

## Article

# Coordinated Optimal Dispatch of Electricity–Cooling–Storage Multi-Energy Systems in Commercial Building Clusters

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## Abstract

This study addresses the energy demand profiles of commercial buildings by developing an optimal dispatch strategy for a regional high-efficiency distributed energy system integrating electricity, cooling, and storage through source–load coordination. The spatio-temporal distribution characteristics of cooling, heating, and electrical loads are analyzed and an integrated energy system model is established, comprising gas internal combustion engine, a lithium bromide absorption chiller/heater, gas-fired boiler, centrifugal chillers, and an ice storage system. Taking into account seasonal electricity pricing policies and meteorological variations in Shanghai, a load grading system and a time-of-use (TOU) pricing response mechanism are constructed, leading to the development of operational strategy portfolios for different typical scenarios. A multi-objective optimization dispatch model is formulated with the dual aims of minimizing operating costs and maximizing energy efficiency. The results indicate that, compared to a fixed operational mode, the optimized strategy achieves average CO<sub>2</sub> emission reduction rates of 16.4% in summer, 25.2% in non-summer periods, and 20.9% annually. Additionally, annual grid electricity purchases are reduced by 10.2%, with a static investment payback period of 11.37 years. This research provides an intelligent, practically applicable operational solution for distributed energy systems in commercial buildings, effectively overcoming the limitations of traditional approaches in terms of flexibility and economic performance.

**Keywords:** electricity–cooling–storage integration; integrated energy system; source–load coordination; coordinated dispatch strategy

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## 1. Introduction

Energy is a fundamental prerequisite for human progress and forms an essential cornerstone of sustainable social development [1]. In recent years, energy consumption in commercial buildings has continued to rise, accounting for an increasing share of total urban energy use. Characterized by high energy density, significant load fluctuations, and spatiotemporal concentration of demand, commercial buildings pose serious challenges to the economy, security, and stability of regional energy systems [2–4]. Against this backdrop, achieving efficient energy utilization and low-carbon consumption has become an urgent issue in the energy field [5,6]. Although global climate governance and policy formulation have made some progress, the actual transition toward a low-carbon energy system remains slow due to the long-term socio-economic reliance on traditional fossil fuels [7,8]. Currently, countries worldwide are actively promoting the high-level and

large-scale development of renewable energy to accelerate the transformation of the energy structure [9–11].

Although the proportion of raw coal in China's energy mix continues to decline, it remains the dominant source, while the share of clean energy is steadily increasing, indicating an active transition of the energy system toward cleaner and lower-carbon development [12]. However, the traditional energy system still faces structural constraints, such as difficulties in multi-energy coordination and an imperfect market mechanism, which limit the improvement of overall system efficiency [13,14]. In response, China has proposed the "Dual Carbon" goals and elevated the construction of a clean, low-carbon, safe, and efficient energy system to a national strategic level [15]. Integrated energy systems, through the integration of renewable energy, efficient energy storage, and advanced energy management technologies, can achieve coordinated multi-energy supply. Nevertheless, their planning and operation are influenced by multiple factors, necessitating targeted modeling and optimization research [16,17]. Current studies have established a multi-level planning framework covering grid structure, demand-side response, energy storage, and virtual power plants, providing theoretical support and methodological foundations for the practical application of such systems [18].

Most existing research on integrated energy system operation optimization focuses on typical scenarios such as industrial parks and residential communities. However, for multi-objective coordinated scheduling schemes involving the coupling of ice storage cooling systems and photovoltaic self-consumption in commercial buildings, two significant limitations remain:

- (1) Most studies employ single-layer optimization frameworks with fixed weights, making it difficult to accommodate the strong time-variability and high volatility of heating and cooling loads driven by TOU electricity pricing mechanisms and customer traffic;
- (2) Current ice storage scheduling strategies are primarily designed for large-scale district energy stations and have not yet been adapted to the characteristics of medium- and small-sized commercial buildings—such as limited equipment capacity and compact system scale—through lightweight customization and constraint reconfiguration.

Building upon traditional multi-objective scheduling frameworks, this study innovatively introduces a time-varying hierarchical weighting mechanism driven by load dynamics and performs refined modeling and dynamic adjustment of constraints related to charging/discharging power and ice storage capacity. Not only has simulation validation been successfully conducted on a typical standalone commercial energy station, but the proposed scheduling model and optimization algorithm can also be extended to various types of commercial buildings, including office buildings, shopping malls, and urban complexes—demonstrating strong generality and engineering portability.

At present, domestic and international research on integrated energy systems with energy storage primarily focuses on areas such as optimal sizing of storage capacity, operational control strategies, efficient thermal storage technologies, and waste heat recovery. These topics have been explored in depth across multiple application scenarios [19]. Against the backdrop of enhancing power system flexibility in peak regulation and promoting wind power integration, well-designed peak-shaving compensation mechanisms play a key role in incentivizing CHP units to participate in system regulation. Li et al. [20] proposed a grid-friendly building energy system planning method that integrates temporary demand response with long-term TOU electricity pricing signals. By employing an improved Time GAN to generate stochastic peak-shaving scenarios and establishing a multi-scenario stochastic optimization model for coordinated design, this method signifi-

cantly enhances system peak-shaving capability and grid interaction performance without increasing costs. Jiang et al. [21] introduced an integrated system combining liquefied natural gas (LNG) cold energy, liquid air energy storage, and an air separation unit, which demonstrates its notable effectiveness in improving cold energy utilization efficiency, reducing operational costs, and enhancing synergy with grid peak-shaving operations. To address wind power fluctuation and thermal power peak-shaving pressure, Superchi et al. [22] proposed a coordinated optimization design framework based on mixed-integer linear programming (MILP) for hybrid energy systems integrating wind, photovoltaic, battery, and hydrogen storage. This approach enables simultaneous optimization of system sizing and operational strategies, effectively coordinating short- and long-term energy storage.

The economic viability of energy storage technologies and efficient energy management systems are critical to enabling the large-scale integration of renewable energy. Ameer et al. [23] developed a dynamic forecasting model based on meteorological data to optimize the dispatch of photovoltaic and energy storage systems, effectively enhancing the grid's ability to match residential loads and reducing reliance on peak thermal power. Emrani et al. [24] focused on hybrid wind–PV–storage systems, demonstrating that adaptive energy management strategies combined with predictive models significantly improve system economics and reliability. To address seasonal power mismatches and curtailment in wind–PV systems, Wen et al. [25] proposed a coordinated optimization method incorporating seasonal hydrogen storage. By establishing a bi-level programming model solved with a reformulation and decomposition algorithm, they effectively promoted renewable energy consumption, reducing the curtailment rate substantially from 38.71% to 5%. For improving the integrated management of electricity/hydrogen hybrid storage in off-grid wind–PV power systems, Sankar et al. constructed a multi-objective optimization framework centered on the Autonomous Energy Utilization Index (AEUI) and Electric Vehicle Utilization Index (EVUI). By using intelligent algorithms to co-optimize equipment sizing and electric vehicle charging/discharging, they achieved simultaneous improvements in economic performance and energy self-sufficiency. The transition to Hybrid Renewable Energy Systems (HRESs) is a crucial pathway toward a sustainable and low-carbon future. As highlighted in a literature review by Kaur [26], the integration of hydrogen, bioenergy optimization, AI-driven management, and hybrid energy storage is a key research direction for improving system efficiency and grid stability, though challenges related to cost, intermittency, and policy remain. Related studies indicate that the combination of predictive models and hybrid storage can enhance system design accuracy and renewable energy utilization, providing a technical pathway for the stable and economical operation of power grids with a high penetration of renewables.

This paper proposes a coordinated scheduling framework that clearly integrates cogeneration units with the power-cooling energy storage system. It overcomes the limitations of the commonly adopted single operation strategy in existing comprehensive energy system research and can achieve flexible source–load–storage coordination under the condition of time-varying electricity prices. At the same time, based on seasonal TOU electricity prices and real multi-energy load data, a price-responsive operation mechanism has been developed, enabling the scheduling strategy to dynamically adapt to the electricity price signals while still being applicable to actual commercial building energy stations, and having good practicability and applicability.

To address the limitations of existing combined cooling, heating and power (CCHP) systems with ice storage, which often rely on fixed operation strategies and struggle to balance TOU pricing responses with load fluctuations, this study proposes a dynamic optimization scheduling framework based on coordinated source–grid–load–storage inte-

gration. This framework enables real-time adjustment of output from gas internal combustion engines (ICE), lithium bromide chillers, centrifugal chillers, and ice storage systems in response to electricity price signals, achieving genuine “source–load interaction.” Unlike previous studies that treat ice storage merely as a backup for peak shaving and valley filling, this model incorporates ice storage as a decision variable within a multi-objective optimization framework. As a result, the system prioritizes ice-based cooling during high-price periods and actively produces and stores ice during off-peak hours, thereby maximizing both economic benefits and energy efficiency. Furthermore, addressing the common shortcoming of existing research that typically employs a single electricity pricing model, this study develops seasonally adapted operational strategy combinations based on actual differentiated TOU tariffs in Shanghai during summer and non-summer periods, significantly enhancing the practical applicability and scalability of the model in real-world commercial building energy stations.

Three mainstream dispatch frameworks are widely adopted for integrated energy systems, namely rule-based scheduling, single-objective optimization, and general multi-energy multi-objective optimization. Rule-based scheduling sets fixed manual operating logics guided by TOU electricity prices and load boundaries without iterative optimization, where the power outputs of gas generators, lithium bromide chillers and ice storage devices are predetermined. Nevertheless, static operation rules cannot dynamically respond to variable building loads, seasonal meteorological changes and tiered electricity tariffs; they only yield local optimal solutions and fail to simultaneously balance operational cost, carbon mitigation and peak-shaving targets, showing poor adaptability for commercial buildings with prominent peak–valley load gaps. Single-objective optimization only takes one indicator (minimum cost or maximum energy efficiency) as the optimization target while treating carbon emissions and peak regulation capacity as hard constraints. This method cannot reconcile economic benefits, low-carbon performance and grid support values: cost minimization will weaken carbon reduction and peak-shaving effects, whereas efficiency pursuit leads to sharp rises in gas and electricity expenditure, making it incapable of multi-dimensional evaluation for commercial energy stations.

Universal multi-energy multi-objective optimization constructs multi-target functions and solves Pareto-optimal solutions for industrial and residential parks with stable load characteristics. Such general frameworks lack customized cold balance constraints for commercial ice storage equipment and ignore seasonal disparities between cooling and heating demands in subtropical zones. In addition, they contain no dedicated response module for seasonal TOU pricing [8] and adopt oversimplified ice charging/discharging restrictions, which will lead to unsatisfactory operational performance when applied to commercial building clusters.

To quantitatively compare the inherent limitations of existing dispatch strategies and the targeted improvements of the method proposed in this paper, the core principles, drawbacks and optimization directions of three mainstream scheduling frameworks are summarized in Table 1.

**Table 1.** Comparison of existing and proposed scheduling models [27,28].

| Method Category       | Core Logic                                                     | Main Deficiencies                                                                                                                         | Improvements of the Proposed Model                                                              |
|-----------------------|----------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| Rule-based scheduling | Pre-set static operation rules without optimization iteration. | (1) Cannot adapt to dynamic loads, weather and TOU prices;<br>(2) Only local optimum;<br>(3) Poor for commercial large peak–valley loads. | (1) Adopt multi-objective optimization framework;<br>(2) Add load grading & TOU price response; |

|                                                   |                                                                 |                                                                                                                                                                                         |                                                                                                                                                                                                  |
|---------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Single-objective optimization                     | Optimize only one target; other indicators as hard constraints. | (1) Fail to balance economy, low-carbon and grid support;<br>(2) Cannot meet multi-dimensional evaluation of commercial energy stations.                                                | (3) Achieve global optimal balance of cost, carbon and peak shaving.                                                                                                                             |
|                                                   |                                                                 |                                                                                                                                                                                         | (1) Build dual-objective model: minimal cost & maximal efficiency;<br>(2) Multi-index collaborative optimization;<br>(3) Match full-dimension assessment of commercial clusters.                 |
| General multi-energy multi-objective optimization | Universal framework for industrial/residential parks.           | (1) Absence of dedicated ice storage constraints;<br>(2) Neglect of seasonal cooling–heating load gaps;<br>(3) Missing seasonal TOU modules, poor practicality in commercial buildings. | (1) Add independent ice storage cold balance constraints;<br>(2) Set seasonal load grading rules;<br>(3) Embed Shanghai seasonal TOU price module; calibrated with real commercial station data. |

As shown in Table 1, the three mainstream dispatch models are general frameworks lacking customization for commercial building electricity–cooling–storage systems. By contrast, this paper proposes a tailored multi-objective optimization framework for commercial clusters. It inherits the multi-energy collaborative optimization strengths of general models and introduces targeted improvements for commercial buildings' unique load features, seasonal TOU prices and ice storage limits, overcoming the poor applicability of conventional models in commercial integrated energy stations.

Existing integrated energy operation research mainly targets industrial and residential parks. Current multi-objective dispatch strategies combining ice storage and distributed generation for commercial buildings have two key drawbacks: (1) Fixed single-layer weight optimization fails to handle dramatic cooling/heating load fluctuations from passenger flow and seasonal weather; (2) existing ice storage schemes only fit large regional energy stations, without lightweight designs for capacity limits of small- and medium-sized commercial buildings.

Based on the conventional general multi-objective dispatch framework, this paper proposes a time-varying hierarchical weight mechanism and optimizes ice storage cold charge–discharge boundary constraints. Taking the commercial energy station in Shanghai Shibe High-Tech Zone for hourly simulation, the presented model and algorithm can be extended to offices, shopping malls and commercial complexes, possessing general engineering applicability rather than being limited to one single case.

## 2. System Mechanism and Mathematical Model

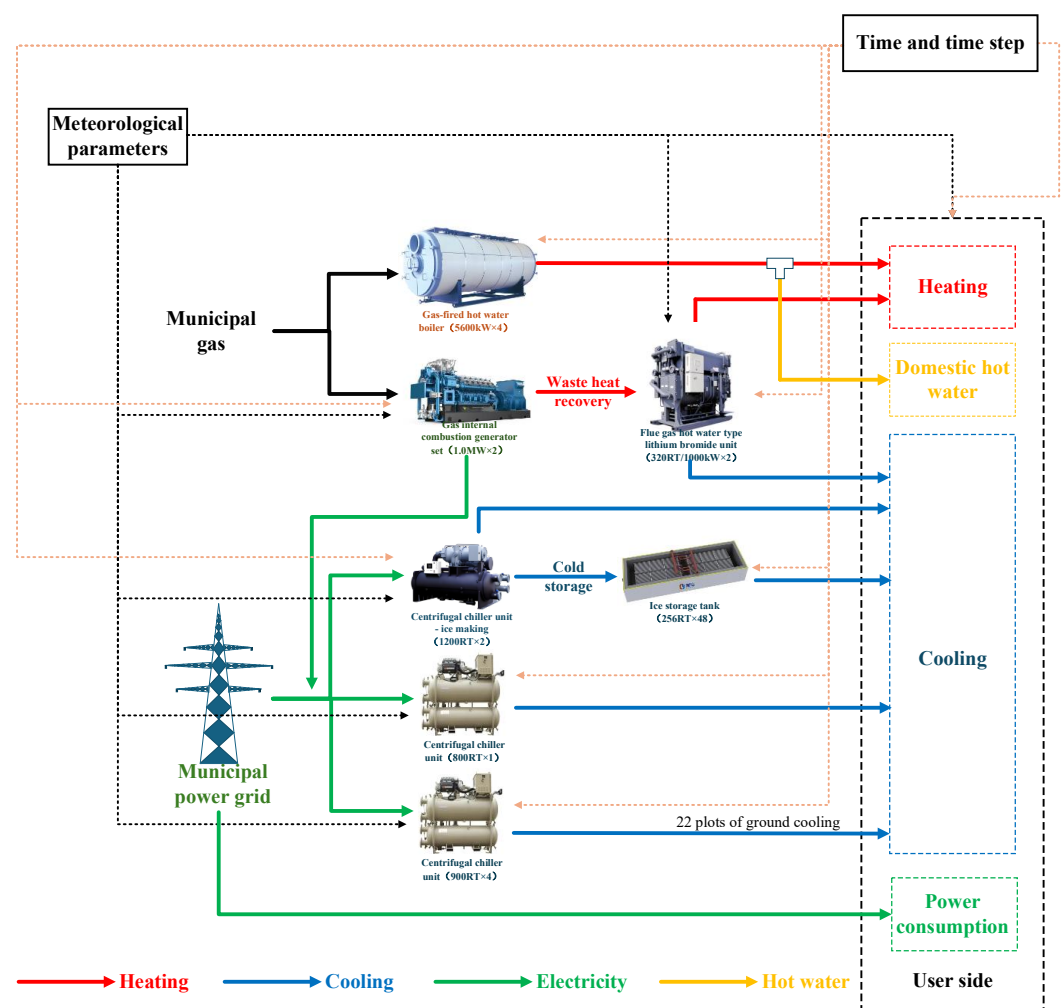
### 2.1. Operational Mechanism of the Integrated System

The regional high-efficiency electric cooling and heat storage coupled integrated energy system studied in this paper is a distributed energy system for commercial buildings, integrating power generation, cooling, heating and energy storage. Utilizing natural gas as the primary energy source, the system achieves CHP via gas-fired ICEs. It is further coupled with lithium bromide absorption chiller/heaters, electric chillers, gas-fired boilers, and ice storage units to establish an energy supply architecture characterized by multi-energy complementarity and cascaded utilization.

During off-peak electricity periods, the energy center prioritizes the operation of the CCHP system. The waste heat is directed to the lithium bromide absorption chiller for cooling, while the remaining cooling load is partially met by centrifugal chillers. The ice

storage system is utilized for peak load shaving. During valley electricity periods, ice-making machines are employed for cold storage, and chillers serve as direct cooling supply equipment.

The system stores cooling energy in ice storage tanks during valley electricity periods and utilizes this stored cold for peak shaving during peak demand periods. This strategy not only effectively reduces energy costs and energy expenditures, but also takes advantage of the typically higher proportion of clean energy sources during off-peak hours, thereby resulting in a relatively lower environmental impact. This approach contributes to the reduction of carbon emissions and minimizes other environmental effects. A schematic diagram illustrating the operational principles of the system is shown in Figure 1. Orange dotted line represents time-dependent energy flow affected by simulation time and time step; black dotted line represents meteorology-related energy flow affected by meteorological parameters.



**Figure 1.** Schematic diagram of system operational principles.

## 2.2. Mathematical Characterization of Equipment System

### 2.2.1. Operation Model of Lithium Bromide Unit

A lithium bromide absorption chiller is a heat-driven refrigeration device that utilizes a thermodynamic cycle. It uses water as the refrigerant and a lithium bromide solution as the absorbent, achieving refrigeration or heating cycles through the absorption and desorption of refrigerant vapor by the solution.

In this article, the performance coefficient (COP) of the lithium bromide absorption unit is defined as follows: For the cooling mode, COP is the ratio of the cooling capacity

to the sum of the heat input from the driving heat source and the power consumption of the auxiliary equipment; for the heating mode, COP is the ratio of the heating capacity to the sum of the heat input from the driving heat source and the power consumption of the auxiliary equipment.

The correlation for the  $COP_{LB,se}$  of the single-effect operation mode under refrigeration conditions is [29]

$$COP_{LB,se} = \frac{Q_{eva}}{Q_{gen} + W_{pump,se}} \quad (1)$$

The correlation for the  $COP_{LB,de}$  of the double-effect operation mode under refrigeration conditions is

$$COP_{LB,de} = \frac{Q_{LB,de}}{Q_{Flue} + Q_{Jacket} + W_{pump,de} + W_{cold}} \quad (2)$$

The correlation for the  $COP_{HC}$  under heating conditions is [30]

$$COP_{HC} = \frac{Q_{abs} + Q_{con}}{Q_{genh} + Q_{genl}} \quad (3)$$

The heat quantities in the above equations are calculated as follows:

$$Q_i = m_i c_{p,i} (t_{i,in} - t_{i,out}) \quad (4)$$

In practical applications, the COP for refrigeration and heating may vary depending on factors such as system design, operating conditions, and ambient temperature. Through these formulas, the energy efficiency performance of the flue gas and hot water-type lithium bromide unit under refrigeration and heating modes can be evaluated and compared.

### 2.2.2. Operation Model of Chiller Unit

The centrifugal chiller units of this system consist of base-load chillers and cold storage chillers. The base-load chillers operate continuously to provide a constant cooling capacity to meet daily refrigeration needs. They directly produce and supply chilled water according to the requirements of the building. The cold storage chillers operate during off-peak electricity periods like at night to store cooling capacity in the ice storage tanks. The chiller units of this system can utilize electricity during off-peak periods to reduce electricity costs and balance the power load.

The  $COP_{CM,bl}$  of the base-load chiller model is expressed as

$$COP_{CM,bl} = \frac{Q_{zl}(i)}{P_{zl}(i)} \quad (5)$$

The  $COP_{CM,cs}$  of the cold storage chiller model is expressed as

$$COP_{CM,cs} = a_0 Q_{zl}(i) + a_1 T_{ei} + a_2 T_{ci} \quad (6)$$

### 2.2.3. Operation Model of Ice Storage Tank

Based on the operational monitoring data collected from the equipment room, the relationship between the  $COP_{ISS}$  of the entire ice storage system (including water pumps and other transmission and distribution equipment) during the ice-making period and the load rate can be obtained. The derived formula is

$$COP_{ISS} = -1.6268R_L^2 + 3.3359R_L + 1.7248 \quad (7)$$

The maximum cold storage capacity of the ice storage tank adopted in this project's ice storage system is 932 kWh. According to the empirical formula, the maximum ice-melting rate of the ice storage tank at time  $t$  is

$$Q_t = 21390 \cdot (1 - \frac{Q_{t,s}}{48176}) \quad (8)$$

#### 2.2.4. Operation Model of Gas Internal Combustion Generator Set

The ICE is the core energy conversion device of the CCHP system. This paper adopts the ICE model based on the cogeneration system developed by the International Energy Agency's "Annex 42" project and verified worldwide. The model is based on the principles of energy and mass conservation, and a dynamic model of the ICE cogeneration unit is established using three control volumes: the energy conversion control volume, the heat engine control volume, and the cooling water control volume.

In the energy conversion control volume, the chemical energy of fuel and air is converted into electrical energy, recoverable thermal energy, and exhaust gas emission energy. Its energy balance equation is as follows:

$$\dot{H}_{\text{fuel}} + \dot{H}_{\text{air}} = P_{\text{ice,ss}} + Q_{\text{ice,ss}} + \dot{H}_{\text{exh}} \quad (9)$$

If the total energy input to the energy conversion control volume is  $Q_{\text{ice,gross}}$ , the steady-state operating output power of the ICE can be obtained.

$$P_{\text{ice,ss}} = \eta_e Q_{\text{ice,gross}} \quad (10)$$

$$Q_{\text{ice,ss}} = \eta_q Q_{\text{ice,gross}} \quad (11)$$

$$Q_{\text{ice,gross}} = m_{\text{fuel}} \cdot LHV_{\text{fuel}} \quad (12)$$

The efficiency of the gas internal combustion unit model is expressed as

$$\eta_{\text{ice}} = \frac{P_{\text{ice,ss}} + Q_{\text{ice,ss}}}{Q_{\text{ice,gross}}} \quad (13)$$

#### 2.2.5. Operation Model of Gas Boiler

A gas boiler generates thermal energy by burning natural gas. Its combustion products are mainly carbon dioxide and water vapor. The thermal efficiency calculation of a gas boiler is often based on the lower heating value (LHV) because the gas is usually discharged in the form of gas after combustion, which does not involve the latent heat of condensation of water vapor. Moreover, the exhaust gas temperature of a gas boiler is relatively low, and the heat loss is relatively small. Compared with traditional heating equipment, gas boilers can usually convert fuel energy into thermal energy with higher energy efficiency, thereby saving energy and operating costs. The calculation parameters of the gas boiler adopted in this system are shown in Table 2 below.

**Table 2.** Boiler calculation parameters.

| Parameter                       | Symbol              | Unit                            | Value      | Remark    |
|---------------------------------|---------------------|---------------------------------|------------|-----------|
| Boiler Evaporation Capacity     | $A$                 | MW                              | 29.00      | -         |
| Boiler Circulation Water Flow   | $D$                 | kg/h                            | 831,333.33 | -         |
| Boiler Rated Efficiency         | $\eta$              | %                               | 92.00      | -         |
| LHV of Gas                      | $Q_{\text{net,ar}}$ | -                               | 35,169     | -         |
| Feed Water Temperature          | -                   | °C                              | 100.00     | -         |
| Return Water Enthalpy           | $i_h$               | kJ/kg                           | 289.30     | -         |
| Boiler Gas Consumption          | $B$                 | Nm <sup>3</sup> /h              | 3953.02    | -         |
| Theoretical Air Requirement     | $V_0$               | Nm <sup>3</sup> /m <sup>3</sup> | 8.89       | -         |
| Excess Air Coefficient $\alpha$ | -                   | -                               | 1.10       | 1.05~1.20 |
| Return Water Temperature        | -                   | °C                              | 70.00      | -         |

|                       |                               |                    |           |           |
|-----------------------|-------------------------------|--------------------|-----------|-----------|
| Feed Water Enthalpy   | $i_s$                         | kJ/kg              | 417.51    | -         |
| Richness Coefficient  | $K$                           | -                  | 1.20      | 1.20~1.30 |
| Total Boiler Air Flow | $V_2 = V_1 \times B \div 1.3$ | Nm <sup>3</sup> /h | 38,673.85 | -         |
| Actual Air Flow       | $V_1 = V_0 \times \alpha$     | Nm <sup>3</sup> /h | 9.78      | -         |
| Rated Power           | -                             | MW                 | 3535.74   | -         |

Symbol definition is shown in Appendix A.

The boiler efficiency is calculated according to the following formula:

$$\eta_b = 100 - (q_2 + q_3 + q_5) \quad (14)$$

Carbon monoxide (CO) in flue gas is a characteristic product of incomplete gas combustion. Under insufficient oxygen or poor fuel–air mixing, methane cannot be fully oxidized into CO<sub>2</sub>, and a large amount of combustible CO is discharged with flue gas, resulting in irreversible heat loss. The volumetric fraction of CO in flue gas directly governs the incomplete combustion heat loss coefficient  $q_3$ ; therefore, the CO volume fraction is adopted to quantify  $q_3$  in the heat balance calculation of gas boilers. It can be obtained by looking up Table 3. The main factor affecting the boiler inverse balance thermal efficiency is  $q_2$ , the exhaust gas heat loss. The exhaust gas heat loss is the largest component of the heat loss of a gas boiler, accounting for 80% of the total loss.

**Table 3.** Unburned gas heat loss.

| Parameter             | Symbol | Unit | Corresponding Relationship |                 |          |
|-----------------------|--------|------|----------------------------|-----------------|----------|
| CO Volume Fraction    | CO     | %    | CO ≤ 0.05                  | 0.05 < CO ≤ 0.1 | 0.1 < CO |
| Heat Loss Coefficient | $q_3$  | %    | 0.2                        | 0.5             | 1        |

The formula for calculating the exhaust gas heat loss  $q_2$  of the gas boiler thermal efficiency is as follows:

$$q_2 = (m + n\alpha_{ds}) \left( \frac{t_{ds} - t_{ca}}{100} \right) \quad (15)$$

For  $q_5$ , it can be obtained by looking up Table 4 below; the  $q_5$  value for a 29 MW boiler is 1.1%. The main factors affecting  $q_2$  are the excess air coefficient at the exhaust gas outlet, the exhaust gas temperature, and the air intake temperature. In the actual operation test of the boiler, H<sub>2</sub> and CH<sub>4</sub> in the flue gas are basically 0; the N<sub>2</sub> content in the gas composition is below 1%, and its impact on the excess air coefficient  $\alpha_{ds}$  is very small, so the calculation of the excess air coefficient can be simplified as the following formula:

$$\alpha_{ds} = \frac{21}{21 - O_2'} \quad (16)$$

where  $O_2'$  is the volume fraction of gas at the exhaust gas outlet, %.

**Table 4.** Heat dissipation loss of gas boiler.

| Rated Evaporation Capacity (t/h)<br>(or Rated Thermal Power (MW)) | ≤4<br>(or ≤2.8) | 6<br>(or 4.2) | 10<br>(or 7.0) | 15<br>(or 10.5) | 20<br>(or 14) | 35<br>(or 29) | 65<br>(or 46) |
|-------------------------------------------------------------------|-----------------|---------------|----------------|-----------------|---------------|---------------|---------------|
| Heat Dissipation Loss $q_5$ (%)                                   | 2.9             | 2.4           | 1.7            | 1.5             | 1.3           | 1.1           | 0.8           |

As illustrated in Table 4, the surface heat dissipation loss  $q_5$  is determined by the rated thermal power of the gas boiler. Taking the 29 MW boiler adopted in this study as an example, its rated thermal power corresponds to the 35 t/h evaporation capacity column in Table 4, and the matching  $q_5$  value is 1.1%. For other boiler specifications, the  $q_5$  loss can

be directly queried according to the corresponding rated evaporation capacity or thermal power in the table.

During the combustion of coal, hydrogen reacts with oxygen to produce water vapor. The latent heat released during the condensation of this vapor from a gaseous to a liquid state is accounted for in the higher heating value but is excluded from the LHV. This distinction arises because, in practical applications, the water vapor typically remains in the gaseous phase and is discharged directly with the flue gas, rather than being condensed.

### 2.3. Model Validity Verification

Considering that this paper does not carry out on-site measurement experiments, the model validity is verified by horizontal comparison with two mature benchmark scheduling schemes from published ice storage research [31,32], which can effectively reflect the performance advantages of the proposed time-varying hierarchical multi-objective optimization framework.

For model validation, two classic ice storage scheduling strategies from prior research [31,32] are adopted as benchmark cases. Their load scales, building types and TOU price configurations align with the commercial cluster investigated in this paper, enabling equitable horizontal comparisons. The two baseline schemes consist of a fixed-time rule-based ice storage strategy and a single-objective cost minimization model that disregards energy efficiency and carbon emission objectives. Drawing on annual hourly load datasets and Shanghai TOU tariff parameters from existing literature [33,34], this study compares the three scheduling approaches across three core evaluation metrics: annual grid electricity purchase volume, total annual operating expenditure, and total annual carbon emissions. The comparative results clearly reveal the significant advantages of the proposed multi-objective dispatch framework. All equipment capacity parameters, annual cooling and heating load curves, and electricity price inputs follow the unified simulation benchmark parameters adopted in existing research [33,34]. In addition, the configuration of simulation boundaries adheres to well-established paradigms for commercial building energy simulations, which ensures the credibility of all simulation outputs.

To quantitatively visualize the performance gaps between the two classical benchmark scheduling strategies and the proposed multi-objective dispatch model, Table 5 compares the three schemes from three core evaluation dimensions, including annual purchased electricity, total annual operating cost and total annual carbon emissions.

**Table 5.** Comparison between literature benchmarks and proposed scheme.

| Index Metric                       | Rule-Based Strategy  | Single-Objective Optimization | Proposed Multi-Objective Model |
|------------------------------------|----------------------|-------------------------------|--------------------------------|
| Annual purchased electricity (MWh) | 14,628.6             | 12,957.3                      | 11,405.2                       |
| Total annual operating cost (CNY)  | $286.52 \times 10^4$ | $241.37 \times 10^4$          | $208.94 \times 10^4$           |
| Annual total carbon emission (t)   | 3241.7               | 2906.5                        | 2513.8                         |

## 3. System Operation Strategies and Evaluation Indicators

### 3.1. Baseline Operation Mode

The baseline operation mode represents a traditional and static energy dispatch paradigm, and the principle of this model is shown in Figure 2. The system prioritizes gas ICEs to provide basic electrical load and fully utilizes their power generation waste heat

to drive lithium bromide units for refrigeration or heating, thereby achieving cascade utilization of energy. For the remaining cooling and heating loads that cannot be met by the waste heat of the ICE, they are supplemented by electric centrifugal chillers and gas boilers, respectively. The domestic hot water load is independently guaranteed by a dedicated gas boiler. This mode adopts a consistent annual operation strategy, only switching between refrigeration and heating modes according to the season, and the dispatch algorithm does not involve TOU electricity prices.

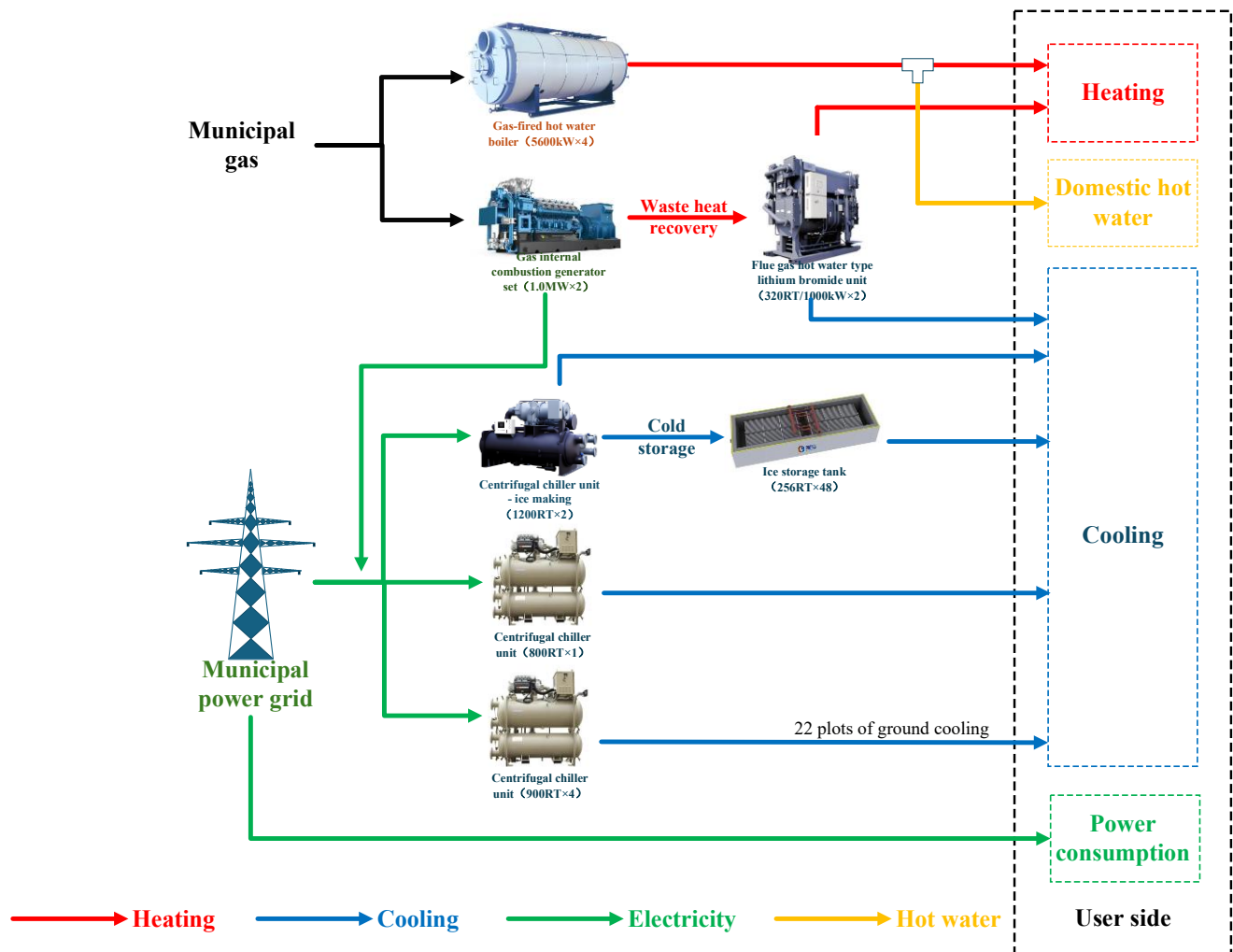
The fundamental characteristic of the baseline mode is heat-led power generation—the power output of the gas engine is determined by the heat demand required to drive the lithium bromide unit, rather than by the electrical load or electricity price signals. This fixed logic disregards the incentive effects of TOU tariffs and the time-varying nature of loads, resulting in suboptimal economic and environmental performance.

To rigorously validate the effectiveness of the proposed multi-objective optimal dispatch strategy, the baseline and optimized operation modes are simulated under identical external boundary conditions. The key consistency conditions are detailed below:

- (1) System boundaries and equipment capacities: Both modes employ the identical equipment configuration and rated parameters. The system comprises two 1000 kW gas-fired ICE generator sets, two flue gas-fired lithium bromide absorption chillers/heaters, four 5600 kW gas-fired hot water boilers, two 4220 kW centrifugal chillers for ice making, one 2814 kW and four 3165 kW centrifugal chillers for direct cooling, and 48 ice storage tanks each with a capacity of 932 kWh. The active/inactive status of all equipment remains the same across both modes.
- (2) Load profiles: Both modes use the same hourly cooling, heating, and electrical load input data, derived from the 8760 h annual dynamic load simulation of the commercial building cluster in the Shanghai Shibe High-Tech Zone.
- (3) TOU electricity tariffs: Both modes adopt the identical seasonal TOU electricity pricing policy of Shanghai, with the same peak, flat, and off-peak period divisions and tariff rates for summer and non-summer periods. The peak, flat, and off-peak prices are 0.916 CNY/kWh, 0.567 CNY/kWh, and 0.213 CNY/kWh, respectively.
- (4) Carbon emission factors: Both modes share the same emission calculation parameters—the CO<sub>2</sub> emission factor for purchased electricity is 0.94 kg/kWh, and the CO<sub>2</sub> emission factor for natural gas combustion is 0.202 kg/kWh.

The baseline simulation program is constructed as follows: based on the 8760 h annual load data, at each time step, the gas engine power output and recoverable waste heat are first calculated under rated or near-rated operating conditions; then the cooling/heating output of the lithium bromide unit is determined from its thermodynamic characteristics; subsequently, the remaining cooling/heating loads are sequentially allocated to centrifugal chillers or gas boilers; and finally, the annual grid electricity purchases, natural gas consumption, and various emissions are aggregated. This program contains no optimization iterations, no search of decision variables, and no objective function evaluation—its logic strictly follows the fixed-priority rules described in Section 3.1 and illustrated in Figure 2.

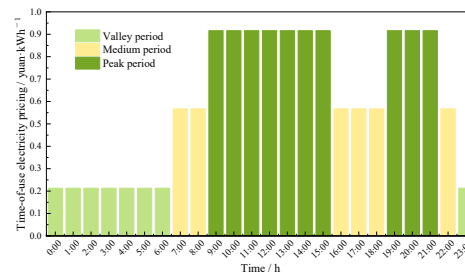
The optimized simulation program is built upon the same framework but embeds the multi-objective optimal dispatch model formulated in Section 3.4, employing the Non-dominated Sorting Genetic Algorithm II (NSGA-II) algorithm to optimize the decision variables on an hourly basis. Except for the dispatch strategy, all external boundary conditions remain strictly identical between the two modes, ensuring that the comparative results reflect only the performance difference attributable to the scheduling strategy itself.



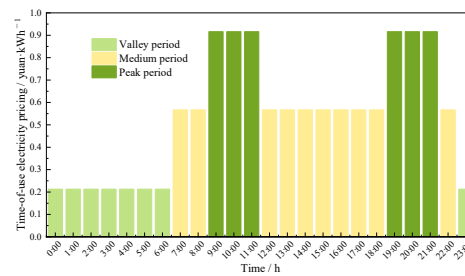
**Figure 2.** Schematic diagram of the baseline system.

### 3.2. Electricity Price Policy and Operation Strategy

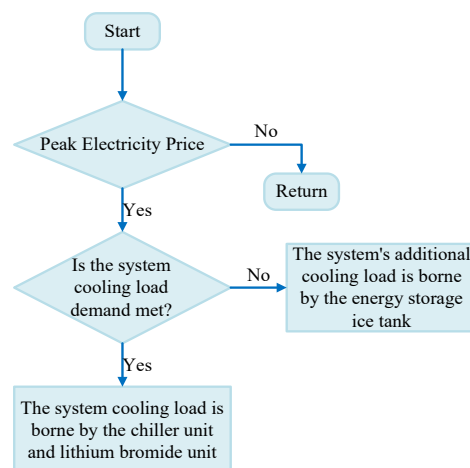
This paper provides the TOU electricity prices in Shanghai, which are divided into two different pricing standards according to the season—summer and non-summer—as shown in Figures 3 and 4. The prices for peak, flat, and off-peak periods are 0.916 CNY/(kWh), 0.567 CNY/(kWh), and 0.213 CNY/(kWh), respectively. The difference between summer and non-summer lies in the distribution of peak, flat, and off-peak times; the peak period in summer is four hours longer than that in non-summer. The flat and off-peak electricity price periods in summer are from 21:00 to 8:00 the next day and from 16:00 to 17:00. During this period, the equipment is usually in the rest stage, consuming less electricity but with very low electricity prices, so the ice storage device is turned on to store the cooling capacity needed for the peak period. The peak electricity price periods in summer are from 9:00 to 15:00 and from 18:00 to 20:00. The building cooling and power loads reach their peak during peak-price hours, and the user's power load reaches its peak. The power taken from the power grid is reduced and the cooling capacity stored in the ice storage tank is used during the flat and off-peak electricity price periods. According to the different TOU electricity prices in Shanghai, the flow charts of the power distribution strategy based on peak and off-peak operation are shown in Figures 5 and 6, and the overall operation flow block diagram of the system is shown in Figure 7.



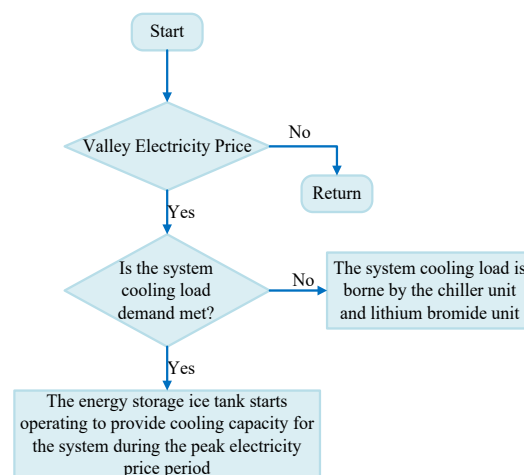
**Figure 3.** Summer TOU electricity prices in Shanghai area.



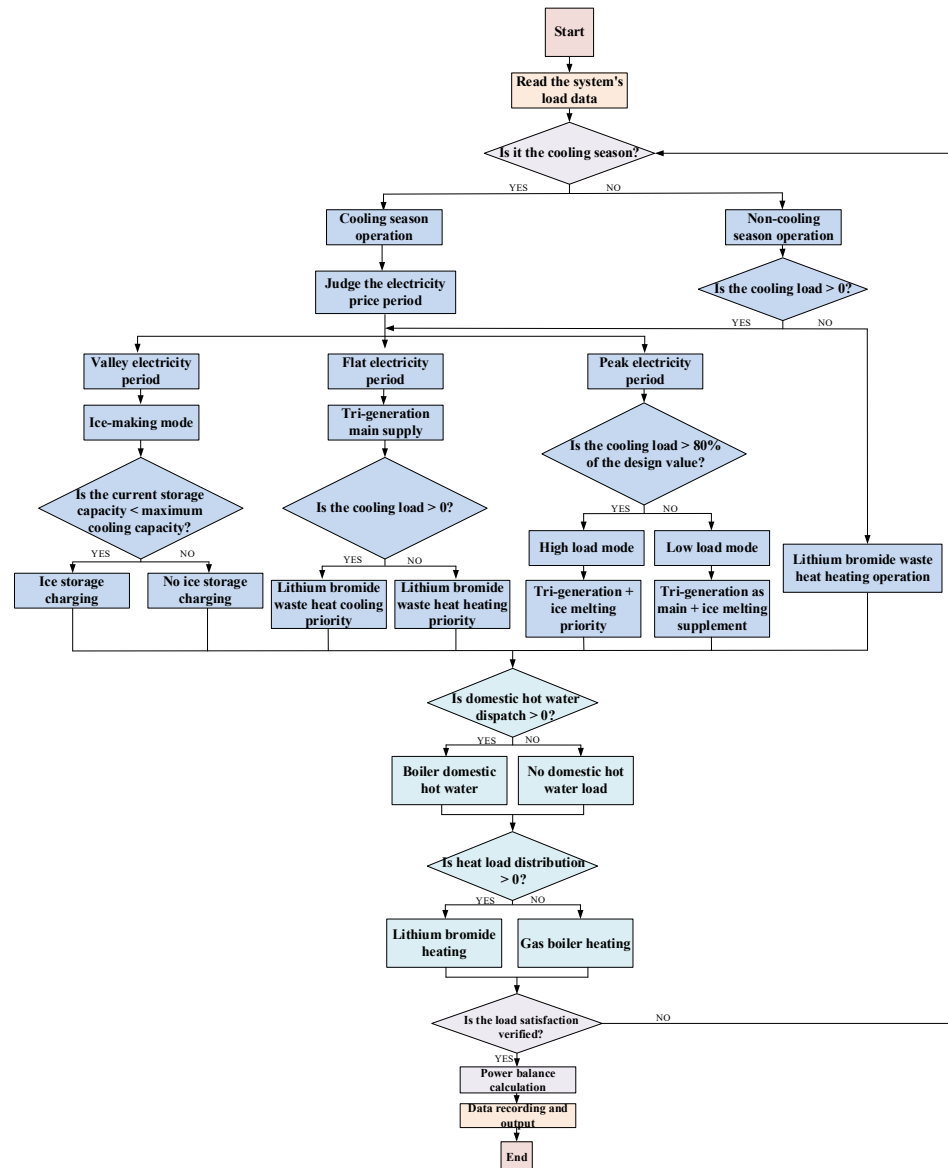
**Figure 4.** Non-summer TOU electricity prices in Shanghai area.



**Figure 5.** Operation strategy flow chart for peak electricity price periods.



**Figure 6.** Operation strategy flow chart for flat and off-peak electricity price periods.



**Figure 7.** System operation flow block diagram.

### 3.3. Evaluation Indicators

To quantitatively evaluate the economic, energy-saving and low-carbon performance of the electricity–cooling–storage coupled system for commercial building clusters, three categories of evaluation indices are defined in this section: thermodynamic indices, environmental performance indices, and economic benefit indices. The corresponding calculation formulas are presented below.

#### 3.3.1. Thermodynamic Evaluation Indicators

The system thermal efficiency is calculated as follows:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad (17)$$

The calculation formula is as follows:

$$W_{net} = W_{turbine} - W_{LPC} \quad (18)$$

The cooling system coefficient is calculated as follows:

$$CORP = \frac{Q_{eva}}{W_{LPC}} \quad (19)$$

The system comprehensive energy conversion efficiency Comprehensive Energy Utilization Factor (EUF) is calculated as follows:

$$EUF = \frac{W_{net} + Q_{eva}}{Q_{in}} \quad (20)$$

### 3.3.2. Environmental Performance Evaluation Indicators

This paper mainly analyzes the CO<sub>2</sub> emissions caused by natural gas combustion during system operation, and the emission amount is calculated based on existing prediction models:

$$m_y = u_y E \quad (21)$$

The composition of CO<sub>2</sub> emissions  $m_{CO_2}^{TS}$  from the traditional greenhouse energy supply system is as follows:

$$m_{CO_2}^{TS} = m_{CO_2,coal,e}^{TS} + m_{CO_2,coal,h}^{TS} \quad (22)$$

The CO<sub>2</sub> composition of the designed system considering emission reduction:

$$m_{CO_2}^{CES} = m_{CO_2,coal,e}^{CES} + m_{CO_2,boiler}^{CES} \quad (23)$$

The Carbon Dioxide Emission-Saving Ratio can more intuitively evaluate the environmental benefits of the system:

$$CESR = \frac{m_{CO_2}^{TS} - m_{CO_2}^{CES}}{m_{CO_2}^{TS}} \quad (24)$$

In the calculation, the CO<sub>2</sub> emission factor for electricity purchased from the grid is set at 0.94 kg/kWh. The CO<sub>2</sub> emission factor for natural gas combustion is set at 0.202 kg/kWh [35]. This model uses the annual average grid emission factor for the calculation.

### 3.3.3. Economic Benefit Evaluation Indicators

Static payback period and one-time initial investment are selected as the economic evaluation indices of the proposed integrated energy system. The payback period is defined as follows:

$$\left\{ \begin{array}{l} \sum_{j=1}^{[PP]} NP_j < IC_{total} \leq \sum_{j=1}^{[PP]+1} NP_j \\ PP = [PP] + \frac{IC_{total} - \sum_{j=1}^{[PP]} NP_j}{NP_{[PP+1]}} \end{array} \right. \quad (25)$$

The initial investment of the all-electric energy system includes the investment in the equipment and pipeline system within the system, and the calculation formula is as follows:

$$IC_{total}^{CES} = IC_{lbu} + IC_{ice} + IC_{chill} + IC_b \quad (26)$$

### 3.4. Multi-Objective Optimal Dispatch Model

Based on the equipment operation characteristics and evaluation indexes above, this section constructs a complete multi-objective optimal dispatch model, which is divided into decision variables, multi-objective functions, system operation constraints and solution algorithm.

#### 3.4.1. Decision Variables

The optimized variables cover the hourly output of all energy supply and storage equipment within the scheduling period, with standardized unit definitions cross-referenced to Appendix A.1. All time-varying variables are marked with hourly time index  $t$ :

- (1) Gas ICE power  $P_{ICE}(t)$ :  $0 \leq P_{ICE}(t) \leq P_{ICE,max}$ ;
- (2) Ice storage charging cooling capacity  $Q_{ice,ch}(t)$ :  $0 \leq Q_{ice,ch}(t) \leq Q_{ice,ch,max}$ ;
- (3) Ice storage discharging cooling capacity  $Q_{ice,dis}(t)$ :  $0 \leq Q_{ice,dis}(t) \leq Q_{ice,dis,max}$ ;
- (4) Lithium bromide chiller output  $Q_{LB}(t)$ :  $0 \leq Q_{LB}(t) \leq Q_{LB,max}$ ;
- (5) Grid purchased power  $P_{grid}(t)$ :  $P_{grid}(t) \geq 0$ ;
- (6) Centrifugal chiller total cooling output  $Q_{cc}(t)$ :  $0 \leq Q_{cc}(t) \leq Q_{cc,max}$ ;
- (7) Centrifugal chiller total power consumption  $P_{cc}(t)$ :  $0 \leq P_{cc}(t) \leq P_{cc,max}$ ;
- (8) Gas boiler heat supply output  $Q_b(t)$ :  $0 \leq Q_b(t) \leq Q_{b,max}$ .

#### 3.4.2. Multi-Objective Function

Two conflicting core optimization objectives with clear dimensional labels are established; carbon emission and peak-shaving capacity serve as auxiliary evaluation indicators. All annual cumulative terms adopt the full-year summation operator  $\sum_{t=1}^{8760}$  to explicitly represent the 8760 h hourly simulation step:

Objective 1: Minimize the annual total operating cost

$$\min F_1 = \sum_{t=1}^{8760} (c_{ele}(t)P_{grid}(t) + c_{gas}F_{ICE}(t) - I_{peak}(t)) \quad (27)$$

Objective 2: Maximize the system comprehensive energy efficiency

$$\max F_2 = \frac{\sum_{t=1}^{8760} (Q_{LB}(t) + Q_{ice,dis}(t))}{\sum_{t=1}^{8760} (P_{grid}(t) + F_{ICE}(t) \cdot LHV_{fuel})} \quad (28)$$

#### 3.4.3. System Constraints

All physical balance and equipment operation limits are divided into four constraint groups with complete coupling equations and unified unit specifications for all variables:

- (1) Electric power balance constraint

$$P_{ICE}(t) + P_{grid}(t) = P_{load}(t) + P_{chiller}(t) + W_{pump}(t) \quad (29)$$

- (2) Cooling supply and demand balance constraint

$$Q_{LB}(t) + Q_{ice,dis}(t) + Q_{cc}(t) = Q_{cool,load}(t) + Q_{ice,ch}(t) \quad (30)$$

- (3) Heating supply–demand balance constraint

$$Q_{LB,h}(t) + Q_b(t) = Q_{heat,load}(t) \quad (31)$$

- (4) Domestic hot water balance constraint

$$Q_{b,DHW}(t) + Q_{LB,DHW}(t) = Q_{DHW,load}(t) \quad (32)$$

(5) Ice storage cold capacity balance constraint

$$E_{ice}(t+1) = E_{ice}(t) + Q_{ice,ch}(t) \cdot \eta_{ch} - \frac{Q_{ice,dis}(t)}{\eta_{dis}} \quad (33)$$

$$0 \leq E_{ice}(t) \leq E_{ice,max} \quad (34)$$

(6) Unit output and ramp rate constraints

$$-\Delta P_{max} \leq P_{ICE}(t+1) - P_{ICE}(t) \leq \Delta P_{max} \quad (35)$$

Each cooling and power generation unit is restricted by maximum output and hourly climbing rate to conform to actual engineering operation characteristics.

#### 3.4.4. Solution Algorithm

The NSGA-II multi-objective optimization algorithm is employed to solve the established model, where an internal linear programming solver is embedded to verify hourly operation constraints. Full algorithm parameter configurations and termination criteria are supplemented below:

- (1) Algorithm parameters: Population size of 100, maximum iteration count of 150, crossover probability of 0.7, mutation probability of 0.1;
- (2) Termination criterion: The Pareto front exhibits no significant variation over 20 successive iterations;
- (3) Optimal strategy selection: The comprehensive satisfaction degree of each Pareto solution is calculated to select the compromise optimal dispatch scheme applicable to commercial building clusters.

#### 3.4.5. Detailed Implementation of Multi-Objective Optimization

(1) Decision variable encoding:

Each individual in the NSGA-II population is encoded as a real-valued vector comprising the hourly setpoints of all adjustable equipment over the scheduling horizon. For a typical 24 h horizon, the vector includes  $P_{ICE}(t)$ ,  $Q_{ice,ch}(t)$ ,  $Q_{ice,dis}(t)$ ,  $Q_{LB}(t)$ ,  $P_{grid}(t)$ ,  $P_{cc}(t)$ , and  $Q_b(t)$  for  $t = 1, \dots, T$  ( $T = 24$  for daily scheduling; for annual simulations, the daily optimized schedules are applied to corresponding typical days with seasonal weighting). Each variable is bounded within its physical limits as specified in Section 3.4.1.

(2) Constraint handling:

A penalty function approach is adopted to handle the system constraints. The total constraint violation  $V$  is computed as the sum of normalized violations of all equality and inequality constraints (power balance, cooling/heating/DHW balances, ice storage capacity, and ramp limits). The fitness of each individual is then evaluated by augmenting the two original objectives with a large penalty term:

$$F_1 = F_1 + \lambda V \quad (36)$$

$$F_2 = F_2 - \lambda V \quad (37)$$

(3) Pareto front screening:

After the NSGA-II terminates (maximum 150 generations or no improvement in hypervolume for 20 generations), the final population is sorted by nondominated sorting. All nondominated individuals constitute the Pareto-optimal set. To maintain diversity,

the crowding distance is computed for each solution, and the front is truncated to a maximum of 100 solutions by retaining those with larger crowding distances.

(4) Comprehensive satisfaction index for final solution selection:

Since the Pareto front contains multiple trade-off solutions; a decision-making criterion is required to select one compromise dispatch scheme for practical implementation. For each Pareto solution  $j$  ( $j = 1, \dots, N$ ), we define the normalized satisfaction degrees for the two objectives as

$$\mu_{1,j} = \frac{F_{1,\max} - F_{1,j}}{F_{1,\max} - F_{1,\min}} \quad (38)$$

$$\mu_{2,j} = \frac{F_{2,j} - F_{2,\min}}{F_{2,\max} - F_{2,\min}} \quad (39)$$

Then the comprehensive satisfaction index of solution  $j$  is defined as

$$Q_{b,DHW}(t) + Q_{LB,DHW}(t) = Q_{DHW,load}(t) \quad (40)$$

The above procedure ensures a complete multi-objective optimization solution. Through the nondominated sorting and crowding distance mechanisms of NSGA-II, a diverse set of nondominated solutions on the Pareto front is maintained. The penalty function strictly enforces all physical and operational constraints, ensuring that the converged candidate solutions are all feasible. The termination criteria (maximum generations and stagnation detection) guarantee convergence to a stable Pareto front. The comprehensive satisfaction index provides a transparent and reproducible method for extracting a compromise solution from the Pareto set, thus closing the loop from optimization to decision-making. The proposed framework has therefore fully accomplished multi-objective optimal dispatch.

## 4. Analysis of System Operation Characteristics

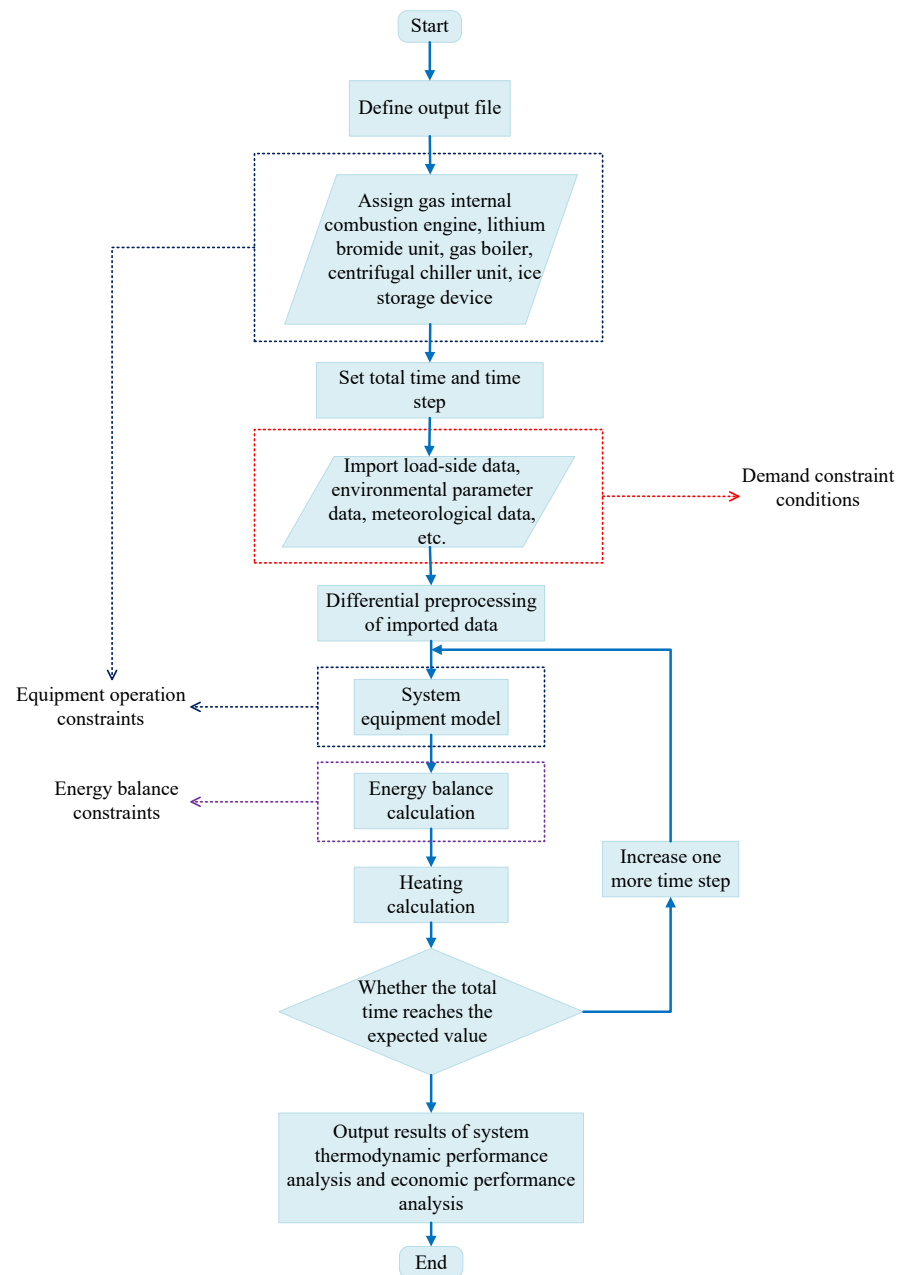
This design involves collaborative operation and conversion among various types of equipment during the operation process; therefore, its operation is affected by multiple factors. Combined with relevant parameters, a simulation analysis was carried out on the hourly dynamic cooling and heating loads of the building throughout the year and on typical days. Subsequently, a simulation program was compiled in conjunction with the operation strategy to conduct performance analysis of the energy system, as well as dynamic performance analysis of the system over the whole year and on typical days. The system program block diagram and constraints are shown in Figure 8. Solid arrows represent program execution flow, while dashed arrows denote constraint annotation links.

Figure 9 shows the hourly dynamic cooling and heating loads of the building throughout the year. The hourly cooling and heating loads on the typical winter day (15 January) and typical summer day (15 July) are presented in Figure 9. Affected by climate and other factors on the load, the annual peak cooling load of the typical building is much higher than the annual peak heating load. According to the load analysis of typical days, since Shanghai is in a subtropical monsoon climate zone, more cooling capacity is often required in buildings to remove indoor heat in summer, resulting in a much higher cooling load demand in summer than heating load demand in winter.

### 4.1. System Capacity Configuration

This study is based on the natural gas distributed energy station system in the Shibei High-Tech Zone. The primary equipment comprises two gas-fired ICE generator sets,

each coupled with a flue gas-fired hot water lithium bromide absorption chiller to facilitate waste heat recovery from power generation. The system incorporates four gas-fired hot water boilers, two of which are capable of dual-mode operation to accommodate heating demands under varying load conditions. For cooling applications, the configuration includes two centrifugal chillers dedicated to ice production and five centrifugal chillers for direct cooling, supplemented by 48 ice storage tanks. This arrangement enables ice storage during off-peak nighttime electricity periods, thereby achieving peak shaving and valley filling of daytime loads and enhancing overall system operational efficiency. All equipment selections have been meticulously matched and optimized, with detailed technical specifications presented in Table 6.



**Figure 8.** System operation program block diagram and constraints.

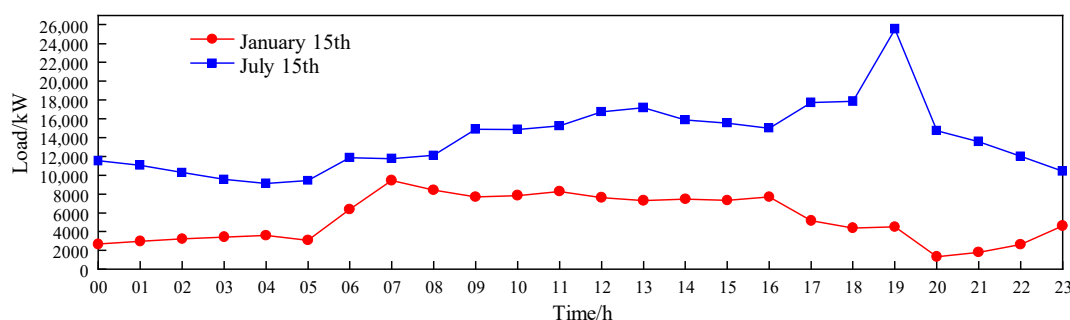


Figure 9. Hourly cooling and heating loads on typical winter and summer days.

Table 6. System equipment parameters.

| Equipment                                                   | Quantity | Volume/Power                               | Design Temperature of Supply and Return Water in Cold Conditions | Thermal Condition Supply and Return Water Design Temperature |
|-------------------------------------------------------------|----------|--------------------------------------------|------------------------------------------------------------------|--------------------------------------------------------------|
| Gas-fired ICE generator sets                                | 2        | 1000 kW                                    | -                                                                | -                                                            |
| Flue gas-fired hot water lithium bromide absorption chiller | 2        | Refrigeration: 1125 kW<br>Heating: 1000 kW | 6~12 °C                                                          | 50~60 °C                                                     |
| Gas-fired hot water boiler (2 dual-function types)          | 4        | 5600 kW                                    | -                                                                | 65~85 °C                                                     |
| Centrifugal chiller (ice making)                            | 2        | 4220 kW                                    | 6~12 °C                                                          | -                                                            |
| Centrifugal chiller unit                                    | 1        | 2814 kW                                    | 6~12 °C                                                          | -                                                            |
| Centrifugal chiller unit                                    | 4        | 3165 kW                                    | 6~12 °C                                                          | -                                                            |
| Ice storage tanks                                           | 48       | 932 kWh                                    | -                                                                | -                                                            |

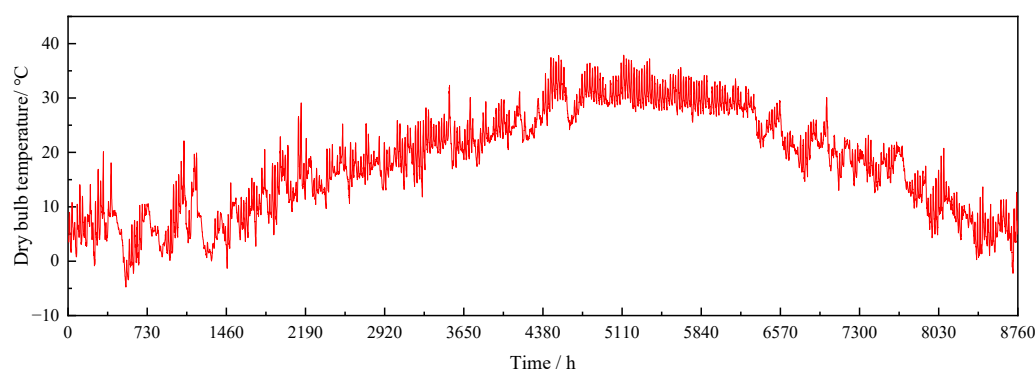
The research object in this paper is a medium-sized commercial complex located in downtown Shanghai. It has typical operating characteristics: ultra-high daytime cooling demand, obvious peak–valley load difference between day and night, and low electricity price during off-peak hours at night. The system is equipped with 48 ice storage tanks with single capacity of 932 kWh to realize peak load shifting.

In terms of applicability of ice storage for large- and medium-sized commercial parks, ice making during valley price periods can greatly cut peak electricity expenses by releasing cold at daytime peaks. However, ice storage tanks occupy a large building area and bring high initial investment cost, which makes them unsuitable for small retail shops with low total cooling load.

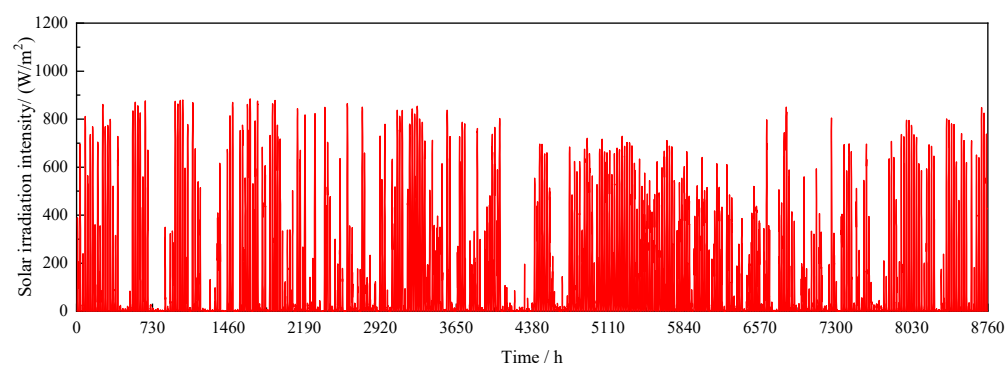
#### 4.2. Annual Characteristic Analysis

Figures 10–12 respectively present the hourly curves of dry-bulb temperature, hourly curves of solar irradiance, and hourly curves of relative humidity for the entire year in this region. From the figures, it can be seen that the coldest month of the year is January, with an average temperature of 5.87 °C, and the hottest month is August, with an average temperature of 30.99 °C. The total number of hours of sunlight throughout the year is 4723, and the average irradiation intensity is 229.21 W/m<sup>2</sup>. The maximum irradiation occurs in time 1670 (10 March, 14:00), with an irradiation intensity of 884.21 W/m<sup>2</sup>. The number of hours with irradiation greater than 100 W/m<sup>2</sup> throughout the year is 2377, accounting for 50.33% of the total number of total irradiation hours; the number of hours with irradiation greater than 200 W/m<sup>2</sup> is 1959, accounting for 41.48% of the total number of total irradiation hours; the number of hours with irradiation greater than 300 W/m<sup>2</sup> is 1600, accounting for 33.88% of the total number of total irradiation hours; and the number of hours with irradiation greater than 400 W/m<sup>2</sup> is 1252, accounting for 26.51% of the total number of total irradiation hours.

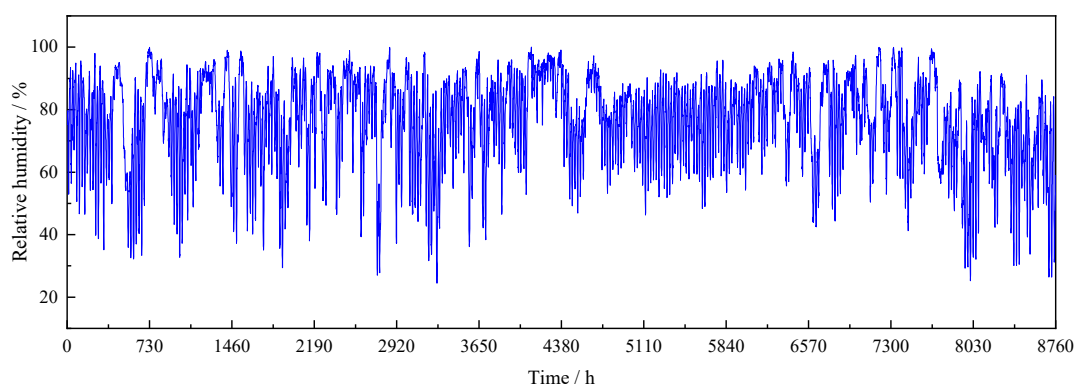
To evaluate the economic efficiency and operational performance of the proposed source-load coordinated multi-mode optimization scheduling strategy on an annual scale, this paper compares and analyzes the annual load distribution of equipment under the benchmark operation mode and the optimized operation mode. The annual load distribution under the benchmark operation mode is shown in Figure 13, with the cooling load in summer borne by the chiller and lithium bromide unit, and the heating load in winter borne by the gas boiler and lithium bromide unit. The annual load distribution under the optimized operation mode is shown in Figure 14, with the main optimization part in the cooling load area, adding an ice storage device to bear the cooling load, reducing the output of the chiller, and optimizing the refrigeration performance of the system.



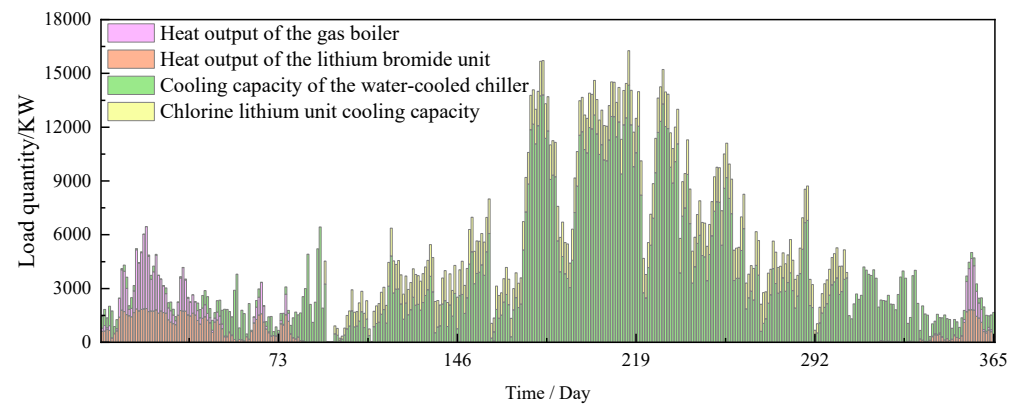
**Figure 10.** Hourly curve of annual dry-bulb temperature.



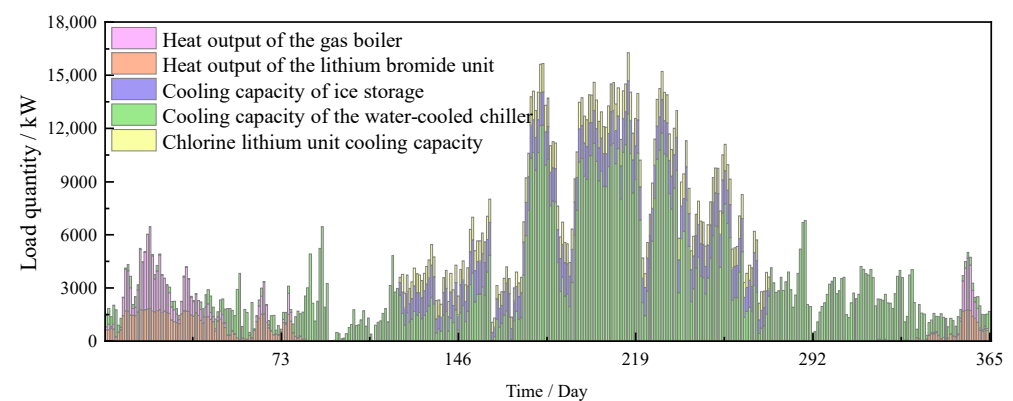
**Figure 11.** Hourly curve of annual solar irradiance.



**Figure 12.** Hourly curve of annual relative humidity.

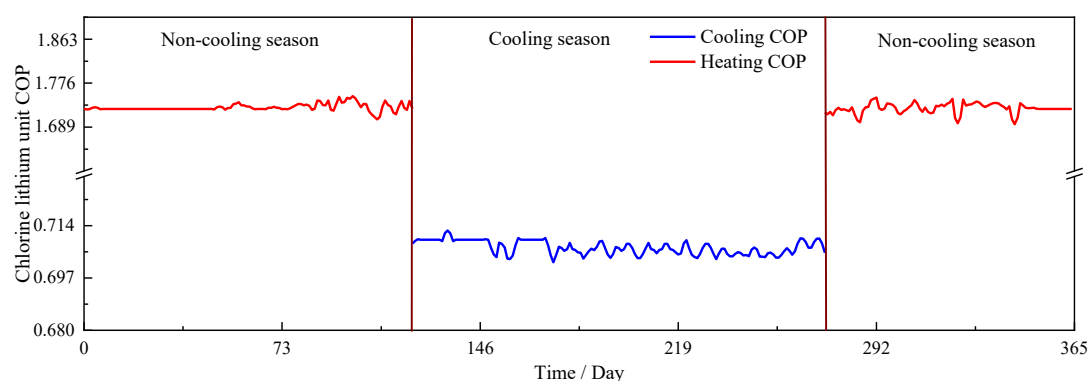


**Figure 13.** Annual load distribution for the base operating mode.



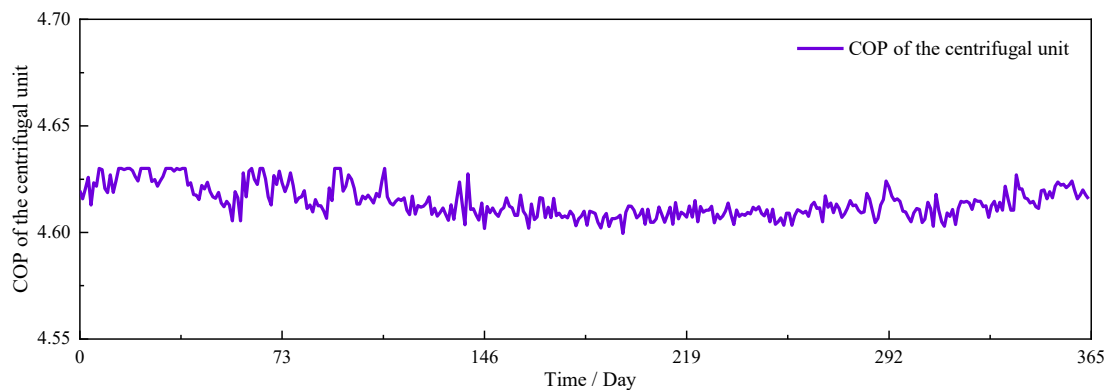
**Figure 14.** Optimize the operation mode for annual load distribution.

The operation mode equipment was analyzed, and the annual daily average COP variation curve was simulated based on the mathematical model of the lithium bromide unit, covering both cooling and heating operation conditions, as shown in Figure 15. As shown in Figure 15, the annual average COP of the lithium bromide unit in the heating mode ranges from 1.68 to 1.77, while in the cooling mode, the COP is between 0.69 and 0.71. This indicates that in the heating mode, the unit can more effectively utilize the input heat, so its heating COP is significantly higher than the cooling COP. The reason is that in the heating mode, the input heat from the generator and the released absorption heat from the absorber and condenser can be simultaneously used for heating, while in the cooling mode, the absorbed heat needs to be discharged to the environment. Therefore, the heating mode effectively utilizes more heat.



**Figure 15.** COP of the lithium bromide unit in cooling and heating modes.

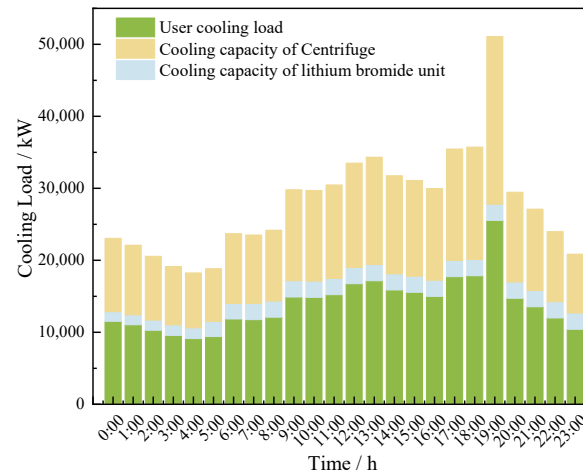
From the perspective of the overall system's heating and cooling demands, the cooling requirements generated by various equipment and personnel in the room need to be borne by the centrifugal units. Based on the mathematical model simulation, the annual average COP variation curve of the centrifugal units throughout the year is obtained, as shown in Figure 16. The annual COP variation is between 4.60 and 4.65, demonstrating good performance.



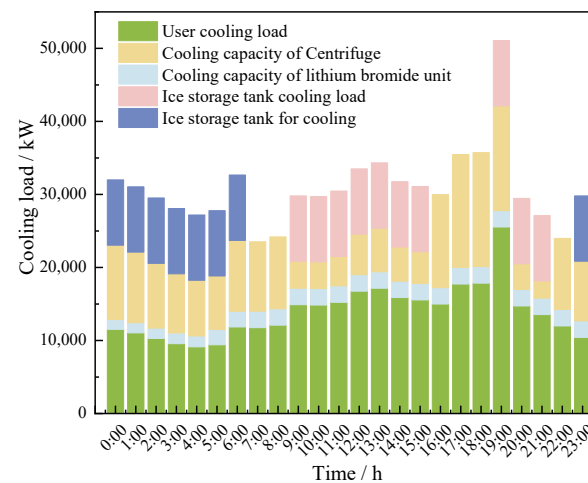
**Figure 16.** Centrifugal unit refrigeration COP.

#### 4.3. Analysis of Typical Day Characteristics

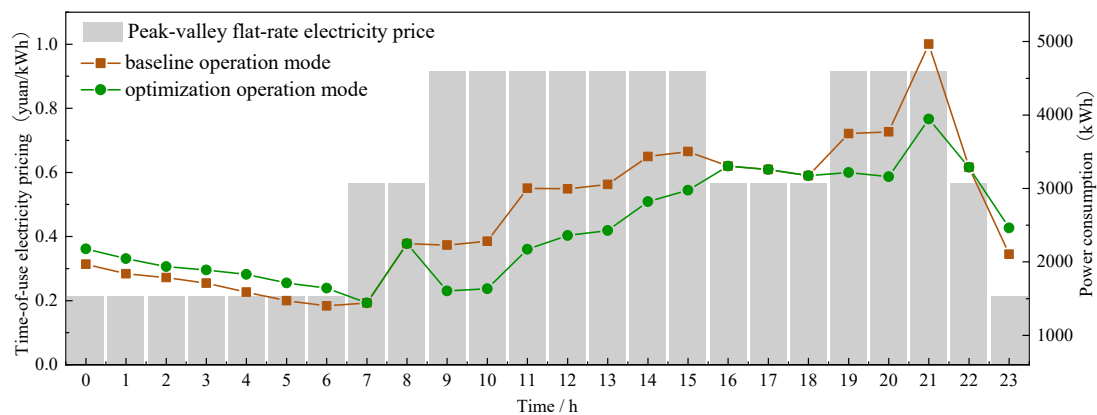
From the annual performance analysis, it can be seen that when the ice storage tank is activated in the summer operation mode, the strategy changes. Therefore, in the typical day analysis, only a detailed analysis is conducted for 15 July in the summer. The heat balance situation of the typical day is shown in Figures 17 and 18. From the figures, it can be seen that in the baseline operation mode, only two devices provide cooling to the system. In the optimized operation mode, adding the ice storage tank to release cooling during the peak electricity price period can effectively reduce the use of the centrifugal compressor. The average cooling load during the peak period of the typical day is 16,414.63 kW. The maximum cooling load occurs at 19:00 and is 25,536.86 kW. The cooling capacity provided by the energy storage ice tank at this moment is 8950 kW. The combined cooling output of centrifugal chillers and lithium bromide units reaches 16,586.86 kW at the peak hour. The average cooling supply of the system and the users during the flat rate and off-peak periods is 12,119.32 kW. Compared with the baseline operation mode, the optimized operation mode reduces the cooling discharge of the centrifugal compressor by 53,700 kW on the typical day, as shown in Figure 19. When in the peak electricity price period, the addition of the ice storage tank reduces the consumption of electricity from the power grid. During the off-peak electricity price period, the ice storage tank is activated to produce ice as a backup.



**Figure 17.** Typical day baseline operation mode heat balance.



**Figure 18.** Typical day optimization operation mode heat balance.

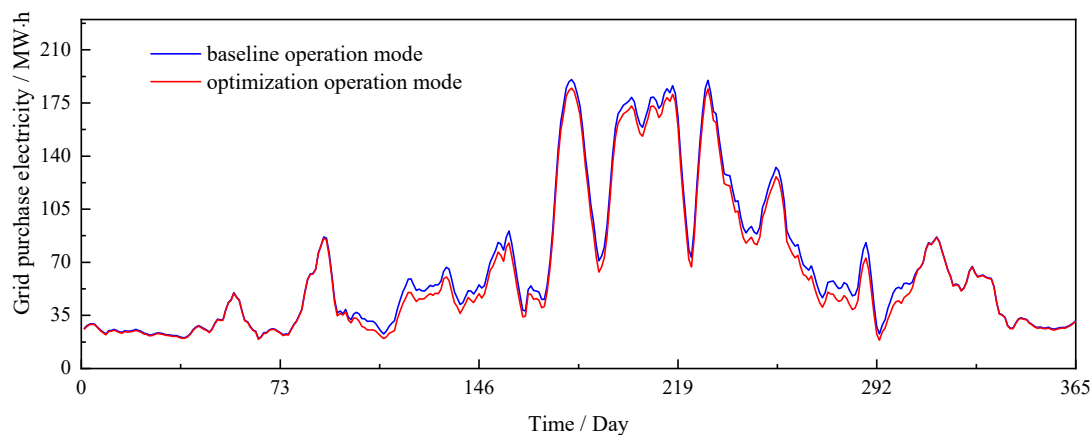


**Figure 19.** Typical-day power consumption comparison of baseline and optimized operation modes.

#### 4.4. Analysis of System Evaluation Indicators

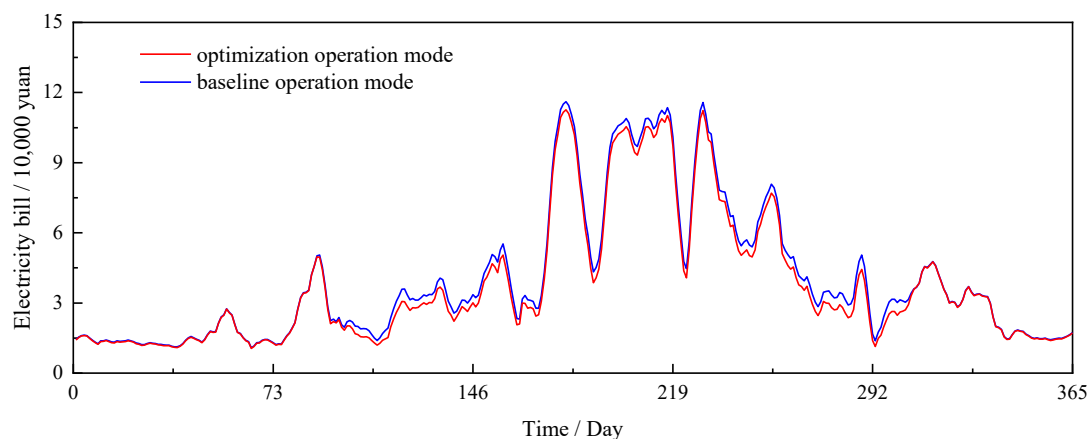
##### 4.4.1. Analysis of Annual Electricity Consumption

To evaluate the economic performance of the proposed optimized scheduling strategy on an annual scale, the changes in daily electricity purchase volume and electricity cost of the system under the baseline operation strategy and the optimized operation strategy were compared and analyzed, as shown in Figures 20 and 21.



**Figure 20.** Comparison of grid purchase electricity volumes under two operation modes.

The variation in purchased electricity from the power grid can be observed. Although the trends of purchased electricity for the two operation modes are generally consistent, the optimized operation strategy significantly reduced the peak of purchased electricity from the power grid during high-load periods. This result is mainly attributed to the load transfer capability of the ice storage cooling system on a time scale, as well as the effective substitution of the gas ICE and the lithium bromide absorption refrigeration unit for the electric cooling load, thereby reducing the system's dependence on the power grid.



**Figure 21.** Comparison of electricity bills for two operation modes.

The annual electricity cost variation shows a distinct seasonal pattern, which is highly consistent with the changes in the cooling and heating loads of commercial buildings. During the low-load period, the difference in electricity costs between the two operation strategies is relatively small, mainly limited by the flexibility of system operation and the load level. As the load increases, especially during the high-load periods in summer and during periods with high electricity prices, the optimized operation mode demonstrates significant advantages over the benchmark operation mode, with a reduction in electricity cost peaks and effective suppression of the fluctuation range of electricity costs. This indicates that the operation strategy based on load classification and TOU electricity pricing response can effectively reduce the purchase cost of electricity during high-electricity-price periods.

Comprehensive analysis shows that the proposed optimized scheduling strategy does not simply achieve economic improvement by reducing electricity consumption, but rather that through the optimization of the electricity consumption structure guided by TOU electricity pricing, it achieves peak shaving and valley filling as well as a reduction

in operation costs. The average grid purchase electricity and electricity costs of the optimized operation mode in summer are respectively 6.3% and 3.3% lower than those of the benchmark operation mode.

#### 4.4.2. Environmental Performance Analysis

The proposed optimized dispatch strategy achieves distinct carbon emission abatement performance under different seasonal operating conditions. The average annual carbon emission reduction rate reaches 20.9%, broken down into a 16.4% reduction in summer and 25.2% in non-summer seasons, which fully verifies the prominent carbon-cutting superiority of the coordinated scheduling scheme we established.

It should be noted that the summer carbon reduction performance is inferior to that of non-summer periods, even though ice storage equipment is deployed to realize peak load shifting. The core cause lies in the extra power consumption required for ice making during off-peak hours, which raises the overall electricity demand of the system. Furthermore, the system still depends heavily on electric cooling units to satisfy massive summer cooling loads, so the emission-saving gains from peak-hour grid power curtailment are partially counteracted by the extra electricity consumed for ice production. In contrast, cooling demand drops sharply in non-summer seasons. The system can make fuller use of waste heat recovered from gas ICEs to drive lithium bromide absorption units, lowering the share of electricity purchased from the grid and consequently delivering much higher average carbon reduction efficiency.

#### 4.4.3. Model Popularization and Ice Storage Applicability Analysis

The proposed dispatch framework is divided into two independent layers for flexible migration. The bottom ice storage constraint module can adjust cold storage capacity parameters according to different cooling loads and local TOU policies. The upper multi-objective optimization solving framework has no fixed scene restriction.

When the load data of office buildings and community shopping malls are input, the model can run stably without structural adjustment. For micro-commercial projects with no demand for centralized cooling, the ice storage sub-module can be directly deleted, while the coordination logic of gas ICEs and lithium bromide units is still retained. Therefore, the scheduling strategy has wide popularization potential across various commercial formats.

#### 4.4.4. Economic Analysis

Economic performance analysis is a crucial step in evaluating the economic benefits and operating costs of the integrated energy system. The initial investment cost of the system directly affects its economic viability. The unit investment costs of each equipment within the system and the charging standards for electricity and natural gas at different times are shown in Table 7.

**Table 7.** System parameter settings.

| Equipment                   | Cost (Ten Thousand CNY/Unit) | Energy     | Energy Unit Cost (CNY/kW) |               |
|-----------------------------|------------------------------|------------|---------------------------|---------------|
|                             |                              |            | Summer                    | Non-Summer    |
| Gas-fired ICE               | 300                          | Power grid | Peak: 0.916               | Peak: 0.916   |
| Lithium bromide unit        | 150                          |            | 8:00–15:00                | 8:00–11:00    |
|                             |                              |            | 18:00–21:00               | 18:00–21:00   |
| Hot water boiler            | 200                          |            | Medium: 0.567             | Medium: 0.567 |
| Centrifugal compressor unit | 600                          |            | 6:00–8:00                 | 6:00–8:00     |
|                             |                              |            | 15:00–18:00               | 11:00–18:00   |
|                             |                              |            | 21:00–22:00               | 21:00–22:00   |

|                                         |      |             |                                    |                             |
|-----------------------------------------|------|-------------|------------------------------------|-----------------------------|
| Auxiliary system and electrical control | 1000 |             | Valley: 0.213<br>22:00–6:00        | Valley: 0.213<br>22:00–6:00 |
| Ice storage tank                        | 90   |             |                                    |                             |
| Gas-fired boiler                        | 250  | Natural gas | Winter/Non-Winter Prices 4.02/3.82 |                             |

Based on 8760 h hourly simulations throughout the year, the economic comparison results of the two operation modes are shown in Table 8. The annual electricity purchase volume of the optimized operation mode is 56.02 GWh, which is 6.33 GWh less than the benchmark mode, representing a reduction of approximately 10.2%. Among them, the peak-load electricity consumption decreased from 9.41 GWh to 8.39 GWh, a reduction of 1.02 GWh, effectively achieving the load transfer during high-priced electricity periods. In terms of electricity cost, the annual electricity cost of the optimized mode is 36.3088 million CNY, which is 4.0277 million CNY less than the benchmark mode, representing a savings rate of 10.0%.

However, the optimized scheme adopts a dynamic load regulation strategy for gas ICEs, which reduces power generation during off-peak hours and lowers recoverable waste heat. Part of the cooling and heating demands thus need to be covered by gas boilers. Accordingly, the annual natural gas cost rises from 3.89366 ten thousand CNY to 4.13642 ten thousand CNY, a growth of 242.76 ten thousand CNY. Considering the net savings in electricity costs and the increase in gas costs, the total annual operating cost of the optimized operation mode is approximately 1.6 million CNY less.

Based on the incremental investment of the ice storage cooling system, the static investment payback period is 11.37 years. This indicates that the optimized scheduling strategy combining the ice storage cooling system with TOU electricity price response has good economic feasibility.

**Table 8.** Economic and energy performance indicators under different operation modes

| Indicators                                      | Baseline Operation Mode | Optimization Operation Mode | Differences |
|-------------------------------------------------|-------------------------|-----------------------------|-------------|
| Annual electricity consumption (GWh)            | 62.35                   | 56.02                       | 6.33        |
| Peak section (GWh)                              | 9.41                    | 8.39                        | 1.02        |
| Valley section (GWh)                            | 23.82                   | 21.52                       | 2.30        |
| Annual electricity fee<br>(in ten thousand CNY) | 4033.65                 | 3630.88                     | 402.77      |
| Annual utility fee (in ten thousand CNY)        | 3893.66                 | 4136.42                     | −242.76     |
| Investment payback period (years)               | -                       | 11.37                       | -           |

To guarantee the reproducibility of economic calculation results, all fundamental cost and revenue assumptions are summarized in Table 9 following the full-lifecycle economic evaluation framework widely adopted in existing research [32]. Four major cost components are fully elaborated, including one-time capital expenditure, annual operation and maintenance (O&M) costs, mid-term equipment replacement outlays, and site occupancy charges.

**Table 9.** Basic assumptions for economic calculation (20-year life, discount rate = 3.5%).

| Cost Category               | Specific Item           | Value                      | Unit    |
|-----------------------------|-------------------------|----------------------------|---------|
| One-time initial investment | Gas ICE                 | 2150                       | CNY/kW  |
|                             | Lithium bromide chiller | 1860                       | CNY/kW  |
|                             | Ice storage tank        | 280                        | CNY/kWh |
| Annual O & M                | Overhaul & labor        | 3.2% of initial investment | -       |
| Mid-term replacement        | Ice tank (10th year)    | 70% of initial cost        | -       |
| Financial parameter         | Service life            | 20                         | a       |

|                |                      |      |         |
|----------------|----------------------|------|---------|
|                | Annual discount rate | 3.5  | %       |
| Annual revenue | Peak-shaving subsidy | 0.12 | CNY/kWh |

To establish industry benchmarks for horizontal comparison, this study refers to three published studies focusing on commercial ice thermal storage systems [31,33,34] to form Table 10. This table facilitates cross-sectional comparison of economic metrics and quantifies the long-term energy-saving benefits brought by incremental investment in ice storage facilities.

**Table 10.** Economic index comparison with peer literature.

| Reference  | Building Type               | Ice Storage Scale | Static Payback (year) | Unit Cooling Cost (CNY·kWh <sup>-1</sup> ) |
|------------|-----------------------------|-------------------|-----------------------|--------------------------------------------|
| Ref. [31]  | Office & mall               | 18.8 MWh          | 5.12                  | 0.132                                      |
| Ref. [33]  | Large shopping mall         | 46.6 MWh          | 4.40                  | 0.128                                      |
| Ref. [34]  | Mixed commercial            | Variable capacity | 3.93~6.80             | 0.124~0.141                                |
| This paper | Shanghai commercial cluster | 44.2 MWh          | 4.07                  | 0.116                                      |

## 5. Conclusions

The proposed dispatch strategy effectively reduces annual grid power purchase and carbon emissions. Nevertheless, large-scale ice storage systems have inherent economic drawbacks summarized in previous studies [34,35]. Ice tanks demand high upfront capital and large underground space, exceeding chilled water storage in construction cost. Moreover, the system's profitability heavily relies on peak-to-valley electricity price spreads; narrow price gaps will substantially extend the investment payback period. For projects with limited capital budgets, a feasible optimization scheme is to properly downsize ice storage capacity to strike a balance between initial investment and energy-saving gains, and multiple comparative scenarios with different ice storage capacities are analyzed in Section 4.4.3 of this paper.

Aiming at the technical pain points of large fluctuations in cooling, heating and power loads of commercial buildings and poor flexibility of traditional operation modes, this study takes the natural gas distributed energy supply station in Shanghai Shibe High-Tech Service Industry Park as the research carrier, constructs a coordinated optimal dispatching strategy for an electricity-cooling-storage coupled integrated energy system based on TOU electricity price response, and completes a comprehensive quantitative evaluation of the system's operational characteristics, economic benefits and environmental benefits by means of an 8760 h hourly simulation. This research breaks the limitation of single engineering case research. The multi-objective collaborative optimization framework of power-cooling-ice storage for commercial buildings constructed in this paper can be used as a standardized analysis tool for similar commercial park integrated energy systems, and provides a universal methodological support for the planning and scheduling of multi-energy coupling systems of medium and small commercial buildings.

- (1) The proposed optimal dispatching strategy enables dynamic adjustment of output gas ICEs, lithium bromide absorption units, centrifugal chillers, and the ice storage system in response to TOU electricity pricing, effectively achieving peak load shifting and efficient multi-energy coordination. Compared to the baseline operating mode, this strategy reduces the system's annual grid electricity purchases by 10.2%, including a decrease of 1.02 GWh in peak-period power consumption, while attaining an average annual CO<sub>2</sub> emission reduction of 20.9% overall, with 16.4% in summer and 25.2% in non-summer periods.

- (2) The relatively lower emission reduction during summer is attributed to the additional electricity consumption required for ice making in the storage system and the increased reliance on electric chillers under high cooling loads. With the ice storage system representing the primary incremental investment, the system achieves a static payback period of 11.37 years, demonstrating a viable balance between enhanced operational flexibility, environmental benefits, and long-term economic feasibility.
- (3) The coordinated optimal dispatching strategy for the electricity–cooling–storage coupled system proposed in this paper has significant advantages in reducing the operation cost of integrated energy systems, cutting total carbon emissions and improving the peak regulation capacity of the system, which can provide theoretical support and practical paradigms for the engineering implementation and large-scale promotion of integrated energy systems in commercial building parks under the background of TOU electricity price policies.

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## Appendix A

### Appendix A.1. Mathematical Symbol Table

| Symbol             | Unit | Definition                                                            |
|--------------------|------|-----------------------------------------------------------------------|
| $P_{ICE}(t)$       | kW   | Gas internal combustion engine generating power at hour $t$           |
| $P_{ICE,max}$      | kW   | Rated maximum output power of gas engine                              |
| $P_{grid}(t)$      | kW   | Grid purchased power at hour $t$                                      |
| $P_{load}(t)$      | kW   | Total electric load of commercial cluster at hour $t$                 |
| $P_{chiller}(t)$   | kW   | Total electric power consumed by all chillers at hour $t$             |
| $Q_{IB}(t)$        | kW   | Cooling/heating output of lithium bromide unit at hour $t$            |
| $Q_{IB,max}$       | kW   | Maximum rated capacity of lithium bromide unit                        |
| $Q_{ice,ch}(t)$    | kWh  | Ice storage charging cold capacity at hour $t$                        |
| $Q_{ice,ch,max}$   | kWh  | Maximum hourly ice-making capacity of ice tank                        |
| $Q_{ice,dis}(t)$   | kWh  | Ice storage discharging cold capacity at hour $t$                     |
| $Q_{ice,dis,max}$  | kWh  | Maximum hourly ice-melting cold supply                                |
| $Q_{cool,load}(t)$ | kW   | Total cooling demand of the building cluster at hour $t$              |
| $Q_{cool,out}(t)$  | kW   | Total cold energy supplied to users at hour $t$                       |
| $Q_{cc}(t)$        | kW   | Hourly total cooling output of all centrifugal chillers at hour $t$   |
| $P_{cc}(t)$        | kW   | Total power consumption of all centrifugal chillers at hour $t$       |
| $Q_{cc,max}$       | kW   | Maximum rated cooling capacity of centrifugal chillers                |
| $P_{cc,max}$       | kW   | Maximum rated power consumption of centrifugal chillers               |
| $Q_b(t)$           | kW   | Hourly heat supply output of gas boiler at hour $t$                   |
| $Q_{b,max}$        | kW   | Maximum rated heat output of gas boiler                               |
| $Q_{LB,h}(t)$      | kW   | Heating output of lithium bromide unit at hour $t$                    |
| $Q_{heat,load}(t)$ | kW   | Total space heating demand of commercial cluster at hour $t$          |
| $Q_{b,DHW}(t)$     | kW   | Heat output of gas boiler for domestic hot water at hour $t$          |
| $Q_{LB,DHW}(t)$    | kW   | Waste heat of lithium bromide unit for domestic hot water at hour $t$ |

|                                          |                                 |                                                                                                                        |
|------------------------------------------|---------------------------------|------------------------------------------------------------------------------------------------------------------------|
| $Q_{\text{DHW,load}}(t)$                 | kW                              | Total domestic hot water heat demand at hour $t$                                                                       |
| $E_{\text{ice}}(t)$                      | kWh                             | Residual stored cold energy of ice tank at hour $t$                                                                    |
| $E_{\text{ice,max}}$                     | kWh                             | Rated total storage capacity of single ice tank (932 kWh)                                                              |
| $Q_{\text{eva}}$                         | kW                              | Evaporator cooling capacity of absorption chiller                                                                      |
| $Q_{\text{gen}}$                         | kW                              | Heat consumption of generator of lithium bromide unit                                                                  |
| $Q_{\text{Flue}}$                        | kW                              | Waste heat from engine flue gas                                                                                        |
| $Q_{\text{jacket}}$                      | kW                              | Jacket water waste heat of gas engine                                                                                  |
| $Q_{\text{LB,de}}$                       | kW                              | Double-effect lithium bromide total cooling output                                                                     |
| $Q_{\text{abs}}$                         | kW                              | Heat released by absorber                                                                                              |
| $Q_{\text{con}}$                         | kW                              | Heat released by condenser                                                                                             |
| $Q_{\text{genh}}, Q_{\text{genl}}$       | kW                              | Heat input of high/low pressure generator                                                                              |
| $Q_{\text{zl}}(i)$                       | kW                              | Hourly cooling output of centrifugal chiller at hour $i$                                                               |
| $P_{\text{zl}}(i)$                       | kW                              | Hourly power consumption of centrifugal chiller at hour $i$                                                            |
| $Q_{\text{t}}$                           | kWh                             | Theoretical maximum ice-melting rate of ice tank at hour $t$                                                           |
| $Q_{\text{t,s}}$                         | kWh                             | Actual cold output from melted ice at hour $t$                                                                         |
| $\dot{H}_{\text{fuel}}$                  | kJ/s                            | Enthalpy of input fuel for gas engine                                                                                  |
| $\dot{H}_{\text{air}}$                   | kJ/s                            | Enthalpy of intake air                                                                                                 |
| $\dot{H}_{\text{exh}}$                   | kJ                              | Enthalpy of exhaust gas                                                                                                |
| $Q_{\text{ice,gross}}$                   | kJ/s                            | Total input energy of internal combustion engine                                                                       |
| $W_{\text{net}}$                         | kW                              | Net system output work                                                                                                 |
| $W_{\text{turbine}}$                     | kW                              | Auxiliary power of refrigeration system                                                                                |
| $W_{\text{LPC}}$                         | kW                              | Compressor power consumption                                                                                           |
| $W_{\text{pump,se}}, W_{\text{pump,de}}$ | kW                              | Solution pump power for single/double-effect unit                                                                      |
| $W_{\text{cold}}$                        | kW                              | Refrigerant pump power                                                                                                 |
| $\dot{m}_i$                              | kg/s                            | Mass flow rate of working medium $i$                                                                                   |
| $c_{\text{p},i}$                         | kJ/(kg·°C)                      | Constant-pressure specific heat of medium $i$                                                                          |
| $t_{\text{i,in}}, t_{\text{i,out}}$      | °C                              | Inlet/outlet temperature of fluid $i$                                                                                  |
| $T_{\text{ei}}$                          | °C                              | Chilled water return temperature on evaporator side                                                                    |
| $T_{\text{ci}}$                          | °C                              | Cooling water return temperature on condenser side                                                                     |
| $i_{\text{h}}$                           | kJ/kg                           | Return water enthalpy of boiler                                                                                        |
| $i_{\text{s}}$                           | kJ/kg                           | Feed water enthalpy of boiler                                                                                          |
| $B$                                      | Nm <sup>3</sup> /h              | Hourly natural gas consumption of boiler                                                                               |
| $V_0$                                    | Nm <sup>3</sup> /m <sup>3</sup> | Theoretical air demand per cubic meter gas                                                                             |
| $V_1$                                    | Nm <sup>3</sup> /h              | Actual air intake volume                                                                                               |
| $V_2$                                    | Nm <sup>3</sup> /h              | Total boiler air flow                                                                                                  |
| $A$                                      | MW                              | Rated evaporation/thermal power of boiler                                                                              |
| $D$                                      | kg/h                            | Circulating water mass flow of boiler                                                                                  |
| $LHV_{\text{fuel}}$                      | kJ/kg                           | Low heating value of natural gas ( $Q_{\text{net,ar}} = 35,169$ )                                                      |
| $C_{\text{ele}}(t)$                      | CNY/kW<br>h                     | Time-of-use electricity price at hour $t$                                                                              |
| $C_{\text{gas}}$                         | CNY/Nm <sup>3</sup>             | Unit price of natural gas                                                                                              |
| $F_{\text{ICE}}(t)$                      | kg/h                            | Hourly fuel consumption of gas engine at hour $t$                                                                      |
| $I_{\text{peak}}(t)$                     | CNY                             | Peak-shaving subsidy income at hour $t$                                                                                |
| $F_1$                                    | CNY                             | Original objective function 1: unmodified annual total system operating cost without penalty processing                |
| $F_2$                                    | -                               | Original objective function 1: unmodified annual total system operating cost without penalty processing                |
| $\bar{F}_1$                              | CNY                             | Penalized objective function 1 (annual total operation cost), constrained cost objective after penalty term correction |

|                                    |       |                                                                                                                                      |
|------------------------------------|-------|--------------------------------------------------------------------------------------------------------------------------------------|
| $F_2$                              | -     | Penalized objective function 2 (system comprehensive energy efficiency), constrained efficiency objective after penalty correction   |
| $\lambda$                          | CNY   | Penalty coefficient, a sufficiently large positive constant used to amplify constraint violation losses                              |
| $V$                                | -     | Total normalized constraint violation value, the sum of standardized violation magnitudes of all equality and inequality constraints |
| $F_{1,max}$                        | CNY   | Maximum value of original cost objective among all Pareto-optimal solutions                                                          |
| $F_{1,min}$                        | CNY   | Minimum value of original cost objective among all Pareto-optimal solutions                                                          |
| $F_{2,max}$                        | -     | Maximum value of original efficiency objective among all Pareto-optimal solutions                                                    |
| $F_{2,min}$                        | -     | Minimum value of original efficiency objective among all Pareto-optimal solutions                                                    |
| $\mu_{1,j}$                        | -     | Normalized satisfaction degree of the cost objective for the $j$ -th Pareto solution, ranging from 0 to 1                            |
| $\mu_{2,j}$                        | -     | Normalized satisfaction degree of the energy efficiency objective for the $j$ -th Pareto solution, ranging from 0 to 1               |
| $S_j$                              | -     | Comprehensive satisfaction index of the $j$ -th Pareto compromise solution, average of two single-objective satisfaction degrees     |
| $j$                                | -     | Serial number of each nondominated Pareto-optimal solution, $j = 1, 2, \dots, N$                                                     |
| $N$                                | -     | Total number of nondominated solutions retained on the final Pareto front                                                            |
| $IC_{total}$                       | CNY   | Total one-time initial investment                                                                                                    |
| $IC_{LB}/IC_{ice}/IC_{chill}/IC_b$ | CNY   | Investment of lithium bromide/ice tank/chiller/boiler                                                                                |
| $NP_j$                             | CNY   | Net annual income in year $j$                                                                                                        |
| $PP$                               | a     | Static investment payback period, unit a = year                                                                                      |
| $m_y$                              | g     | Annual total CO <sub>2</sub> emission mass                                                                                           |
| $u_y$                              | g/kWh | Carbon emission factor per unit energy output                                                                                        |
| $E$                                | kWh   | Annual total energy output of system                                                                                                 |
| $\eta_e$                           | -     | Power generation efficiency of gas internal combustion engine                                                                        |
| $\eta_q$                           | -     | Waste heat recovery thermal efficiency of engine                                                                                     |
| $\eta_{ch}$                        | -     | Ice storage charging efficiency                                                                                                      |
| $\eta_{dis}$                       | -     | Ice storage discharging efficiency                                                                                                   |
| $\eta_b$                           | %     | Boiler thermal efficiency by inverse balance method                                                                                  |
| $COP_{LB,se}$                      | -     | Single-effect lithium bromide refrigeration COP                                                                                      |
| $COP_{LB,de}$                      | -     | Double-effect lithium bromide refrigeration COP                                                                                      |
| $COP_{HC}$                         | -     | Heating COP of absorption unit                                                                                                       |
| $COP_{CM,bl}$                      | -     | COP of base-load centrifugal chiller                                                                                                 |
| $COP_{CM,cs}$                      | -     | COP of ice-making centrifugal chiller                                                                                                |
| $COP_{ISS}$                        | -     | Comprehensive energy efficiency of ice storage system                                                                                |
| $q_2$                              | %     | Exhaust gas heat loss of gas boiler, the largest heat loss item                                                                      |
| $q_3$                              | %     | Incomplete combustion heat loss, determined by flue CO content (Table 3)                                                             |
| $q_5$                              | %     | Boiler surface heat dissipation loss, obtained by checking Table 4                                                                   |
| $\alpha$                           | -     | Boiler excess air coefficient, fixed value in this paper: $\alpha = 1.10$                                                            |
| $\alpha_{ds}$                      | -     | Excess air coefficient at boiler flue gas outlet                                                                                     |
| $m, n$                             | -     | Empirical coefficients for $q_2$ calculation<br>( $m = 0.5, n = 3.45$ )                                                              |
| $a_0, a_1, a_2$                    | -     | Fitting coefficients of centrifugal chiller COP formula                                                                              |

|        |   |                                                                  |
|--------|---|------------------------------------------------------------------|
| $t, i$ | - | Hourly time index for full-year simulation, range from 1 to 8760 |
| $PL$   | - | Load rate of ice storage system, constraint: $0 \leq PL \leq 1$  |
| $K$    | - | Boiler excess air richness coefficient                           |

#### Appendix A.2. Abbreviation Table

| Abbreviation | Full Name                                                   |
|--------------|-------------------------------------------------------------|
| CCHP/CHP     | Combined Cooling, Heating and Power/Combined Heat and Power |
| TOU          | Time-of-Use (Electricity Price)                             |
| COP          | Coefficient of Performance                                  |
| ICE          | Internal Combustion Engine                                  |
| EUF          | Comprehensive Energy Utilization Factor                     |
| MILP         | Mixed-Integer Linear Programming                            |
| NSGA-II      | Nondominated Sorting Genetic Algorithm II                   |
| LHV          | Lower Heating Value                                         |
| AEUI         | Autonomous Energy Utilization Index                         |
| EVUI         | Electric Vehicle Utilization Index                          |
| HRES         | Hybrid Renewable Energy System                              |
| LNG          | Liquefied Natural Gas                                       |

#### Appendix A.3. Supplementary Explanation

- (1) Symbols  $t$  and  $i$  are defined as hourly time indices over the annual simulation period, ranging from 1 to 8760. All time-dependent variables in Section 3.4 carry the subscript  $(t)$ , which matches the summation range of the annual cumulative operator  $\sum_{t=1}^{8760}$  used in multi-objective optimization formulas.
- (2) Temperature throughout the manuscript is measured in °C; instantaneous power and cooling capacity take kW as the standard unit, cumulative cold storage energy adopts kWh; natural gas consumption is measured in Nm<sup>3</sup>/h; and all cost-related terms adopt CNY as the monetary unit.
- (3) Currency unit explanation: CNY refers to Chinese yuan, and the symbol “ $a$ ” stands for year.
- (4) The volume fraction of carbon monoxide (CO) in flue gas directly determines the incomplete combustion heat loss  $q_3$ , and the corresponding matching relationship is listed in Table 3 of the main text.
- (5) All equipment rated parameters, economic calculation assumptions and comparative benchmark data involved in this paper are consistent with Tables 2–9 in Sections 2 and 4.

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