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Flexible Regulation and Synergy Analysis of Multiple Loads of Buildings in a Hybrid Renewable Integrated Energy System

Mou Wu ¹, Junqiu Fan ², Rujing Yan ^{1,*}, Xiangxie Hu ¹, Jing Zhang ¹ , Yu He ¹, Guoqiang Cao ¹, Weixing Zhao ² and Da Song ²

¹ The Electrical Engineering College, Guizhou University, Guiyang 550025, China; gs.mwu22@gzu.edu.cn (M.W.)

² Guizhou Power Grid Co., Ltd., Guiyang 550025, China

* Correspondence: rjyan@gzu.edu.cn; Tel.: +86-13158035810

Abstract: The insufficient flexibility of the hybrid renewable integrated energy system (HRIES) causes renewable power curtailment and weak operational performance. The regulation potential of flexible buildings is an effective method for handling this problem. This paper builds a regulation model of flexible heat load according to the dynamic heat characteristics and heat comfort elastic interval of the buildings, as well as a regulation model of the flexible electrical load based on its transferability, resectability, and rigidity. An operation optimization model, which incorporates flexible regulation of multiple loads and a variable load of devices, is then developed. A case study is presented to analyze the regulation and synergy mechanisms of different types of loads. Its results show a saturation effect between heat and electrical loads in increasing renewable energy consumption and a synergistic effect in decreasing the operating cost. This synergy can reduce the operating cost by 0.73%. Furthermore, the operating cost can be reduced by 15.13% and the curtailment rate of renewable energy can be decreased by 12.08% when the flexible electrical and heat loads are integrated into the operation optimization of HRIES.

Keywords: hybrid renewable integrated energy system; flexible buildings; renewable energy consumption; regulation and synergy mechanism; operation optimization



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1. Introduction

Massive greenhouse gas emissions are the root of environmental problems such as global warming, rises in sea levels, and frequent extreme weather, seriously threatening human survival and development [1]. Many countries have reached a consensus to reduce carbon emissions over the next several decades to address the issue [2]. The Chinese government has made a major strategic choice to “achieve carbon peak by 2030 and achieve carbon neutrality by 2060”. The International Energy Agency reports that the energy consumption of the buildings sector is about 40%, which contributes nearly 40% of the global carbon dioxide [3]. As a critical contributor, the Chinese building sector underwent a sharp increase in carbon emissions, increasing from 0.67 Gigatons of CO₂ in 2000 to 2.16 Gigatons of CO₂ in 2020, with an average annual increase rate of 6.03%, and the carbon emissions of buildings accounted for 21.7% of the total in 2020 [4]. The building sector must significantly decrease its carbon emissions to realize carbon neutrality [5].

Increasing the energy efficiency and consumption ratio of renewable energy in building energy systems is the key path to building carbon reduction [6]. An integrated energy system employs advanced technology and management modes to meet various energy demands of buildings in various forms of energy supply, including electricity, heat, and gas [7]. It breaks technical, market, and institutional barriers in traditional single energy systems, realizing complementary and operational coordination of multiple energy sources, effectively increasing energy efficiency [8]. Accordingly, a hybrid renewable integrated energy system (HRIES) in buildings can effectively reduce carbon emissions.

The combined heat and power (CHP) unit is the key to linking multi-energy coupling synergy and increasing energy efficiency in HRIES [9]. However, its inherent heat–electricity coupling feature limits the flexible regulation ability of HRIES, which makes it difficult to handle uncertain fluctuations in renewable energy and loads. It is urgent to enhance the flexible regulation ability to improve the operational performance (e.g., increasing renewable energy share and energy efficiency) of HRIES, which can reduce building carbon emissions.

Recent investigations have looked into enhancing the flexibility of HRIES from two perspectives: coupling auxiliary equipment and excavating its potential flexibility. The former is mainly used to integrate energy transfer or transform devices to optimize the structure of HRIES, thus increasing its ability to follow the load changes of buildings [10]. In integrating energy transform devices, [11] integrated electric boilers and electric heat pumps were used to expand the structure of HRIES, demonstrating potential annual cost savings of USD 180,000 and USD 190,000, respectively. Ref. [12] integrated gas-fired boilers to expand the structure of HRIES and revealed that it improved the renewable consumption of the expanded system. Ref. [13] used bidirectional power to gas (P2G) to expand the structure of HRIES and revealed its effectiveness in boosting renewable consumption. In integrating energy transfer devices, ref. [14] integrated compressed air energy storage to HRIES and proved that it can decrease the operation cost and reduce the carbon emission of the integrated system. Ref. [15] highlighted that the heat storage system (HES) can reasonably allocate the load in HRIES, thereby reducing the energy cost of the integrated system. Furthermore, ref. [16] pointed out that integrated low-temperature solar thermochemical energy storage can reduce the life cycle cost of HRIES by 2.84%. In [17], electrical energy storage (EES) was integrated into HRIES and demonstrated that its integration can reduce energy supply costs by 0.82% and costs by 4.5% per year. However, the integration of auxiliary devices will bring additional maintenance and investment costs.

The essence of excavating the potential flexibility of HRIES is to utilize the operational optimization, considering the flexibility regulation potential on the transmission network (e.g., the characteristics of low-dynamic energy flow) and the building load side (e.g., the heat dynamic characteristics and the heat comfort elasticity). For the network side, ref. [18] established a dynamic gas storage model of the multi-gas transmission network in HRIES and revealed that the storage characteristics can alleviate the uncertainty fluctuation of wind power. Ref. [19] established a collaborative optimization model of the power–gas HRIES, revealing that the gas transmission delay can reduce the power fluctuation of renewable energy. Ref. [20] used the node method to establish the dynamic heat model of the heat transmission network and revealed the effectiveness of heat transfer delay in promoting renewable consumption. Furthermore, ref. [21] coupled the storage characteristics of the heat transmission network to the operation optimization of the HRIES, reducing its total cost by 2.41% and increasing the renewable energy consumption by 5.51%. Ref. [22] proposed a unit commitment considering combined electricity and reconfigurable heating network to enhance the flexibility of the power system by readjusting the configuration for heat supply. The results revealed that the total operation cost decreased by 1.3% and the wind curtailment reduced by 51.7%. The above research mainly focused on the transmission time scales of different energy flows in HRIES, which are mainly used for urban-level IES. However, the coupling promotion impact of different low-dynamic energy flow transmission time scales in user-side HRIES is relatively low.

For the load side, the dynamic heat characteristics and heat comfort elasticity of the building can transform the heat load from rigid demand to flexible demand, which improves the flexibility and renewable consumption of HRIES. Accordingly, ref. [23] established a bi-level optimization model of HRIES considering the heat comfort of heat customers. The results revealed that the heat comfort enhanced system flexibility and reduced the dependence of the upper power grid and the gas transmission network by 24.8%. Ref. [24] proposed a day-ahead optimal scheduling model for the standalone IES considering heat inertia and user comfort, and the results showed that the integration

of heat inertia and user comfort decreased the utilization ratio of the EES and HES by 75% and 30%, respectively. Ref. [25] presented a bi-level robust optimization model with demand response and heat comfort, revealing that the combination of demand response and heat comfort can improve and enhance the planning and operation of HRIES. Ref. [26] applied the global sensitivity analysis model to obtain the optimally combined strategy of energy-saving renovation. According to [27], building heat capacity can reduce daily operating costs by 6.4% and wind curtailment penalty costs by 36.3%.

The flexible load also has the characteristics of flexible regulation. Accordingly, [28,29] established a flexible model of shiftable electrical load based on the demand response and thermodynamic model of integrated flexible heat load. Ref. [30] proposed an operation method in which electrical and heat loads collaboratively participate in demand response, and the results showed that the demand response synergy of electrical and heat loads can also save costs by 8.27% and 6.8%, reduce carbon emissions by 3.23% and 2.06%, and increase renewable consumption rates by 5.36% and 3.25%, respectively. Additionally, ref. [31] established a flexible model including three kinds of electrical loads and introduced it into a low-carbon economic operation optimization. The results demonstrated that the flexible load can effectively smooth the load curve, lower carbon dioxide emissions, and reduce energy purchase costs. Existing research on the potential flexibility on the load side mainly concentrates on the regulation of a single type of flexible load. Few studies have introduced multiple flexible loads into optimization simultaneously and analyzed the synergy between multiple types of flexible loads from the economy and renewable energy consumption.

HRIES is a comprehensive energy utilization system characterized by multi-energy input, coupling, and output. It is difficult to fully improve the operation performance of HRIES and the consumption of renewable energy by considering the flexibility regulation potential of only one type of flexible load. Accordingly, this paper establishes the flexible regulation model of heat and electrical loads. The flexible regulation is then introduced into an operation optimization. The main contributions of this work are as follows:

- (1) A flexible regulation model of heat load is built according to the dynamic heat characteristics and heat comfort elastic interval of the buildings. Flexible regulation of the electrical load is modeled according to its transferability, resectability, and rigidity.
- (2) An operation optimization model, which incorporates flexible regulation of multiple loads and the variable load of devices, is then developed to improve the operational performance and reduce the renewable energy curtailment of HRIES.
- (3) Comparatively analyze the operation performance of minimum total operating cost and renewable curtailment rate with various flexible loads. Present the flexible regulation and synergy mechanism of multiple types of flexible loads in reducing the operating cost and renewable energy consumption of HRIES.

The remainder of this paper is organized as follows: Section 2 presents the structure of HRIES with flexible buildings. In Section 3, flexible load models of buildings are formulated. Section 4 develops the optimization model for introducing flexible load. The results are analyzed in Section 5, followed by the conclusions in Section 6.

2. HRIES with Flexible Buildings

The system structure of HRIES with flexible buildings is illustrated in Figure 1. The energy production devices in the HRIES comprise a gas CHP unit, wind turbines, gas boiler (GB), and energy storage, including EES and HES. The electrical and heat energy generated by each device is converged to the power hub and the heat hub, respectively. Subsequently, it is transmitted to the consumers in flexible buildings through the corresponding transmission network. To ensure power supply reliability and real-time power balance, EES is installed in a power hub. Any excess or insufficient electricity beyond the regulation range of the HRIES is balanced through the power grid. HES is also installed in the heat hub to ensure heat balance. Additionally, the heat and electrical loads of flexible buildings possess regulation potential. Excavating this potential flexibility can effectively improve op-

erational performance, such as reducing operational costs and renewable curtailment rates.

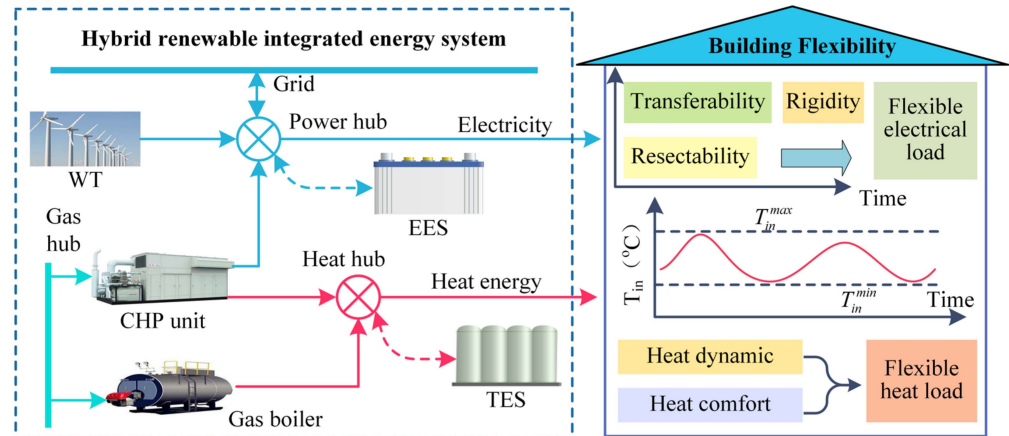


Figure 1. System structure of HRIES with flexible buildings.

3. Flexible Load Model of Buildings

3.1. Flexible Heat Load Model

The heat demand of buildings intended to maintain indoor temperature at a comfortable temperature perceived by the human body under the interference of outdoor environmental factors is determined by the dynamic heat transfer process. This process is influenced by a lot of factors, e.g., wind speed, irradiation intensity, ambient temperature, and the characteristics of the building envelope. Such a process is extremely complex and hardly achieves its fine model. In addition, there are many buildings and different rooms in the HRIES; it is thus impossible and unnecessary to model the buildings one by one [32]. A lumped model, in which a multi-story building or some adjacent building clusters with similar features can be abstracted as a typical large room, is employed to simplify the heat transfer process [32]. The dynamic heat balance of this room is employed to describe the buildings approximately. Accordingly, the heat dynamic balance and indoor temperature changes are shown in Figure 2.

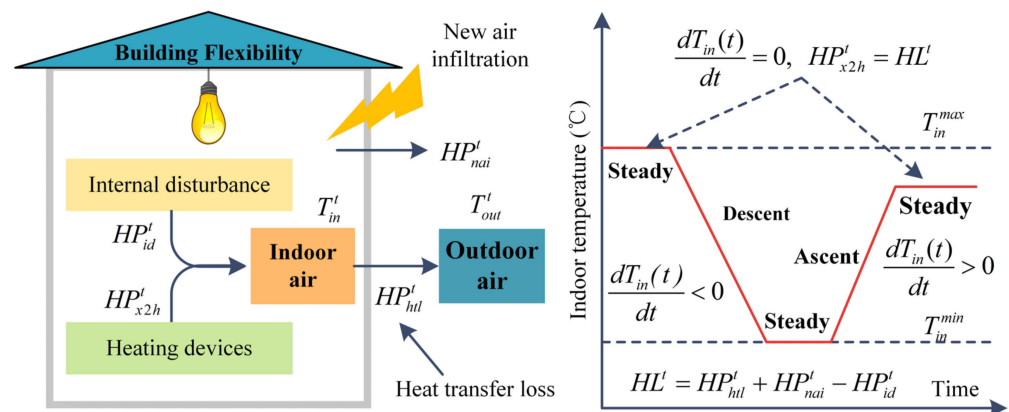


Figure 2. Schematic diagram of a dynamic heat transfer process.

According to Figure 2, the heat dynamic balance is realized under the combined action of internal disturbance heat generation, equipment heating, envelope heat transfer, and fresh air infiltration heat transfer. The balance can be expressed as [32],

$$C_{bu} \frac{dT_{in}(t)}{dt} = HP_{id}^t + HP_{x2h}^t - HP_{htl}^t - HP_{nai}^t \quad (1)$$

where C_{bu} represents the total capacity of buildings (MJ/°C); HP describes heat power (MW); T represents temperature (°C); t denotes the time interval (h); the subscript in represents indoor; HP_{id}^t , HP_{htl}^t , and HP_{nai}^t are the heat powers contributed by internal disturbance, the heat transfer power caused by indoor and outdoor temperature differences, and the heat loss from new air infiltration, respectively. HP_{x2h}^t describes the sum of heat power of heating devices, which can be expressed as,

$$HP_{x2h}^t = HP_{CHP}^t + HP_{GB}^t + HP_{HES}^{t,ex} - HP_{HES}^{t,im} \quad (2)$$

where subscripts CHP , GB , and HES represent CHP units, gas boilers, and heat storage devices; the superscripts im and ex denote energy input and energy output, respectively.

According to Figure 2, the heat load (HL^t) is the difference between the heat power contributed by internal disturbance (e.g., heat energy from household appliances and heat dissipation via server operation) and the sum of that contributed by heat transfer and cold air infiltration. When the sum of the heat power of the heating devices (HP_{x2h}^t) is equal to the heat load, the derivative $dT_{in}(t)/dt$ is 0 and the indoor temperature of buildings remains constant (namely the steady period). When HP_{x2h}^t is greater than the heat load, the derivative exceeds 0 and the indoor temperature of buildings increases (namely the ascent period), realizing the storage of heat energy in buildings. When HP_{x2h}^t is less than the heat load, the derivative is less than 0 and the indoor temperature decreases (namely the descent period), releasing the heat energy stored in buildings.

The heat power brought by the internal disturbance is usually less than that of the heating devices. Usually, it is defined by an empirical formula [33].

$$HP_{id}^t = ahp \cdot A \quad (3)$$

where ahp denotes the average heat power of the unit heating area contributed by the internal distribution, whose empirical value is 3.8 W/m². A is the heating area of buildings.

The process of heat transfer loss from the building envelope is extremely complex. It is thus assumed that the temperature of indoor air equals that of the inner surface of the envelope, and the temperature of outdoor air equals that of the outer surface of the envelope to simplify this process. Heat loss from the building envelope equals the sum of that from doors, windows, walls, floors, roofs, etc. Accordingly, the heat power contributed by heat transfer loss can be defined by the main heat transfer loss and the correction factor of the corresponding influence element e.g., orientation, wind velocity, and radiation intensity [32].

$$HP_{htl}^t = (1 + \theta_{he}) \sum_{i=1}^{ne} (\lambda_i \cdot A_i \cdot \theta_T \cdot (T_{in}^t - T_{out}^t) \cdot (1 + \theta_{SR} + \theta_v)) \quad (4)$$

where θ_{he} , θ_T , θ_{SR} , and θ_v are the correction factors for additional height, environment temperature, solar radiation, and wind velocity, respectively; λ_i and A_i describe the heat transfer coefficient and the area of the i -th envelope, respectively; T_{out}^t denotes the temperature of the outdoor environment; ne is the number of the envelope.

In addition, the pressure difference caused by the temperature difference in indoor and outdoor environments drives cold air infiltration through the doors and windows, resulting in heat energy loss. For civil buildings, the heat power contributed by cold air infiltration is defined in [34] as:

$$HP_{nai}^t = 2.78 \times 10^{-4} \cdot c_{air} \cdot \rho_{air} \cdot n_{air} \cdot V \cdot (T_{in}^t - T_{out}^t) \quad (5)$$

where c_{air} and ρ_{air} refer to the isobaric specific heat capacity (1.0 kJ/(kg·K)) and the density (1.29 kg/m³) of air, respectively; V represents the volume of building space; n_{air} describes the ventilation frequency of buildings.

The energy loss of heat transfer and cold air infiltration is driven by the indoor and outdoor temperature difference. Their sum is thus simplified by introducing a comprehensive heat transfer coefficient (λ_{bu}).

$$HP_{htl}^t + HP_{nai}^t = \lambda_{bu} \cdot (T_{in}^t - T_{out}^t) \quad (6)$$

The comprehensive heat transfer coefficient is defined as

$$\lambda_{bu} = 2.78 \times 10^{-4} \cdot c_{air} \cdot \rho_{air} \cdot n_{air} \cdot V + (1 + \theta_{he}) \sum_{i=1}^{ne} (\lambda_i \cdot A_i \cdot \theta_T \cdot (1 + \theta_{SR} + \theta_v)) \quad (7)$$

As a result, a comprehensive time coefficient that evaluates the level of heat storage time of building space can be developed as

$$t_{bu} = C_{bu} / \lambda_{bu} \quad (8)$$

Accordingly, the dynamic heat balance equation can be rewritten as

$$t_{bu} \cdot \lambda_{bu} \cdot \frac{dT_{in}(t)}{dt} = HP_{x2h}^t + HP_{id}^t - \lambda_{bu} \cdot (T_{in}^t - T_{out}^t) \quad (9)$$

The above equation is discretized and its discretized form is obtained.

$$T_{in}^{t+\Delta t} = T_{out}^t + \frac{HP_{x2h}^t + HP_{id}^t}{\lambda_{bu}} + \left(T_{in}^t - T_{out}^t - \frac{TP_{x2h}^t + TP_{id}^t}{\lambda_{bu}} \right) \cdot \exp\left(\frac{-\Delta t}{t_{bu}}\right) \quad (10)$$

According to Equation (10), the indoor temperature at the next time relies on the current time and the sum of the heat power of heating devices. When a constant temperature control strategy is employed, the derivative $dT_{in}(t)/dt$ equals zero. Accordingly, Equation (9) can be rewritten as the following equation.

$$HP_{x2h}^t = \lambda_{bu} \cdot (T_{in}^t - T_{out}^t) - HP_{id}^t \quad (11)$$

According to Equation (11), the sum of the heat power of heating devices equals the heat demand. The heat load thus loses the flexible regulation potential.

The temperature variation of the indoor air lags behind that of the heat transfer medium. Some heat can be stored in the internal space of the building, showing heat inertia. Additionally, the perception of the human body to the heat environment is fuzzy, providing a flexible regulation potential. The heat environment is affected by many factors, such as indoor temperature, humidity, air velocity, metabolism, and clothing heat resistance. Its calculation model is thus extremely complex. To simplify the model, the influence of minor factors is usually ignored in engineering. Accordingly, the predicted mean vote (PMV) is introduced to measure the heat comfort of the building [35].

$$PMV = 2.43 - \frac{3.67 \cdot (T_{rt} - T_{in}^t)}{ME \cdot (I_{cl} + 0.1)} \quad (12)$$

where T_{rt} represents the average temperature of the skin surface in a comfortable state, with an approximate value of 32.6 °C; I_{cl} describes the heat resistance of the garment, which is approximately 0.11 (m²·°C)/W in winter; ME denotes the human metabolic rate, with an approximate value of 80 W/m² in [36].

According to “the design standards of heating, ventilation and air conditioning in China”, the value of PMV is ± 1 . The maximum value of indoor temperature in winter can be calculated as 26.0 °C and 16.9 °C, respectively.

When the operation optimization fails to consider the flexible regulation of the heat load (namely constant temperature control strategy), the heat load of the building is only a time series curve. Inversely, if the variable temperature control strategy is introduced into

the operation of HRIES, there are countless time series curves of heat load. The operation optimization aims to find an optimal indoor temperature curve in its elastic range to promote the operational performance (e.g., operating cost reduction) of HRIES. The regulation model of the flexible heat load is thus defined as

$$T_{in}^{t+\Delta t} = \left(T_{in}^t - T_{out}^t - \frac{HP_{x2h}^t + HP_{id}^t}{\lambda_{bu}} \right) \cdot \exp\left(\frac{-\Delta t}{t_{bu}}\right) + \frac{HP_{x2h}^t + HP_{id}^t}{\lambda_{bu}} + T_{out}^t \quad (13)$$

st. $16.9 \leq T_{in}^t \leq 26.0$

where Δt represents the time step and its value in this paper is 1 h.

3.2. Flexible Electrical Load Model

Electrical loads can be divided into shiftable, transferable, reducible, and rigid loads. The shiftable load needs to shift its working time cycle, such as a load of washing machine, dryer, and electric oven. The transferable load must maintain its energy balance in a scheduling cycle, without the continuity limitation of working time, such as a load of electric vehicles and water heaters. Reducible load refers to the demand that can withstand a certain interruption or reduction during the scheduling cycle. The rigid load is unchanged and is fully responded to by HRIES.

Accordingly, this paper establishes a flexible regulation model of electrical load based on its transferability, reducibility, and rigidity.

$$EL_t = EL_b^t + \left(\alpha_{tr}^{t,im} - \alpha_{tr}^{t,out} \right) \cdot EL_{rig}^t - \alpha_{red}^t \cdot EL_{rig}^t \quad (14)$$

where EL is the electrical load; α is the ratio of flexible electrical regulation; and the subscripts of the *rig*, *tr*, and *red* represent rigid, transferable, and reducible loads, respectively. Accordingly, EL_{rig}^t describes the rigid electrical load; $\alpha_{tr}^{t,im}$ and $\alpha_{tr}^{t,ex}$ are the ratios of the import and export of the transfer load, respectively. $\alpha_{tr}^{t,im} EL_{rig}^t$ and $\alpha_{tr}^{t,ex} EL_{rig}^t$ are the electrical loads of import and export of transfer, respectively.

The transferable load needs to meet the energy balance in the scheduling period.

$$\sum_{t=1}^{24} \left(\alpha_{tr}^{t,im} - \alpha_{tr}^{t,ex} \right) \cdot EL_{rig}^t = 0 \quad (15)$$

In addition, the transfer-in ratio, transfer-out ratio, and load-shedding ratio of the flexible load model should be less than their respective maximum values.

$$\alpha_{tr}^{t,im} \leq \alpha_{tr}^{\max,im}, \alpha_{tr}^{t,ex} \leq \alpha_{tr}^{\max,ex}, \alpha_{red}^t \leq \alpha_{red}^{\max} \quad (16)$$

4. Optimization Model for Introducing Flexible Load

4.1. Optimization Objectives

The optimization objectives in the model include maintenance cost (MC), energy purchase cost (EC), carbon emission penalty cost (CEC), and renewable curtailment cost (REP). They are defined as

$$MC = \sum_{t=1}^{24} \left(\left(um_{HHS} \left(HP_{HES}^{t,im} + HP_{HES}^{t,ex} \right) + um_{CHP} \cdot EP_{CHP}^t + um_{WT} \cdot EP_{WT}^t + um_{GB} \cdot HP_{GB}^t + um_{EES} \left(EP_{EES}^{t,im} + EP_{EES}^{t,ex} \right) \right) \cdot \Delta t \right) \quad (17)$$

$$EC = \sum_{t=1}^{24} \left(\left(\varphi_{NG} \cdot (F_{CHP}^t + F_{GB}^t) + \varphi_G^{t,im} EP_G^{t,im} + \varphi_G^{t,ex} EP_G^{t,ex} \right) \cdot \Delta t \right) \quad (18)$$

$$CEC = \sum_{t=1}^{24} \varphi_{CO2} \cdot \left(\left(\xi_{NG} \cdot (F_{CHP}^t + F_{GB}^t) + \xi_G \cdot (EP_G^{t,ex} - EP_G^{t,im}) \right) \cdot \Delta t \right) \quad (19)$$

$$REP = \sum_{t=1}^{24} \left(\varphi_{REC} \cdot \left(\left(\hat{EP}_{WT}^t - EP_{WT}^t \right) \cdot \Delta t \right) \right) \quad (20)$$

In the above equations, um represents the unit maintenance cost (Yuan/MWh); φ_{NG} , φ_{CO2} , and φ_{REC} are the unit cost of natural gas purchase, the penalty cost of carbon emissions, and the penalty cost of renewable curtailment, which are set at 2.324 ¥/m³, 0.02269 ¥/kg, and 0.316 ¥/kWh, respectively; the subscript G represents the power grid; $\varphi_G^{t,im}$ and $\varphi_G^{t,ex}$ represent the price of selling and purchasing electricity to and from the power grid (Yuan/kWh); ξ_{NG} and ξ_G represent the carbon emission coefficients of natural gas combustion and power grid purchase, respectively, with values of 0.968 and 0.22 kg/kWh; F is natural gas flow rate; EP represents electrical power (MW); $EP_G^{t,ex}$ and $EP_G^{t,im}$ represent the real-time power of purchasing and selling electricity from and to the power grid, respectively; the subscript WT is the wind turbine; $\hat{EP}_{WT}^t$ and EP_{WT}^t represent the actual power generated by the wind turbine and the real output power, respectively.

Accordingly, the total operating cost (TOC) objective function is defined as

$$TOC = MC + EC + CEC + REP \quad (21)$$

4.2. Model Constraints

The model constraints include the operation model constraints of each piece of equipment in HRIS, energy balance constraints, and grid constraints.

4.2.1. Device Model Constraints

(1) Wind power

The output power of wind power is closely related to the size of the wind velocity and its rate power (RP), and the energy conversion model is described as [25]

$$EP_{WT}^t = \begin{cases} 0, & v^t \leq v^{\min} \text{ or } v^t \geq v^{\max} \\ \frac{v^t - v^{\min}}{v^{ra} - v^{\min}} RP_{WT}, & v^{\min} \leq v^t \leq v^{ra} \\ RP_{WT}, & v^{ra} \leq v^t \leq v^{\max} \end{cases} \quad (22)$$

where v denotes wind speed (m/s); $v^{\min}$, $v^{\max}$, and v^{ra} represent cut-in, cut-out, and rated wind speeds, respectively, which are usually 3 m/s, 20 m/s, and 10 m/s.

(2) Gas-fired CHP units

The energy conversion model of a gas-fired CHP unit can be expressed as

$$F_{CHP}^t = \begin{cases} EP_{CHP}^t / (\eta_{CHP}^{t,e} \cdot LHV_{NG}), & 0.2 \leq LR_{CHP}^t \leq 1 \\ 0, & 0 \leq LR_{CHP}^t < 0.2 \end{cases} \quad (23)$$

$$HP_{CHP}^t = \begin{cases} F_{CHP}^t \cdot \eta_{CHP}^{t,h} \cdot LHV_{NG}, & 0.2 \leq LR_{CHP}^t \leq 1 \\ 0, & 0 \leq LR_{CHP}^t < 0.2 \end{cases} \quad (24)$$

where LR_{CHP}^t is the load rate of the CHP units; LHV_{NG} is the low calorific value of natural gas (MJ/m³); $\eta_{CHP}^{t,e}$ and $\eta_{CHP}^{t,h}$ are the efficiency of power generation and heat generation of gas CHP units, respectively, which can be fitted as [37]

$$\eta_{CHP}^{t,e} = -0.24196 \cdot (LR_{CHP}^t)^3 + 0.5203 \cdot (LR_{CHP}^t)^2 - 0.47096 \cdot LR_{CHP}^t + 0.69857, 0.2 \leq LR_{CHP}^t \leq 1 \quad (25)$$

$$\eta_{CHP}^{t,h} = 0.02045 \cdot (LR_{CHP}^t)^3 - 0.27649 \cdot (LR_{CHP}^t)^2 + 0.59816 LR_{CHP}^t + 0.00613, 0.2 \leq LR_{CHP}^t \leq 1 \quad (26)$$

The power of CHP units in scheduling periods needs to meet ramping constraints.

$$\begin{aligned} EP_{CHP}^t - EP_{CHP}^{t-1} &\leq UR_{CHP} \cdot \Delta t, \\ EP_{CHP}^{t-1} - EP_{CHP}^t &\leq DR_{CHP} \cdot \Delta t \end{aligned} \quad (27)$$

where UR and DR are the up and down climbing rates (MW/h) of the device, respectively.

Additionally, the maximum output power of the CHP unit needs to be less than the rated capacity of the equipment.

$$0 \leq EP_{CHP}^t \leq RP_{CHP} \quad (28)$$

(3) Gas-fired boiler

The model of the gas-fired boiler (GB) can be expressed as

$$HP_{GB}^t = \begin{cases} \eta_{GB}^t \cdot F_{GB}^t \cdot LHV_{NG}, & 0.2 \leq LR_{GB}^t \leq 1 \\ 0, & 0 \leq LR_{GB}^t < 0.2 \end{cases} \quad (29)$$

where η_{GB}^t represents the efficiency of the GB, which is set to 0.72; LR_{GB}^t represents the load rate of the GB. It stops when the load rate is less than 0.2.

In addition, the output constraint of GB in scheduling periods also needs to meet the climbing constraint.

$$\begin{aligned} HP_{GB}^t - HP_{GB}^{t-1} &\leq UR_{GB} \cdot \Delta t \\ HP_{GB}^{t-1} - HP_{GB}^t &\leq DR_{GB} \cdot \Delta t \end{aligned} \quad (30)$$

The output of the GB also needs to be less than its rated capacity.

$$0 \leq HP_{GB}^t \leq IC_{GB} \quad (31)$$

(4) Energy storage

The energy state of energy storage at each moment is affected by the charging and discharging power and the energy state at the previous moment. The model can be expressed as

$$E_{es}^t = E_{es}^{t-1} + \left(P_{es}^{t-1,im} \cdot \eta_{es}^{im} - P_{es}^{t-1,ex} / \eta_{es}^{ex} \right) \cdot \Delta t, es \in \{EES, HES\}, P \in \{HP, EP\} \quad (32)$$

where E denotes the energy state (MWh) of the energy storage; the superscripts im and ex represent the import and export of energy; η_{es}^{im} and η_{es}^{ex} represent the efficiency of charging (import) and discharging (export), respectively. Overcharge and over-discharge will affect the life of energy storage, so it needs to follow the following constraints.

$$\lambda_{es}^{\min} \cdot RC_{es} \leq E_{es}^t \leq \lambda_{es}^{\max} \cdot RC_{es} \quad (33)$$

Additionally, the powers of the charge and discharge needed to lower the maximum allowable.

$$\begin{aligned} 0 \leq P_{es}^{t,im} &\leq st_{es}^{t,im} \cdot \lambda_{es}^{\max,im} \cdot RC_{es} \\ 0 \leq P_{es}^{t,ex} &\leq st_{es}^{t,ex} \cdot \lambda_{es}^{\max,ex} \cdot RC_{es} \end{aligned} \quad (34)$$

where $\lambda_{es}^{\max,im}$ and $\lambda_{es}^{\max,ex}$ represent the ratios of maximum charge and discharge power to rated capacity (RC), respectively; $st_{es}^{t,im}$ and $st_{es}^{t,ex}$ denote the charging and discharging state variables of the energy storage at time t , respectively; when the variable is equal to 1, it means that the state exists; if it is equal to 0, it means that the state does not exist. The charging/discharging process will involve energy loss and affect the life of the equipment. Accordingly, it is prohibited to have a charging/discharging state at the same time.

$$st_{es}^{t,ch} + st_{es}^{t,dis} \leq 1 \quad (35)$$

Additionally, the energy storage needs to be restored to its initial state after the end of the scheduling cycle.

$$E_{es}^0 = E_{es}^{t=24} \quad (36)$$

4.2.2. Energy Balance Constraints

The operation optimization model of HRIES needs to meet the energy balance constraint, and the flexible regulation of electrical load is coupled with the energy balance constraint. The balance constraint is described as

$$EP_{CHP}^t + EP_{WT}^t + EP_G^{t,ex} - EP_G^{t,im} + EP_{EES}^{t,ex} - EP_{EES}^{t,im} = EL_{rig}^t + (\alpha_{tr}^{t,im} - \alpha_{tr}^{t,ex})EL_{rig}^t - \alpha_{red}^t EL_{rig}^t \quad (37)$$

The heat balance constraint is a flexible heat load regulation model (Equation (7)).

4.2.3. Constraints of the Power Grid

The HRIES is connected to the power grid and is constrained by the power of the contact line. Therefore, it is necessary to limit the power purchased and the power sold to within a specific range.

$$\begin{aligned} 0 &\leq EP_G^{t,im} \leq st_G^{t,im} \cdot EP_G^{\max,im} \\ 0 &\leq EP_G^{t,ex} \leq st_G^{t,ex} \cdot EP_G^{\max,ex} \end{aligned} \quad (38)$$

In Equation (38), $st_G^{t,im}$ and $st_G^{t,ex}$ represent the state variables of selling electricity (import to the grid) and purchasing electricity (export from the grid), respectively. The HRIES cannot purchase electricity from the grid and sell electricity to the grid at the same time, thus the optimization needs to satisfy the following constraint.

$$st_G^{t,im} + st_G^{t,ex} \leq 1 \quad (39)$$

4.3. Model Solution

There are nonlinear output constraints of gas-fired CHP units in the operation optimization model, which leads to the nonlinearity of the model. The piecewise linear approximation method is used to address the problem. The model is then transformed into a mixed integer linear programming model, which is directly solved.

5. Case Study

To investigate the regulation mechanism and performance promotion degree of different flexible loads, the optimization method was used in an HRIES of an industrial park in Harbin city. The data on related devices in the park are shown in Table 1.

Table 1. Economic and technical parameters of devices.

Devices	Unit Maintenance Cost (Yuan/MWh)	Technical Parameters
GB	20	$RP_{GB} = 12 \text{ MW}; UR_{GB} = DR_{GB} = 6 \text{ MW/h}$
EES	83	$\eta_{EES}^{im} = \eta_{EES}^{ex} = 0.95; \lambda_{EES}^{\max,im} = \lambda_{EES}^{\max,ex} = 0.35; \chi_{EES}^{\min} = 0.2,$ $\chi_{EES}^{\max} = 0.9; RC_{EES} = 20 \text{ WMh}; E_{EES}^0 = 4 \text{ WMh}$
HES	20	$\eta_{HES}^{im} = \eta_{HES}^{ex} = 0.88; \lambda_{HES}^{\max,im} = \lambda_{HES}^{\max,ex} = 0.4; \chi_{HES}^{\min} = 0,$ $\chi_{HES}^{\max} = 0.9; RC_{HES} = 20 \text{ WMh}; E_{HES}^0 = 0 \text{ WMh}$
CHP	20	$RP_{CHP} = 35 \text{ MW}; UR_{CHP} = DR_{CHP} = 12.25 \text{ MW/h}$
WT	68	$RP_{WT} = 50 \text{ MW}$

Moreover, the typical hourly wind velocities and outdoor ambient temperatures of the industrial park are shown in Figure 3; the corresponding typical hourly electrical loads and sale/purchase electricity prices are displayed in Figure 4.

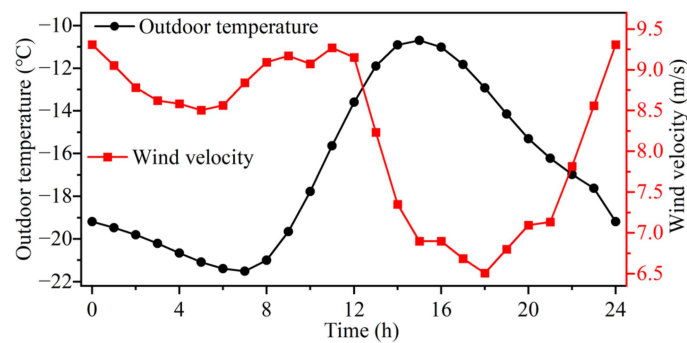


Figure 3. Typical outdoor temperatures and wind speeds in the park.

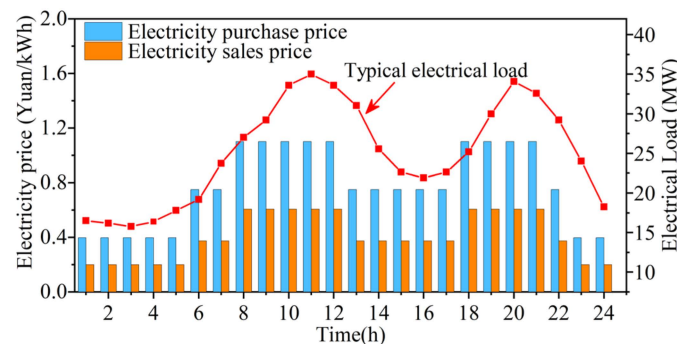


Figure 4. The typical electrical loads of the park and the electricity prices.

Additionally, the price of natural gas purchased in the park is 2.324 ¥/m³, and the low calorific value of natural gas purchased is 36 MJ/m³; the heating area of the building is 1.16×10^6 m² and the comprehensive heat transfer coefficient and internal disturbance power per unit temperature are 1.45 MW/°C and 3.8 W/m², respectively.

5.1. Model Solution

To compare and analyze the effectiveness and synergy of the flexible regulation of various types of loads, four cases are set as follows:

Case 1: Flexible regulation of loads is not considered in the optimization.

Case 2: Only flexible electrical load regulation is considered in the optimization.

Case 3: Only flexible heat load regulation is considered in the optimization.

Case 4: Flexible regulation of both heat load and electrical load are considered.

In addition, to analyze the effectiveness of flexible regulation from the perspectives of the economy and renewable consumption, the optimization model targets minimum operating cost and renewable curtailment rate, respectively. For the case with the minimum renewable curtailment rate, only the penalty coefficient of renewable curtailment needs to be set to an infinite number to realize the transformation of the objective function.

5.2. Optimized Results

Tables 2 and 3 show the optimized results from the perspectives of minimum total operating cost and renewable curtailment rate.

Table 2. Optimized results under the minimum total cost.

Optimized Results	Curtailment Rate (%)	TOC (Thousand Yuan)	MC (Thousand Yuan)	EC (Thousand Yuan)	CEC (Thousand Yuan)	REP (Thousand Yuan)
Case 1	27.24	413.8	48.6	310.5	12.8	45.6
Case 2	19.06	385.6	47.6	290.3	14.1	33.6
Case 3	22.68	382.4	45.5	282.2	15.8	38.8
Case 4	15.04	351.2	50.0	263.1	12.4	25.7

Table 3. Optimized results of minimum renewable curtailment rate.

Optimized Results	Curtailment Rate (%)	TOC (Thousand Yuan)	MC (Thousand Yuan)	EC (Thousand Yuan)	CEC (Thousand Yuan)	REP (Thousand Yuan)
Case 1	26.73	417.6	48.6	310.5	12.8	45.7
Case 2	19.06	385.6	47.6	290.3	14.1	33.6
Case 3	22.05	386.0	50.7	282.3	15.8	37.7
Case 4	14.65	354.2	53.7	263.1	12.4	25

From an economic point of view, flexible regulation of electrical load can reduce the total operating cost of HRIES from 413.8 thousand Yuan to 385.6 thousand Yuan, a reduced rate of 6.81%. Furthermore, the flexible regulation of heat load can reduce the total operating cost of HRIES from 413.8 thousand Yuan to 382.4 thousand Yuan, a reduced rate of 7.59%. When considering flexible regulation of both electrical and heat loads in HRIES, the total operating cost is reduced to 351.2 thousand Yuan, a reduced rate of 15.13%. It is worth noting that the rate of decline in the total operating cost when considering flexible regulation of both heat and electrical loads is greater than the sum of the rates of decline when integrating the flexible regulation of heat load or electrical load alone (14.40%), which indicates that there is a synergistic effect between flexible electrical load and heat load regulation in reducing the total operating cost. This synergistic effect can reduce the total operating cost by 0.73%.

In addition, energy purchase costs accounted for the largest share of the total operating costs of HRIES, reaching 75.04% (case 1). In general, integrating flexible load regulation into the optimization reduces the total operating cost mainly by reducing the penalty for renewable energy curtailment and energy purchase costs.

From the perspective of renewable energy consumption, the integration of flexible regulation of heat load and electrical loads can reduce the renewable curtailment rate in HRIES. Among them, flexible electrical load regulation can reduce the renewable curtailment rate from 26.73% to 19.06%, a decrease of 7.67%, while flexible heat load regulation can reduce it to 22.05%, a decrease of 4.68%. If flexible regulation of both electrical and heat loads is considered in the operation of HRIES, the curtailment rate decreases to 14.65%, a decrease of 12.08%. Therefore, this reduction is less than the sum of the reductions in the curtailment rate (12.35%) when the flexible electrical load or flexible heat load are integrated alone, revealing that there is a saturation effect of the flexible electrical and heat load regulation in increasing renewable consumption.

Comparing Table 2 with Table 3, in Case 2 where flexible electrical load regulation is integrated, the optimized results of the minimum total operating cost and renewable curtailment rate are consistent, indicating that flexible electrical load regulation mainly reduces the total operating cost by reducing the renewable curtailment rate. Conversely, in Case 3, where flexible heat load regulation is integrated, the optimized results of the minimum total operating cost and the minimum renewable curtailment rate differ. When the optimization method targets a minimum renewable curtailment rate, the curtailment rate decreases from 22.68% to 22.05%. However, this decrease comes at the cost of a total operating cost increase from 382.4 to 386.0 thousand Yuan.

Additionally, when the operation optimization of the HRIES considers both flexible regulation of the electrical load and the heat load (Case 4), the total operating cost of the system drops to 351.2 thousand Yuan, a decrease rate of 15.13%, while the renewable curtailment rate drops to 15.04%, a decrease rate of 12.2%. Similarly, the optimized results are also different between minimum total operating cost and minimum renewable curtailment rate. The pursuit of renewable consumption also increases the total operating cost.

5.3. Discussion of Results

In Case 2, where flexible electrical load regulation is considered, the comparison between the regulated load and the original load is shown in Figure 5.

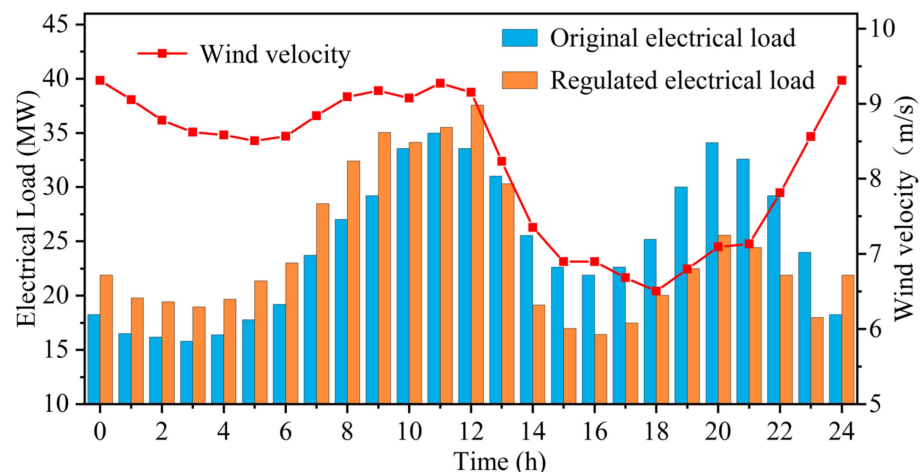


Figure 5. Optimal hourly electrical load considering flexible electrical load regulation.

Figure 5 shows that the wind velocity in the park is larger during the period 0:00–12:00. After 12:00, the wind velocity shows a downward trend. After 18:00, the wind velocity in the park shows an upward trend. On the whole, the flexible electrical load can consume renewable energy as much as possible by transferring the load to the high wind velocity period to reduce the total operating cost. Therefore, it presents the characteristics of turning in the high wind velocity period and turning out in the low wind velocity period. Accordingly, in the 0:00–12:00 period, the regulated electrical load is higher than the original electrical load; in the 12:00–23:00 period, the regulated electrical load is lower than the original electrical load.

The park has a low electrical load during the 0:00–6:00 period, and the outdoor low-temperature environment increases heat demand and the output of gas-fired CHP units, sufficient to meet most of the electrical demand. To consume the abundant wind power, part of the load is transferred to this period. Subsequently, after 6:00, although the electrical load increases, the original load remains lower than the electric energy output of HRIES. Similarly, to increase the consumption of renewable energy, some loads are also transferred into this period. Accordingly, the actual electrical load after regulation is higher than the original electrical load during 0:00–12:00.

At 12:00–18:00, on the one hand, the decrease in wind velocity leads to a reduction in the output of the wind turbine; on the other hand, at the same time, the outdoor temperature rises, the heat load decreases, and the output of the CHP units also decreases accordingly. Consequently, a portion of the electrical load is transferred to reduce the actual electric demand. After 18:00, the electrical load and wind velocity show an upward trend. To optimize the overall performance of HRIES, part of the load is also transferred to the 0:00–12:00 period. As a result, the regulated electrical load is lower than the original load from 12:00–23:00.

In Case 3, where flexible heat load regulation is considered, the comparison between the regulated indoor temperature and the original temperature is shown in Figure 6. Due to the large output of wind turbines in HRIES during the 0:00–12:00 period, to reduce the output of gas-fired CHP units to increase the capacity for renewable consumption, the indoor temperature during this period is low. Hence, after 12:00, the outdoor temperature rises, the output of the wind turbine decreases, and the indoor temperature rises again.

It is noteworthy that indoor temperatures show a similar trend at a minimum total operating cost and a minimum renewable curtailment rate, with only a small difference at 13:00–17:00; Notably, when the output of the wind turbine is minimal, the indoor temperature under targeting a minimum renewable curtailment rate is greater than that under targeting the minimum total operating cost.

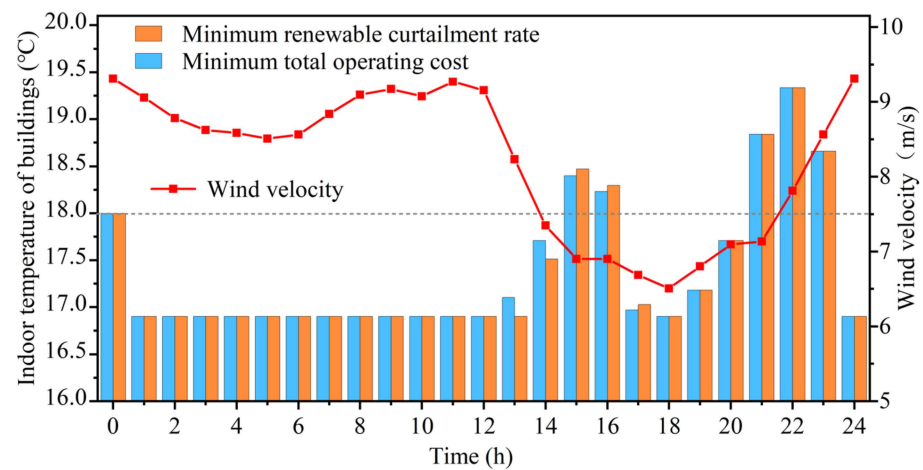


Figure 6. Optimal indoor temperature curve considered under flexible heat load regulation.

In addition, to analyze the effect of flexible electrical load and heat load regulation in reducing operating costs and boosting renewable consumption, the average efficiency and total natural gas consumption data of the gas-fired CHP unit during HRIES operation are extracted, as shown in Figures 7 and 8.

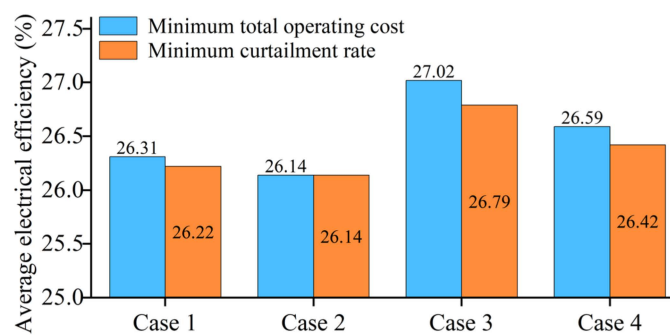


Figure 7. Average electrical efficiency of gas CHP units in four cases.

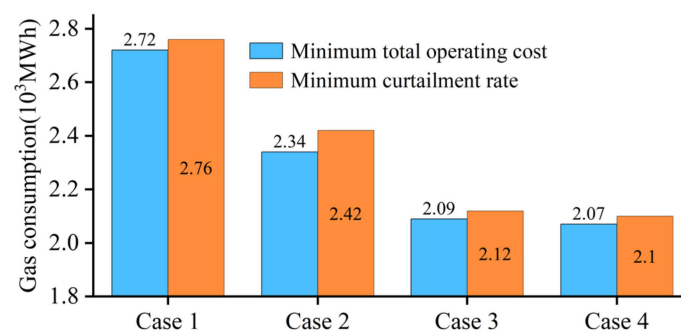


Figure 8. Total natural gas consumption of HRIES in the four cases.

According to Figure 7, when the operation optimization targets the minimum total cost, the average electrical efficiency of the gas-fired CHP unit in the original HRIES is 26.31%. If flexible electrical load regulation is considered in the operation optimization of HRIES (case 2), the average electrical efficiency will be reduced to 26.14%. Under the same load, this case needs to consume more natural gas. Nevertheless, the flexible electrical load regulation leads to a reduction in the renewable curtailment rate, enabling a portion of the electrical load to be supplied by wind turbines, resulting in a decrease in the total consumption of natural gas from 2.72×10^3 MWh in Case 1 to 2.34×10^3 MWh (Figure 8). The data again proves that flexible electrical load regulation reduces the total operating cost by increasing renewable energy consumption.

In contrast, when the flexible heat load is involved in the regulation, the average electrical efficiency of the gas-fired CHP units is increased to 27.02%. Coupled with the substitution of some renewable energy, the total natural gas consumption during system operation is reduced to 2.09×10^3 MWh. However, when the optimization pursues a minimum renewable curtailment rate, the average electricity efficiency will drop to 26.79%. As a result, relative to pursuing the minimum total operating cost, the total natural gas consumption increases to 2.12×10^3 MWh, resulting in the total operating cost increasing from 382.4 thousand Yuan to 386.0 thousand Yuan. These findings prove that the flexible heat load regulation reduces the total operating cost by coordinating the reduction in the renewable curtailment rate and the increase in the average electrical efficiency. Blindly pursuing the consumption of renewable energy will worsen the total operating cost.

For Case 4, which considers flexible regulation of both electrical load and heat load, the average electrical efficiency of the gas-fired CHP unit is improved compared with the case without considering flexible regulation due to the flexible regulation of heat load. This optimization coupled with the partial substitution of renewable energy results in a notable reduction in total natural gas consumption to 2.07×10^3 MWh. Moreover, similar to the case considering flexible heat load regulation alone, blindly pursuing the consumption of renewable energy will also reduce the average electrical efficiency of gas-fired CHP units, which in turn leads to an increase in natural gas consumption, an increase in energy purchase costs, and ultimately a deterioration in total operating costs.

6. Conclusions

Aiming at the problem of potential flexibility excavating in a hybrid renewable integrated energy system (HRIES), this paper proposes an operation optimization model considering flexible regulation of multiple loads and variable conditions of devices. The regulation mechanism of flexible electrical load and heat load is analyzed from the two perspectives of the minimum total operating cost and the minimum renewable curtailment rate. The conclusions are as follows:

- (1) Flexible electrical load increases the compatibility between load and renewable energy output by regulating the actual load curve of HRIES, thereby increasing the consumption of renewable energy. In addition, flexible electrical load regulation mainly reduces the total operating cost of HRIES by increasing renewable energy consumption.
- (2) The flexible heat load reduces the total operating cost of the system by coordinating the renewable energy consumption with the increase in the average electrical efficiency of the gas-fired CHP unit. Blindly pursuing renewable energy consumption will reduce the average power efficiency, which in turn worsens the total operating cost.
- (3) Flexible electrical load and heat load regulation have a saturation effect in improving the consumption of renewable energy during HRIES operation and a synergistic effect in reducing the total cost of the system, which can reduce the total cost by 0.73%.
- (4) If the regulation of flexible electrical and heat loads is considered in the operation optimization of HRIES, the total economic cost of the system will decrease by 15.13%, and the renewable energy curtailment rate will decrease by 12.08%.

The research proves that the flexible electrical and heat loads of the building can improve the energy efficiency of the hybrid renewable energy system and the consumption of renewable energy. Therefore, the future engineering practice of the scheduling operation and planning of the hybrid renewable energy system of buildings should deeply consider the impact of flexible loads in reducing operational costs and building carbon emissions. Additionally, a policy support mechanism including financial incentives and tax relief should be built by the government management department to encourage enterprises and institutions to adopt flexible regulation strategies. Moreover, considering the uncertainty fluctuation of renewable energy and loads, the operation optimization can be further improved by considering the adaptability of building infrastructures in diverse

environments and using uncertain optimization methods (e.g., stochastic optimization, robust optimization, and distributionally robust optimization).

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