$	The power generation from the gas turbine at time t, kW
$P_{i,t}^{Heating}$	The heating energy demand of the i^{th} energy net at time t, kW
$P_{i,t}^{L}$	The residential/commercial load of the i^{th} energy net from the gas turbine at time t, kW
$P_{i,t}^{L,IDC}$	The internet data center load of the i^{th} energy net from the gas turbine at time t, kW
P_t^{PV}	The power generation from PV at time t, kW
$\hat{P}_{i,t}^{GB}$	The input gas of gas boiler of the i^{th} energy net at time t in the real-time market, kW
$\hat{P}_{i,t}^{Grid}$	The electricity demand required of the i^{th} energy net from the grid at time t in the real-time market, kW
$\hat{P}_{i,t}^{GT\_E}$	The power generation of the i^{th} energy net from the gas turbine at time t in the real-time market, kW
$\hat{P}_{i,t}^{BE,Dis}$, $\hat{P}_{i,t}^{BE,Chr}$	Battery discharging power and charging power of the i^{th} energy net at time t in the real-time market, kW
$Q_t^{AC\_Cooling}$	The cooling energy generated by absorption chiller at time t, kWh
$Q_t^{AC\_heating}$	The heating energy consumed by absorption chiller at time t, kWh
$Q_t^{EC\_heating}$	The cooling energy generated by electric chiller at time t, kWh
Q_t^{GB}	The heating energy generated by gas boiler at time t, kWh
Q_t^{GT}	The heating energy generated by gas turbine at time t, kWh
$Q_t^{GT\_HE}$	The output heating energy of heat exchanger at time t, kWh
$Q_t^{heating}$	The heating energy distributed to end users at time t, kWh
SOC_t	Battery state of charge at time t, %
V_t^{Gas}	The gas demand required from the natural gas grid at time t, m^3
$V_t^{Gas\_GB}$	The input gas of gas boiler at time t, m^3
$V_t^{Gas\_GT}$	The input gas of gas turbine at time t, m^3
$\chi_t^{BE,Chr}$	The charging indicator for BESS at time t
$\chi_t^{BE,Dis}$	The discharging indicator for BESS at time t

I. INTRODUCTION

Cloud computing is developing rapidly in the last decade due to a large amount of data in everyday residential and commercial activities. The internet traffic is growing exponentially and has reached a Zettabyte in 2017. The information technology (IT) services, coming with the emergence of cloud computing, have risen and become the critical infrastructure nowadays. In addition to the occurrence of IT services, the energy centers are facing explosive growth in terms of size and number. Some data centers can consume up to 50 MW or more power [1], and the energy consumption is growing rapidly [2] by approximately 10% every year. According to a Nature report [3], current global energy data centers use an estimated 200 TWh each year, which is even more than the total energy consumption of some countries. Besides a large amount of energy consumption in data centers [4], they also contribute around 0.3% of global carbon emissions.

Another important characteristic of data centers is the load's flexibility. According to an empirical study conducted by Lawrence Berkeley National Laboratory, 5% of data centers load can be shed in 5 minutes, and 10% of load can be shed in 15 minutes without changing the IT workload [1]. Accompanied by large energy consumption and loads flexibility, the symbiotic feature of data center makes it a good candidate for participating demand response programs [5]. A large amount of research has been conducted on the flexible load management of data centers, which can be categorized into load shifting [6], quality degradation, and geographical load balancing [7]. Data centers have a mixture of workload, including interruptible workload (i.e. delay tolerant) and non-interruptible workload. Hence, some researchers have proposed to apply load shifting algorithms in data centers to minimize the energy cost. Zhang *et al.* [8] presented a stochastic competitive algorithm to minimize electricity cost for interruptible workload in data center servers. The workload is executed at periods of relatively low electricity prices. Liu *et al.* [9] suggested a holistic approach to schedule IT workload and allocate the data center IT resources based on power supply variation and cooling efficiency variation. Zhang *et al.* in [10] summarized the workload scheduling algorithms towards joint optimization over information and communications technology and cooling systems. Besides load shifting in data centers, load shedding is another form of load flexibility in data centers, reflected by quality degradation [11]. Mashayekhy *et al.* [12] proposed two heuristic algorithms to minimize energy consumption for data centers. In addition to load flexibility within a data center, geographically distributed data centers can be efficient in reducing energy costs and increasing energy efficiency via geographic load balancing. Yao *et al.* [13] presented a stochastic based approach to optimize distributed routing and IT servers management for geographically distributed data centers. Chen *et al.* [14] put forward an approach to optimally balance load and improve computation efficiency for geographical load among data center networks.

CCHP has been around since the beginning of the late 1800s and is widely used in many aspects, including hospitals, biotech facilities, and refineries. The energy, greenhouse gas emissions, and cost savings have been documented via using CCHP at the food processing plant in Portland, Oregon [15]. Via integrating various components into the system, CCHP improves energy usage efficiency and reduces greenhouse gas emission [16], therefore it has been widely utilized in modern power system energy management [17]. Bui *et al.* [18] proposed a hierarchical energy management system for CCHP system to reduce the external trading in building microgrids. By adopting the proposed strategy, the operating cost is reduced by 7.43% compared with the traditional operating cost. In [19], Ren *et al.* showed the performance of hybrid CCHP system integrated with solar and geothermal energies and evaluated the impacts of energy costs on optimization results. Hussain *et al.* [20] suggested an optimal energy management strategy for different demand types of buildings with CCHP and seasonal demand variations taken into account. Considering geothermal and waste heat from industry, Nami *et al.* [21] designed CCHPs supplying energy demand of the residential area to minimize energy cost. Jiang *et al.* [22] carried out the optimal dispatch model to reduce energy cost with CCHP and demand response. In [23], the potential of electrical space heating was studied for demand response. To alleviate the uncertainty of load and reduce the operation cost, Majid *et al.* [24] developed a robust optimization method for optimal operation of the combined heat and power considering demand response. The optimization model was solved based on mixed-integer linear programming to minimize daily operating cost. A detailed review had been given on the modelling, planning, and optimal energy management for CCHP microgrid in [25]. Yang *et al.* [26] proposed an optimal scheduling model for regional multi-energy prosumers combining CCHP, renewable energy and energy storage. Mirzaei *et al.* [27] applied multi-carrier energy storage systems to save operation cost of the integrated energy system, and the uncertainty of wind power was alleviated by the information gap decision theory. Further, considering the uncertainties of wind power, load and gas, a hybrid framework was proposed to minimize the operation cost in [28]. In [29], the risk of CCHP was analyzed considering various uncertainties including renewable energy and energy demand. In recent years, CCHP is bringing new ideas to the construction and operation of data centers. In [30], the authors presented the equivalent scheme for calculating power usage effectiveness via comparing traditional Tier III topology and CCHP system. The results showed that CCHP had overall higher energy efficiency and brings environmental benefits. In [31], the authors demonstrated that CCHP had better advantages in cooling energy performance and reliability compared with the traditional cooling system in data centers.

Through comprehensive literature review, it can be observed that previous similar research has been focusing on the demand response strategy for internet data centers [32], including load shifting, quality degradation, and geographical load balancing [33]. In addition, some researchers are investigating the utilization of CCHP on data centers to reduce greenhouse gas emissions and lower electricity cost [34]. However, to the best of the authors' knowledge, no previous research has been conducted to thoroughly investigate the optimal energy management of data centers considering the existence of demand response strategy, CCHP utilization, and renewable energy integration. It is worth noting that renewable energy is playing an increasingly important role in data centers nowadays. For example, Google had announced that Google data centers aim to achieve 100% renewable energy supply to its data centers in 2017 [35]. Also, internet data centers are usually geographically adjunct to residential buildings and commercial buildings in some practical scenarios. To close the research gap, this paper proposes an optimal energy management framework for data center coupled energy nets, via integrating solar photovoltaic (PV), battery energy storage, demand response technologies and CCHP. PV and battery energy storage have plummeted in cost in recent years due to technology maturity [36], [37]. In the proposed framework, energy nets include internet data centers, residential buildings and commercial buildings. The electricity demand, heating demand and cooling demand among different buildings are met in the interconnected energy nets through electricity network, heating network, and cooling network. Also, different buildings demand response characteristics are considered in energy modelling. The proposed operational strategy determines the optimal scheduling results for various resources in the framework, including electricity trading amount, CCHP power generation amount, demand response loads, and battery charging/discharging status. The distinguishing features of this work are summarized as the following threefold:

- Energy nets are formed by integrating solar PV, energy storage, CCHP and the external electricity grid. In the energy nets, heating flow, cooling flow, and electricity flow are provided to data centers, commercial buildings and residential buildings.
- An optimal energy management strategy for proposed energy nets is established considering CCHP and different building demand response characteristics. With the proposed model, the optimal electricity and gas supply

can be determined while meeting system demands and satisfying various constraints.

- A two-stage coordinated control scheme is proposed by taking electricity tariff change in the day-ahead market and real-time market into account. In the day-ahead control stage, the control objective is to minimize the system overall operating cost. In real-time control stage, the control objective is to minimize the imbalance cost between day-ahead market and real-time market.

The remaining parts of the paper are as follows. The formulation of energy nets, together with the flow directions of heat, cooling and electricity are introduced in Section 2. The system components modelling including CCHP, solar PV generation, battery energy storage and demand response models are described in Section 3. Section 4 presents the proposed control approach, including day-ahead model and real-time model. In Section 5, case studies are carried out, and simulation results and discussion are analyzed to demonstrate the performance of the proposed method. Conclusions and future work are given in Section 6.

II. PROBLEM DESCRIPTION

In this section, components and configuration of the proposed framework are given, which describe the connection of various devices and heating/cooling/electricity flows.

In practical scenarios, data centers are usually adjunct to commercial buildings, even residential buildings. In this paper, internet data centers are not solely controlled, instead the energy net achieving system-wide optimal control results is proposed. The basic components of the proposed energy net include CCHP, renewable energy resources (i.e. solar PV), battery energy storage systems, and cooling/heating/electricity demand. Solar PV can provide sustainable and clean energy [38] to the energy-hungry appliances. Battery energy storage systems act as an energy buffer [39], which chooses to work in charging periods when the electricity price is low and work in discharging periods when electricity price is high. CCHP is a decentralized power generation resource, which has better energy efficiency and can reduce greenhouse gas emissions [40]. In Fig. 1, the internal cooling flow, heating flow, electricity flow, and natural gas flow of the proposed energy nets are given. Electricity flow starts from electricity grid and natural gas network, and runs into electrical supply and electricity grid. Heating flow and cooling flow start from gas turbine and gas boiler in CCHP, and run into heating supply and cooling supply.

In Fig. 2, the simplified structure of energy nets is presented. In the proposed control framework, the end-users in energy nets can be internet data centers, commercial buildings, and residential buildings. Different types of buildings have various load characteristics. For instance, the load demand in data centers is relatively stable throughout the day, commercial buildings load usually peaks in the daytime, and residential buildings load usually peaks at off-work time around 18:00 – 21:00. The electricity in the framework is

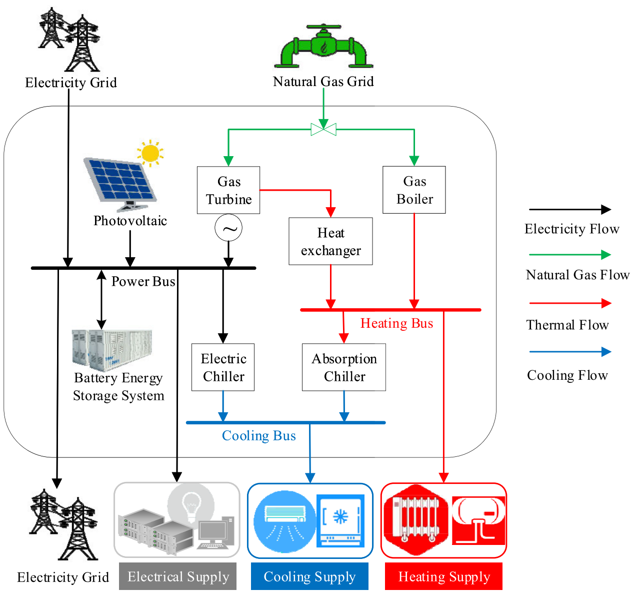


FIGURE 1. Internal flow of the energy net.

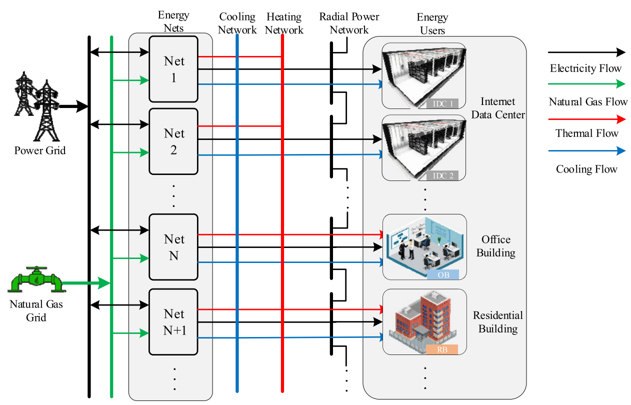


FIGURE 2. Simplified structure of energy nets.

provided by the external electricity grid, CCHP power generation, and solar PV generation; the cooling supply is provided by electric chiller or absorption chiller; the heating supply is generated as by-products of CCHP generation. Via coordinated control of the proposed energy nets, the optimal operation results can be achieved within the whole framework.

III. SYSTEM COMPONENTS MODELLING

In this section, the modelling of various components in the proposed framework is introduced, which includes modelling of CCHP, solar PV generation, battery energy storage, data center demand response model, and commercial/residential demand response model.

A. CCHP

The tri-generation characteristic of CCHP generation system provides the possibility for many institutes such as hospital, data centers to meet electricity, cooling, and heating from a single energy source. Natural gas can be more attractive compared with coal and oil etc. [36] due to factors such as availability, low cost and less environmental impact. According to [26], the model associated with CCHP system can be formulated.

As shown in Fig.1, the gas from natural gas grid is allocated to gas turbine and gas boiler below:

$$V_t^{Gas} = V_t^{Gas\_GT} + V_t^{Gas\_GB} \tag{1}$$

The electricity power and heat are generated through burning natural gas in the gas turbine, which are given in Eqs. (2) – (3). Furthermore, the heat is provided to the heating bus by the heat exchanger as shown in Eq. (4).

$$P_t^{GT\_E} = V_t^{Gas\_GT} \cdot H^G \cdot \eta^{GT\_E}/\Delta t \tag{2}$$

$$Q_t^{GT} = \frac{P_t^{GT\_E}}{\eta^{GT\_E} \cdot \eta^{GT\_Q}} \tag{3}$$

$$Q_t^{GT\_HE} = \eta^{HE} \cdot \frac{P_t^{GT\_E}}{\eta^{GT\_E} \cdot \eta^{GT\_Q}} \tag{4}$$

When the heating generated by gas turbine is insufficient, the gas boiler can provide heating capacity to satisfy the heating supply. The modelling is described as:

$$Q_t^{GB} = V_t^{Gas\_GB} \cdot H^G \cdot \eta^{GB}/\Delta t \tag{5}$$

The cooling energy is generated by two parts in the CCHP system. One part is provided by absorption chiller via the utilization of heating from gas turbine or gas boiler as shown in Eq. (6). The other part is given through the electric chiller in Eq. (7), which is an auxiliary cooling source.

$$Q_t^{AC\_cooling} = COP^{AC} \cdot Q_t^{AC\_heating} \tag{6}$$

$$Q_t^{EC\_cooling} = COP^{EC} \cdot P_t^{EC} \tag{7}$$

The heating energy is distributed to end users, which is computed as follows:

$$Q_t^{heating} = Q_t^{GB} + Q_t^{GT\_HE} - Q_t^{AC\_heating} \tag{8}$$

B. SOLAR PV GENERATION

PV generation is mainly influenced by solar irradiance and ambient temperature [42]. According to [43], the modelling of PV generation is given as:

$$P_t^{PV} = A^{PV} \cdot G_t \cdot \eta^{PV} \cdot \eta^{inv} \tag{9}$$

$$\eta_t^{PV} = \eta^{ref} \cdot [1 - \beta_{PV} \cdot (T_t^C - T^{C_{ref}})] \tag{10}$$

$$T_t^C - T_t^{amb} = \frac{T^{rated}}{800} \cdot G_t \tag{11}$$

C. BATTERY ENERGY STORAGE

Battery energy storage system (BESS) acts as the energy buffer in the proposed energy system. When the electricity price is low, battery works in charging mode; when the electricity price is high, battery works in discharging mode to reduce electricity cost. The modelling of battery energy storage is described as below [44]:

$$E_{t+1}^{BE} = E_t^{BE} + P_t^{BE,Dis} \cdot \Delta t/\eta^{BE,Dis} + P_t^{BE,Chr} \cdot \Delta t \cdot \eta^{BE,Chr} \tag{12}$$

$$\begin{cases} SOC_t = E_t^{BE}/E_R^{BE} \\ \underline{SOC} \le SOC_t \le \overline{SOC} \end{cases} \tag{13}$$

$$\begin{cases} \chi_t^{BE,Dis} \cdot \overline{P}^{BE,Dis} \le P_t^{BE,Dis} \le 0 \\ 0 \le P_t^{BE,Chr} \le \chi_t^{BE,Chr} \cdot \overline{P}^{BE,Chr} \\ \chi_t^{BE,Dis} + \chi_t^{BE,Chr} = 1 \\ \chi_t^{BE,Dis}, \chi_t^{BE,Chr} \in \{0, 1\} \end{cases} \tag{14}$$

$$E_t^{BE} = E_{ini}^{BE}, \quad if\ t = 1 \tag{15}$$

D. DATA CENTER DEMAND RESPONSE MODEL

In this manuscript, data centers are geographically distributed, where they can transfer load demand with each other via geographical load balancing technology through the proposed network [45]. The electric demand response refers to data centers can optimally shift cloud service tasks among geographically distributed internet data centers. Therefore, data center can have energy consumption reduction through its demand response provision capability. It is assumed that data center $n \in N$ consists of M^n servers, and the overall amount of inter-active workload in time slot t at the front end server $\delta \in \Phi$ is denoted as L_t^δ. According to [46], the allocated quantity of interactive workload from front end server δ to data center at time t is denoted as:

$$\sum_{n \in N} \lambda_t^{\delta,n} = L_t^\delta \tag{16}$$

M/M/1 queuing model [47] is employed to denote interactive workload response time in each data center, as shown below:

$$0 < \frac{1}{\mu_n - \sum_{\delta \in \Phi} \frac{\lambda_t^{\delta,n}}{m_t^n}} < D \tag{17}$$

$$0 \le m_t^n \le M^n \tag{18}$$

E. COMMERCIAL/RESIDENTIAL BUILDING DEMAND RESPONSE MODEL

In commercial and residential buildings, demand response programs are being employed to encourage end-users to participate in peak load shaving in an electrical system [48]. This paper mainly investigates incentive-based demand response strategy [49], such as direct load control, interruptible services, and emergency demand response programs. End users will be paid incentives, such as cash reward, when they are willing to adjust their energy consumption when requested. According to [50], the controllable load generates the controllable load cost, which can be formulated as a linear function:

$$C_t^{CL} = a_1 + a_2 \cdot P_t^{CL} \tag{19}$$

The controllable load amount is constrained by the electricity load to a certain ratio, as:

$$\underline{\varsigma^{CL}} \le \frac{P_t^{CL}}{P_t^L} \le \overline{\varsigma^{CL}} \tag{20}$$

IV. MATHEMATICAL MODEL FOR THE PROPOSED STRATEGY

In this section, a two-stage coordinated control scheme is proposed for the energy nets framework considering the electricity price change between the day-ahead market and real-time market. The overall objective for the proposed system is to minimize the system cost, while providing system required heating, cooling, and electricity demand, as well as reducing greenhouse gas emissions. The paper utilizes the concept of cooperative multi-community due to the explicit merits such as the entire network minimum operating cost and network-level resource optimization. Hence, cooperative multi-energy nets are regulated to realize the proposed approach.

At the first stage, a cooperative network for different types of demand response energy nets is coordinated and controlled. The objective in this stage is to minimize the operating cost while satisfying system constraints. A mixed-integer linear programming model has been developed for scheduling the resources in the network. The uniform scheduling period is set as 1 hour. At the second stage, the electricity price change is considered in real-time market compared with the day-ahead market. The objective in this stage is to minimize the imbalance cost between the two markets, and the scheduling period is achieved at 15-minute temporal resolution. The detailed mathematical models are explained in the following subsections.

A. STAGE 1: DAY-AHEAD COST MINIMIZATION MODEL

1) OBJECTIVE OF THE MODEL

In this stage, a mixed-integer linear programming model is developed to minimize the overall energy cost of the proposed energy nets over the scheduling periods. Via coordinated control of various components in the energy nets, the system-level optimal results can be achieved. In this stage, the time slot is set to be 1 hour. The cost minimization model is formulated as below:

$$\min \sum_{t=1}^{T} \sum_{i=1}^{I} (C_{i,t}^{CCHP} + C_{i,t}^{Grid} + C_{i,t}^{DR} + C_{i,t}^{Degradation} + C_{i,t}^{Emission}) \tag{21}$$

where i refers to the i^{th} energy net; t refers to time slot t. Noted that the BESS degradation cost is considered in this paper due to frequent charge and discharge. As the detailed BESS degradation modeling is not the focus in this work, the simplified model is used to calculate degradation cost [51]–[53].

The various cost formulation is further explained below:

$$\begin{aligned} C_{i,t}^{CCHP} &= r_{i,t}^{GT} \cdot (P_{i,t}^{GT} + P_{i,t}^{GB}) \\ &= r_{i,t}^{GT} \cdot (P_{i,t}^{GT\_E}/\eta^{GT\_E} + Q_{i,t}^{GB}/\eta^{GB}) \end{aligned} \tag{22}$$

$$C_{i,t}^{Grid} = r_{i,t}^{Grid} \cdot P_{i,t}^{Grid} \tag{23}$$

$$\begin{aligned} C_{i,t}^{DR} &= C_{i,t}^{DR,IDC} + C_{i,t}^{CL} \\ &= r_{i,t}^{Grid} \cdot \lambda_{i,t}^{\delta} + (a_1 + a_2 \cdot P_t^{CL}) \end{aligned} \tag{24}$$

$$\begin{cases} C_{i,t}^{Degradation} = \dfrac{C_i^{BESS\_total}}{n_{Cycle} \cdot E_R^{BE}} \cdot (P_{i,t}^{BE,Chr} \cdot \eta_i^{BE,Chr} + \left|\dfrac{P_{i,t}^{BE,Dis}}{\eta_i^{BE,Dis}}\right|) \cdot \Delta t \\ C_i^{BESS\_total} = C_i^{BESS\_P} \cdot P_R^{BE} + C_i^{BESS\_E} \cdot E_R^{BE} \end{cases} \tag{25}$$

$$C_{i,t}^{Emission} = 0.01 \cdot \xi \cdot \mu \cdot (P_{i,t}^{GT\_E}/\eta^{GT\_E} + Q_{i,t}^{GB}/\eta^{GB}) \cdot \Delta t \tag{26}$$

The objective is subject to various constraints described below.

2) CONSTRAINTS

a: CONSTRAINTS OF ENERGY BALANCE

The energy balance inside the proposed energy net includes power balance, cooling balance, and heating balance.

$$\begin{aligned} &P_{i,t}^{Grid} + \left|P_{i,t}^{BE,Dis}\right| + P_{i,t}^{PV} + P_{i,t}^{GT\_E} \\ &\quad = P_{i,t}^{BE,Chr} + P_{i,t}^{EC} + P_{i,t}^{L} - P_{i,t}^{CL} + P_{i,t}^{L,IDC} - L_{i,t}^{\delta} \end{aligned} \tag{27}$$

$$Q_{i,t}^{AC\_Cooling} + Q_{i,t}^{EC\_Cooling} = P_{i,t}^{Cooling} \tag{28}$$

$$Q_{i,t}^{GB} + Q_{i,t}^{GT\_HE} - Q_{i,t}^{AC\_heating} = P_{i,t}^{Heating} \tag{29}$$

The input and output power balance in each energy net i at time slot t is denoted in Eq. (27). The input power consists of power purchased from external grid, BESS discharging power, PV panel power generation, and power generation from CCHP gas turbine. The power consumption consists of BESS charging power, the electric chiller power load, residential/commercial load minus controllable load amount, and internet data center load minus interactive workload. The cooling balance is denoted in Eq. (28). The left-hand side refers to input power, which is composed of cooling energy generated from absorption chiller in CCHP and electric chiller. The right-hand side denotes the cooling energy demand in the system. Eq. (29) shows the heating balance in the system, where the left-hand side is composed of heating energy generated from gas boiler and heat exchanger minus heat consumed by absorption chiller, and the right-hand side denotes heating energy demand.

b: CONSTRAINTS OF INTERNET DATA CENTER

The data center demand response model is given in Section 3.4, where the relevant constraints are given in Eqs. (16)- (18).

c: CONSTRAINTS OF CCHP

The operational constraints of CCHP are given in Eqs. (1) - (8). In addition to this, various operational constraints still should be satisfied as follows:

$$P_{\min}^{Gas} \leq P_{i,t}^{Gas} \leq P_{\max}^{Gas} \tag{30}$$

$$P_{\min}^{GT\_E} \leq P_{i,t}^{GT\_E} \leq P_{\max}^{GT\_E} \tag{31}$$

$$Q_{\min}^{GB} \leq Q_{i,t}^{GB} \leq Q_{\max}^{GB} \tag{32}$$

$$Q_{\min}^{AC\_heating} \leq Q_{i,t}^{AC\_heating} \leq Q_{\max}^{AC\_heating} \tag{33}$$

$$P_{\min}^{EC} \leq P_{i,t}^{EC} \leq P_{\max}^{EC} \tag{34}$$

d: CONSTRAINTS OF PV PANELS

PV generation model is given in Eqs. (9) – (11). The lower and upper limits of PV generation are shown in Eq. (35):

$$0 \leq P_t^{PV} \leq P_{\max}^{PV} \tag{35}$$

e: CONSTRAINTS OF BATTERY ENERGY STORAGE

The operation of BESS should satisfy the constraints given in Eqs. (12) – (15).

B. STAGE 2: REAL-TIME COST MINIMIZATION MODEL

Considering the electricity price change between day-ahead market and real-time market, a second stage real-time cost minimization model is proposed. The time slot in real-time dispatch interval is set to be 15 minutes, which means the overall 96 time slots exist in 24-hour scheduling period. In this stage, the objective is to minimize the imbalance cost between day-ahead and real-time electricity markets, defined as:

$$\min \sum_{t=1}^{NT} \sum_{i=1}^{I} \begin{pmatrix} C_{i,t}^{CCHP} + C_{i,t}^{Grid} + C_{i,t}^{DR} + C_{i,t}^{Degradation} \\ +C_{i,t}^{Emission} - \hat{C}_{i,t}^{CCHP} - \hat{C}_{i,t}^{Grid} - \hat{C}_{i,t}^{DR} \\ -\hat{C}_{i,t}^{Degradation} - \hat{C}_{i,t}^{Emission} \end{pmatrix} \tag{36}$$

where $\hat{C}$ refers to the relevant cost function in real-time stage; NT is total number of time slots in real-time stage. The relevant cost function in real-time market is formulated as:

$$\begin{aligned} \hat{C}_{i,t}^{CCHP} &= r_{i,t}^{GT} \cdot (\hat{P}_{i,t}^{GT} + \hat{P}_{i,t}^{GB}) \\ &= r_{i,t}^{GT} \cdot (\hat{P}_{i,t}^{GT\_E}/\eta^{GT\_E} + \hat{Q}_{i,t}^{GB}/\eta^{GB}) \end{aligned} \tag{37}$$

$$\hat{C}_{i,t}^{Grid} = r_{i,t}^{Grid,RT} \cdot \hat{P}_{i,t}^{Grid} \tag{38}$$

$$\begin{aligned} \hat{C}_{i,t}^{DR} &= \hat{C}_{i,t}^{DR,IDC} + \hat{C}_{i,t}^{CL} \\ &= r_{i,t}^{Grid,RT} \cdot \hat{\lambda}_{i,t}^{\delta} + (a_1 + a_2 \cdot \hat{P}_t^{CL}) \end{aligned} \tag{39}$$

$$\begin{cases} \hat{C}_{i,t}^{Degradation} = \dfrac{C_i^{BESS\_total}}{n_{Cycle} \cdot E_R^{BE}} \cdot \Big(\hat{P}_{i,t}^{BE,Chr} \cdot \eta_i^{BE,Chr} \\ \qquad + \left|\dfrac{\hat{P}_{i,t}^{BE,Dis}}{\eta_i^{BE,Dis}}\right|\Big) \cdot \Delta t \\ C_i^{BESS\_total} = C_i^{BESS\_P} \cdot P_R^{BE} + C_i^{BESS\_E} \cdot E_R^{BE} \end{cases} \tag{40}$$

$$\hat{C}_{i,t}^{Emission} = 0.01 \cdot \xi \cdot \mu \cdot (\hat{P}_{i,t}^{GT\_E}/\eta^{GT\_E} + \hat{Q}_{i,t}^{GB}/\eta^{GB}) \cdot \Delta t \tag{41}$$

where $(\hat{\cdot})$ denotes the variable in real-time market; $r_{i,t}^{Grid,RT}$ is the real-time electricity price.

In this stage, the control objective should meet the same operational constraints defined in previous subsection STAGE 1. With the proposed second stage real-time control, the electricity variation in the real-time market is fully considered, and more accurate control performance is achieved.

V. CASE STUDIES AND DISCUSSION

The proposed approach is tested in the data center energy network of Foshan City, Guangdong Province, China. The tested energy network is composed of internet date centers, adjunct commercial/residential buildings, and mixed sources of energy sources. The simplified system structure is demonstrated in Fig. 3. As observed in Fig. 3, three energy nets are located at Bus 5, Bus 8 and Bus 9, where different types of buildings are available. Each energy net provides electricity, cooling, and heating energy to the nodes in the system. The energy nets are also interconnected through the network, which can mutually support each other. In this study, the internet data center is located at Bus 5, the commercial building is located at Bus 8, and the residential building is located at Bus 9.

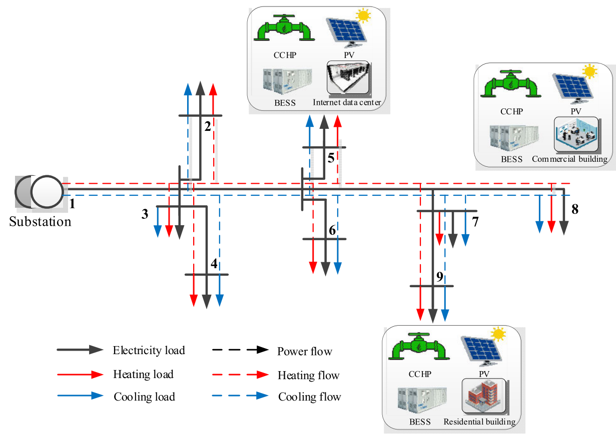


FIGURE 3. Simplified structure of the energy network.

A. EXPERIMENT SETTING

The parameters related to CCHP in three nodes are specified in Table 1. BESS parameters are given in Table 2, which include BESS rated power, maximum charging/discharging power, state of charge lower/upper limits, and charging/discharging efficiency. The day-ahead electricity tariff and gas price are denoted in Fig. 4, which are based on the data in Foshan City, Guangdong Province, China. As seen from Fig. 4, the bottom electricity price is 0.43 RMB/kWh, the flat electricity price is 0.83 RMB/kWh, and the peak electricity price is 1.35 RMB/kWh. The natural gas price is 2.7 RMB/m^3 throughout the day. The electricity selling price is 0.37 RMB/kWh. It should be noted here that 1 RMB is equivalent to 0.14 USD (i.e. 1 USD = 6.76 RMB). The carbon emission price ξ is 0.02 RMB/kg, and natural gas emission efficient μ is 220 g/kWh. The intercept and slope a_1, a_2 in commercial/residential demand response model, are set as 0.05 RMB and 0.63RMB/kWh.

The solar radiation data and ambient temperature data are obtained from the meteorological bureau of Guangdong Province, China. The PV peak power in the system is set as 1500 kW, with tilt angles as 35°. Based on Eqs. (9)-(11), the overall solar PV generation amount in the system on a typical summer day is denoted in Fig. 5. The electricity load, cooling load, and heating load characteristics for the internet data center, commercial buildings, and residential buildings

TABLE 1. Simplified structure of the energy network.

Parameters	CCHP		
	Bus 5 (Internet data centers)	Bus 8 (Commercial buildings)	Bus 9 (Residential buildings)
$P_{min}^{GT\_E}$, $P_{max}^{GT\_E}$	255, 1500 kW	150, 1000 kW	150, 1000 kW
Q_{min}^{GB}, Q_{max}^{GB}	113, 750 kW	90, 600 kW	90, 600 kW
$Q_{min}^{AC\_heating}$, $Q_{max}^{AC\_heating}$	0, 1500 kWh	0, 1000 kWh	0, 1000 kWh
P_{min}^{EC}, P_{max}^{EC}	0, 700 kW	0, 600 kW	0, 600 kW
P_{max}^{Gas}	0, 5500 kW	0, 5000 kW	0, 5000 kW
H^{G}	10.8kWh/m^3	10.8kWh/m^3	10.8kWh/m^3
η^{GT_E}	0.35	0.30	0.30
η^{GT_Q}, η^{HE}	0.30, 0.90	0.35, 0.90	0.35, 0.90
η^{GB}	0.75	0.75	0.75
COP^{AC}, COP^{EC}	1.20, 4.00	1.20, 4.00	1.20, 4.00

TABLE 2. Parameters of BESS in the three nodes.

Parameters	BESS		
	Bus 5 (Internet data centers)	Bus 8 (Commercial buildings)	Bus 9 (Residential buildings)
$C_i^{BESS\_P}$	1568.6 RMB/kW	1568.6 RMB/kW	1568.6 RMB/kW
$C_i^{BESS\_E}$	1426.5 RMB/kWh	1426.5 RMB/kWh	1426.5 RMB/kWh
n_{Cycle}	5000	5000	5000
E_R^{BE}	500 kWh	400 kWh	300 kWh
$\overline{P}^{BE,Dis}$, $\overline{P}^{BE,Chr}$	±400 kW	±320 kW	±240 kW
$\underline{SOC}$, $\overline{SOC}$	20%, 80%	20%, 80%	20%, 80%
$\eta^{BE,Dis}$, $\eta^{BE,Chr}$	0.95, 0.97	0.98, 0.96	0.95, 0.95

in a typical summer day are given in Fig. 6. The system maximum allowed electricity load is 10,000 kW, maximum cooling load is 6500 kW, and the maximum heating load is 7000 kW. The numerical simulations have been coded using MATLAB software in an Intel Core i5-4210, 8.00 GB RAM personal computer.

B. SIMULATION RESULTS

To demonstrate the effectiveness of the proposed control scheme, the day-ahead control scheduling results and real-time scheduling results are analyzed.

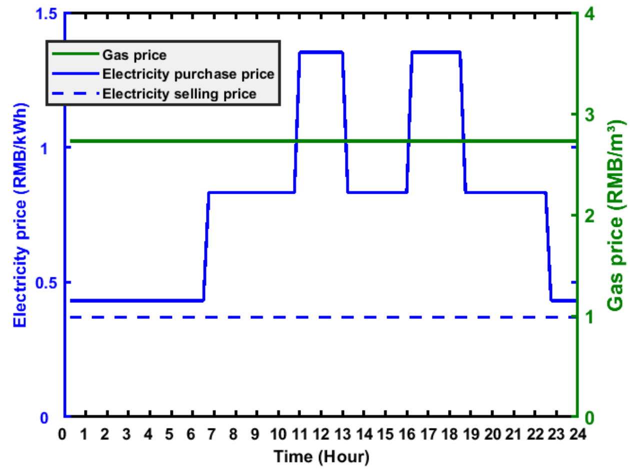


FIGURE 4. Day-ahead electricity price and natural gas price.

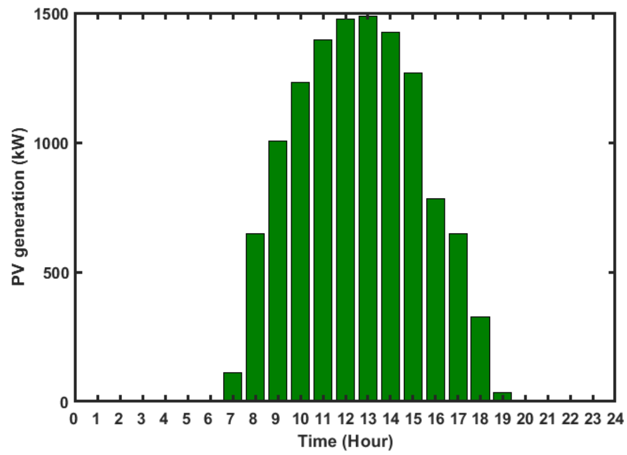
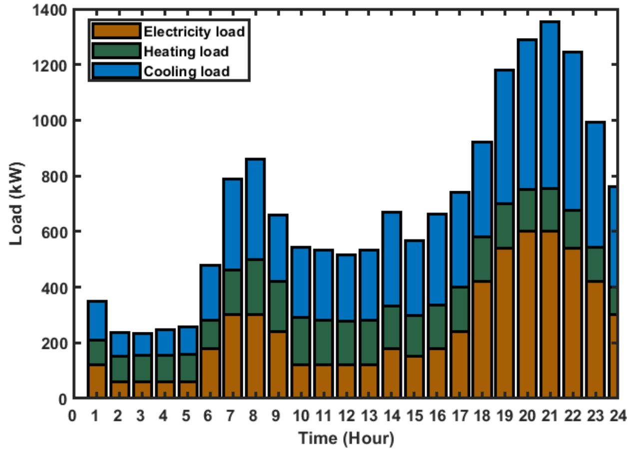


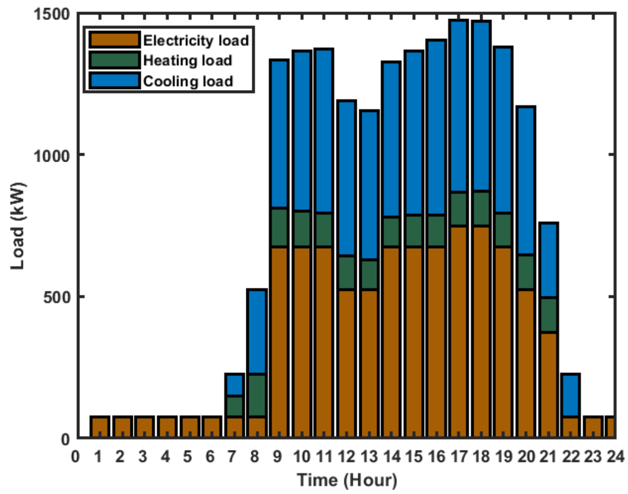
FIGURE 5. System PV generation amount in a typical summer day.

The CCHP power generation, power exchange amount with external grid, and demand response load for residential building, commercial building and internet data center are separately given in Fig. 7(a), Fig. 8(a), and Fig. 9(a) respectively. The BESS charging/discharging power behavior, state of charge behavior in BESS for residential building, commercial building, and internet data center are denoted in Fig. 7(b), Fig. 8(b), and Fig. 9(b) respectively. It should be noted in Figs. 7(a)-9(a), the positive values denote the power purchase amount from external grid, and the negative values denote the amount of power fed back to the grid. In Figs. 7(b)-9(b), the positive BESS power represents BESS is in charging mode, and the negative BESS power represents BESS is in discharging mode.

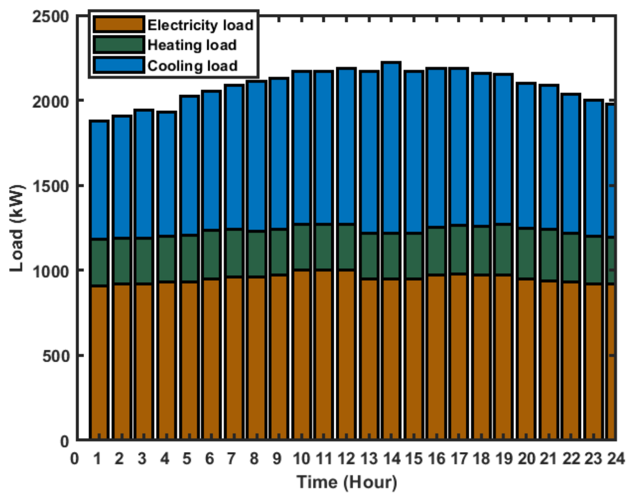
As seen in Figs. 7(a)-9(a), CCHP mainly serves in high load periods and peak electricity price periods to reduce the electricity purchase cost from the external grid. During off-peak load periods and low electricity price periods, the outputs of CCHP are reduced, or even shut down, where the power is mainly served by the external grid. For



(a) Residential building electricity load, cooling load, and heating load



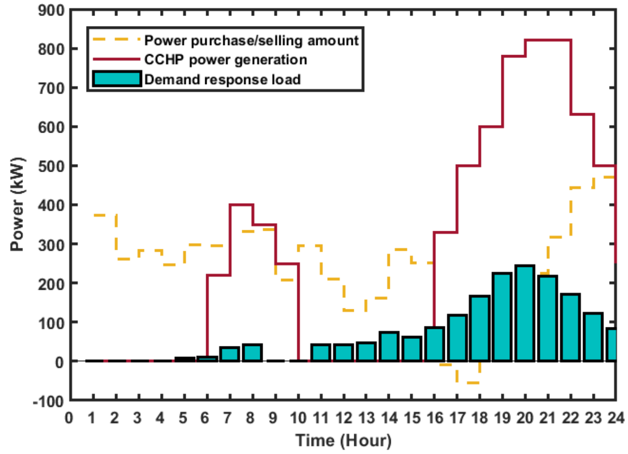
(b) Commercial building electricity load, cooling load, and heating load



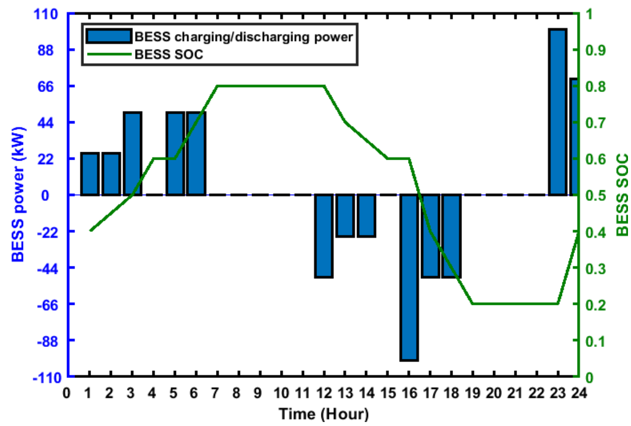
(c) Internet data center electricity load, cooling load, and heating load

FIGURE 6. **Residential building, commercial building, and internet data center electricity load, cooling load and heating load.**

instance, as observed in Fig. 7, CCHP is shut down during 10:00 - 16:00 in residential buildings. Similarly, CCHP is shut down during 1:00 – 8:00 in commercial buildings. The



a) Residential building: CCHP power generation, power exchange amount with external grid, and demand response load

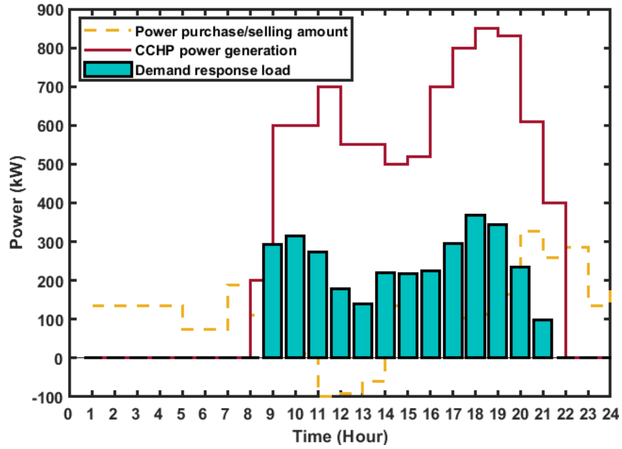


b) Residential building: BESS charging/discharging power, BESS SOC

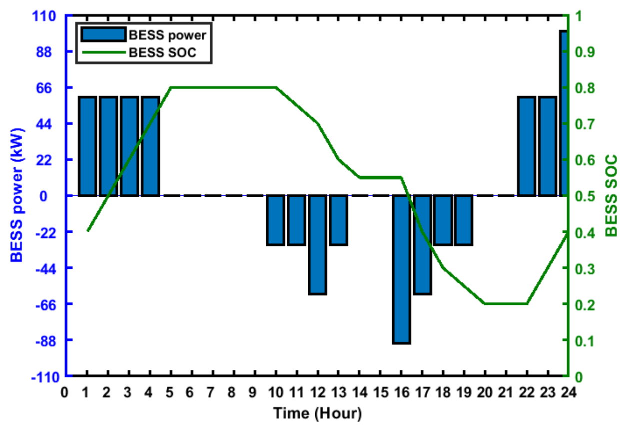
FIGURE 7. **Residential building: a) CCHP power generation, power exchange amount with external grid, and demand response load. b) BESS charging/discharging power, BESS SOC.**

output of CCHP is cut down in the internet data center during 1:00 – 4:00 and 8:00 – 11:00. The prosumer can also choose to sell electricity back to the grid in peak hours to maximize their avenue. For instance, the power is fed back to the grid during 16:00 – 18:00 in residential buildings, 11:00 – 14:00 in commercial buildings. The demand response characteristics for different types of energy nets are also denoted in Figs. 7(a)-9(a). As observed, demand response loads are mainly reduced in peak load periods to reduce the electricity cost. For instance, residential buildings have peak demand response load during 18:00-22:00; commercial buildings have relatively high demand response load during 9:00 – 20:00. Demand response load in the internet data center is relatively stable, due to flat electricity demand in data centers.

Battery energy storage system behavior is explained in Figs. 7(b) – 9(b). It can be identified that BESS mainly works in charging mode during low electricity purchase price periods, and in discharging mode during peak electricity purchase price periods. For instance, BESS is in discharging

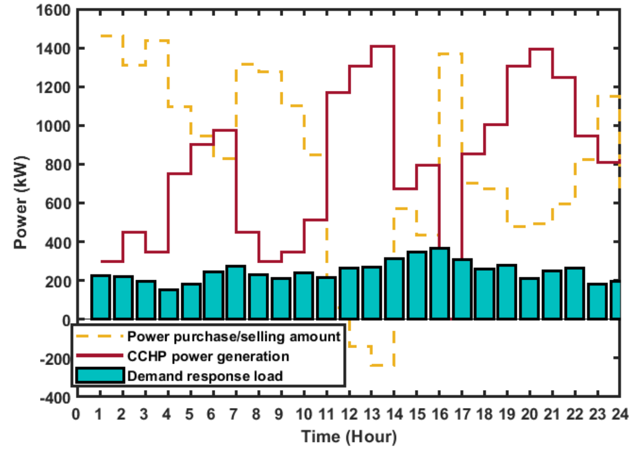


a) Commercial building: CCHP power generation, power exchange amount with external grid, and demand response load

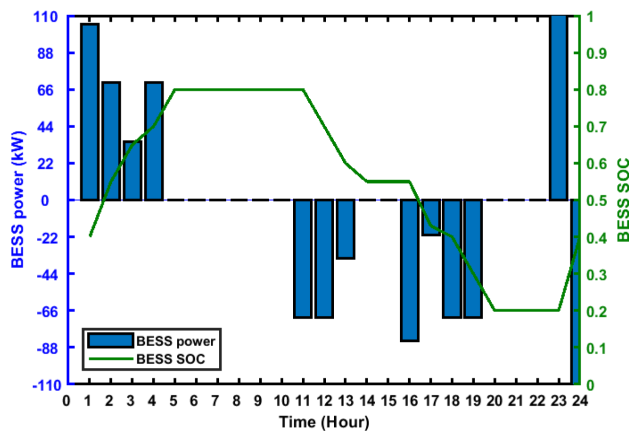


b) Commercial building: BESS charging/discharging power, BESS SOC

FIGURE 8. **Commercial building: a) CCHP power generation, power exchange amount with external grid, and demand response load. b) BESS charging/discharging power, BESS SOC.**



a) Internet data center: CCHP power generation, power exchange amount with external grid, and demand response load



b) Internet data center: BESS charging/discharging power, BESS SOC

FIGURE 9. **Internet data center: a) CCHP power generation, power exchange amount with external grid, and demand response load. b) BESS charging/discharging power, BESS SOC.**

mode during 12:00 – 18:00 in residential buildings, and in charging mode during 1:00 – 6:00 and 23:00 – 24: 00. Noted that BESS state of charge is controlled within 20% - 80% to keep long life cycle.

The values of system inputs and outputs for electricity, heating load, and cooling load are given in Fig. 10. As denoted in Eq. (27), electricity load in the system can be provided by multiple sources, such as BESS, CCHP, PV generation, and external grid. Hence, the system has certain periods when system prosumers can sell surplus electricity back to the grid, such as 9: 00 – 18:00.

Fig. 11 gives a comparison between day-ahead electricity tariff and real-time electricity tariff. The system overall CCHP power generation, power purchase/selling amount with external grid, PV generation, BESS charging/discharging behavior, and demand response load in the real-time stage are denoted in Fig. 12. Similar to day-ahead scheduling results, BESSs work in charging mode during the off-peak electricity tariff periods and work in discharging mode during the peak electricity tariff periods. For instance, the grid charges BESSs during 1:00 – 9:00 and 19:00-24:00. BESSs discharge to reduce the power purchase amount from the grid during 9:00 –13:00 and 14:00 – 19:00.

Table 3 presents the system cost analysis under three different scenarios, i.e. uncoordinated control, day-ahead control and real-time control. Uncoordinated control scheme refers to the power consumption in the system is bought directly from the grid, without considering CCHP and demand response load participation. It should be noted that the cooling/heating energy is from electricity directly in uncoordinated control scenario. As seen in Table 3, the proposed control scheme can effectively reduce system operating cost. Compared with uncoordinated control, day-ahead control scheme can reduce the daily cost by 26.01%, and real-time control scheme can reduce the daily cost by 22.01%. It is worth noting that real-time control results generate slightly higher operating costs due to the imbalance cost between the day-ahead market and real-time market.

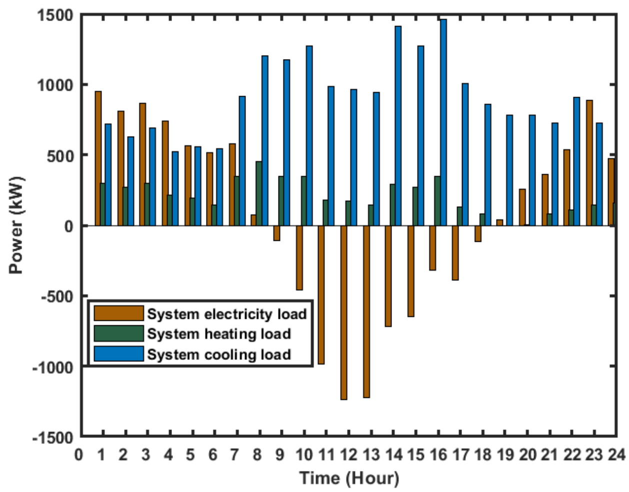


FIGURE 10. System inputs and outputs for electricity load, cooling load and heating load.

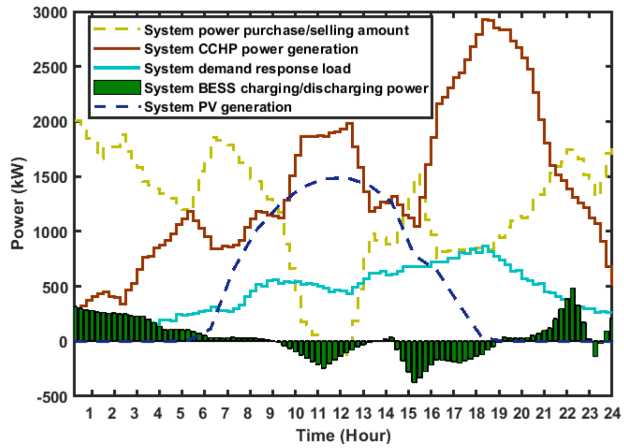


FIGURE 12. System overall CCHP power generation, power purchase/selling amount with external grid, PV generation, BESS charging/discharging behaviour, and demand response load in real-time stage.

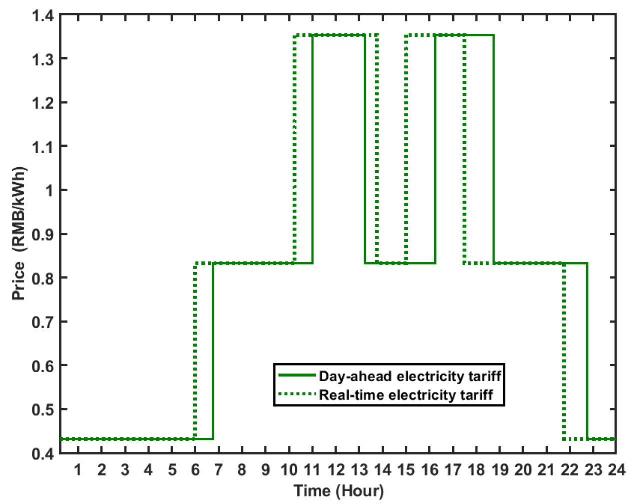


FIGURE 11. Comparison between day-ahead electricity tariff and real-time electricity tariff.

TABLE 3. System costs analysis.

Cost	Uncoordinated control	Day-ahead control	Real-time control
Gas cost	0	￥7043.8 ($1041.9)	￥7285.1 ($1077.7)
Electricity cost	￥21694.7 ($3209.3)	￥6325.4 ($935.7)	￥6748.1 ($998.2)
Demand response cost	0	￥1034.2 ($152.9)	￥1148.3 ($169.9)
BESS degradation cost	0	￥1216.7 ($179.9)	￥1278.3 ($189.1)
Natural gas emission cost	0	￥432.8 ($64.0)	￥459.5 ($67.9)
Overall cost	￥21694.7 ($3209.3)	￥16052.9 ($2374.7)	￥16919.3 ($2502.9)

(Exchange rate: Chinese RMB￥1 = US $ 0.14, US $ 1 = Chinese RMB￥ 6.76)

C. DISCUSSION

In this paper, the energy nets including PV, BESS, CCHP and the external power grid are innovatively proposed to supply cooling, heating and electricity demand to data centers, commercial buildings and residential buildings. As shown in Figs. 7(a) – 9(a), different demand response models are exploited to make full use of the unique load characteristics in different types of buildings. Simulation results demonstrate that the energy resources can be managed optimally by the proposed optimal energy management strategy, and the energy efficiency can be improved as different buildings participate in demand respond programs. In addition, as described in Figs. 7(b) – 9(b), the energy arbitrage can be realized through BESS dispatching considering the degradation cost. On the other hand, it can be observed from Table 3 that the proposed control scheme can reduce operation cost through the energy framework proposed. It is worth noting that the cost of real-time control is higher than the cost of day-ahead control due to various uncertainties including PV and load etc.

Compared with existing research, this work firstly comprehensively evaluates the utilization of CCHP and different types of demand response models in the data center coupled energy nets via a two-stage control model. There are already well-known research works, such as [21], [24], [27], and [28], focusing on the application of CCHPs and demand response programs in an integrated energy network. However, to the best of the authors' knowledge, there are no existing research demonstrating CCHP and different types of demand response models in the data center coupled energy nets. In addition, this work proposes a two-stage coordinated control scheme by taking electricity tariff change in the day-ahead market and real-time market into account, which further improves the control accuracy in the proposed energy network. The present study does not thoroughly investigate the impact of resources uncertainties such as PV generation uncertainty and load uncertainties on system control performances. In addition, a compare study with existing CCHP and demand response model is needed in future to demonstrate the control performance of the proposed framework.

VI. CONCLUSIONS AND FUTURE WORK

This paper puts forward an optimal energy management strategy for internet data center coupled energy nets. The geographically adjunct residential buildings and commercial buildings have also been included in the energy nets, where CCHP, PV power, electricity grid and BESSs are main energy supplies. The proposed energy nets are interconnected via electricity network, cooling network, and heating network. A two-stage optimal energy management strategy is proposed considering CCHP and different types of demand response loads in the energy nets. In the day-ahead control stage, the objective is to minimize system costs. In the real-time stage, electricity tariff chance is considered to improve control efficiency. The objective in this stage is to minimize the imbalance cost between day-ahead market and real-time market. Simulations are conducted in the internet data center network of Foshan City, China. Simulation results demonstrate that the proposed energy management scheme can effectively enhance energy utilization efficiency and shave peak load. The system daily operation cost is reduced by 22.01% in the proposed energy management scheme.

Future work will focus on the following aspects: 1) Coordinated control of the CCHP system to follow the load of the cooling or electricity demand, and more seasonal electricity, cooling, heating load and climatological data will be included; 2) System uncertainties will be more thoroughly investigated with risk-averse measure introduced; 3) Comparable studies with existing models will be included to demonstrate the proposed framework control performance.

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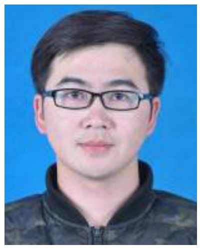

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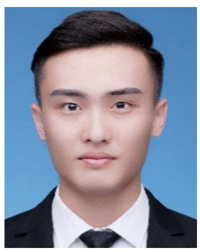

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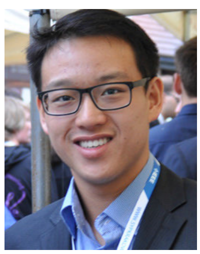

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