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Thermodynamic Analysis-Based Economic Evaluation Model for Hybrid Energy Systems Incorporating Renewable Energy Generation

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ABSTRACT

Driven by global carbon neutrality goals, hybrid energy systems integrating renewable energy sources have emerged as a critical pathway for energy transition due to their potential for efficient energy utilization and enhanced renewable energy integration. However, the complexity of thermodynamic characteristics and multi-objective optimization requirements pose significant challenges to economic evaluation. These challenges include unclear mechanisms of energy flow coupling, incomplete cost factor coverage, and insufficient consideration of uncertainties. Existing studies often separate thermodynamic analysis from economic assessment or overlook key factors such as energy price fluctuations, equipment life cycles, environmental costs, and the stochastic nature of renewable energy outputs, thereby limiting the reliability of evaluation results for supporting full life-cycle system optimization. This study focuses on the synergistic optimization of thermodynamic performance and economic viability in hybrid energy systems. A system architecture incorporating renewable energy generation is proposed. Through exergy analysis, the study reveals the patterns of energy flow and exergy loss distribution. Additionally, an economic scheduling evaluation model is established, which comprehensively considers multi-dimensional cost factors and the uncertainties of renewable energy output. This enables the coupled optimization of thermodynamic efficiency and economic indicators. The findings provide interdisciplinary theoretical support for system configuration and operational scheduling, enhance the life-cycle economic performance of hybrid energy systems, and promote the large-scale, efficient application of renewable energy in integrated energy systems.

1. INTRODUCTION

Under the background of actively promoting the "dual carbon" goals globally, the energy structure is undergoing profound transformation, and the development and utilization of renewable energy have become core issues in the energy field [1-4]. Hybrid energy systems incorporating renewable energy generation, due to their advantages in effectively improving energy utilization efficiency [5], promoting renewable energy consumption [6], and enhancing energy supply stability [7], have gradually become an important direction for the development of energy systems. However, such systems involve the conversion and coupling of multiple forms of energy [8-10], with complex thermodynamic characteristics and multi-objective optimization requirements, making economic evaluation face many challenges.

Conducting thermodynamic analysis and economic evaluation of hybrid energy systems containing renewable energy generation has important theoretical and practical significance. Related research can deeply reveal the laws of internal energy flow, conversion, and loss within the system, providing thermodynamic theoretical support for the optimal design of the system. Such research also helps to reasonably allocate energy resources within the system, reduce system operating costs, improve economic benefits, promote the efficient utilization of renewable energy in energy systems, and thereby promote energy transition and the achievement of sustainable development goals.

At present, in the research on hybrid energy systems incorporating renewable energy generation, some scholars focus on energy analysis. For example, literature [11, 12] only studied the energy balance of the system, without incorporating economic factors into the analysis framework, making it impossible to comprehensively evaluate the overall performance of the system. Some other studies [13-16], in terms of economic evaluation, adopted relatively simple models, considering only a few factors such as initial investment cost and operating cost, while ignoring important influencing factors such as energy price fluctuations, equipment life cycle, and environmental costs. For example, the economic evaluation models constructed in literature [17, 18] did not fully consider the impact of the uncertainty of renewable energy output on the economic performance of the system, resulting in deviations between the evaluation results and actual situations. In addition, most existing studies separate thermodynamic analysis and economic evaluation [19], lacking an organic combination between the two, and thus it is difficult to achieve synergistic improvement of thermodynamic performance and economic efficiency in system design and operational optimization.

The main research content of this paper includes two parts. The first part is the architecture and exergy analysis of hybrid energy systems incorporating renewable energy generation, aiming to construct a reasonable system architecture, deeply analyze the exergy flow characteristics and exergy loss distribution of each component in the system, and reveal the influencing factors of system thermodynamic performance. The second part is the construction of an economic scheduling evaluation model for hybrid energy systems incorporating renewable energy generation. By comprehensively considering various cost factors and the uncertainty of renewable energy output, a scientific and reasonable economic scheduling evaluation model is established to achieve economic optimization of the system under different operating scenarios. The research value of this paper lies in combining thermodynamic analysis and economic evaluation to provide a complete theoretical and methodological framework for the design, operation, and optimization of hybrid energy systems incorporating renewable energy generation. The research results can not only provide new research ideas and methods for scholars in related fields, but also provide scientific basis for energy enterprises to reasonably select system architectures and formulate economic scheduling strategies in practical projects, which is helpful to promote the application of hybrid energy systems incorporating renewable energy generation and facilitate the efficient, economic, and sustainable development of energy systems.

2. EXERGY AND DESIGN OF HYBRID RENEWABLE SYSTEMS

This paper first carries out the architecture and exergy analysis of hybrid energy systems containing renewable energy generation. As the physical carrier of the economic evaluation model, the rationality of the system architecture directly affects the energy flow path and equipment coupling efficiency. Only by clarifying the functional positioning and connection relationships of each device through architecture analysis can a clear energy flow network be provided for subsequent economic evaluation, avoiding the omission of cost elements caused by ambiguous architecture. In addition, the core role of renewable energy in the system needs to be concretized through architectural design. For example, under a high proportion of renewable energy access, the "electricity-heat-gas" coupling architecture, with its unique energy supply and demand mode, inevitably requires the economic evaluation model to match it, and architecture analysis is the key step to reveal the internal logic of this mode. The prior implementation of exergy analysis stems from the essential demand of economic evaluation for the quantification of energy quality. The traditional first law of thermodynamics only focuses on the quantity balance of energy and cannot reflect the quality difference between electric energy and thermal energy in the conversion process, while exergy analysis converts different forms of energy to the same energy level through the method of energy quality coefficient, which can accurately describe the utilization efficiency of "available energy" of the equipment. These thermodynamic parameters are the core basis for constructing the cost function in economic evaluation. The incremental operating cost corresponding to high exergy loss links, and the cost advantages brought by zero-payment exergy of renewable energy equipment, all need to be quantified through exergy analysis and embedded into the economic model.

2.1 Regional-level integrated energy system structure

The architecture of hybrid energy systems containing renewable energy generation takes a high proportion of renewable energy access as its core feature, achieving coordinated operation of heterogeneous energy subsystems through the organic coupling of multiple types of energy equipment. The system integrates renewable energy conversion devices such as wind turbines, photovoltaics, and solar collectors, which convert wind energy and solar energy into electric energy and thermal energy, respectively, forming the basic unit of the low-carbon energy supply of the system. Among them, wind turbines and photovoltaics serve as the main power generation units, directly supplying electric loads, and convert surplus electricity into hydrogen or methane and other gaseous fuels through power-to-gas devices, storing them in energy storage equipment, effectively absorbing the intermittent output of renewable energy and mitigating its impact on the stability of energy supply. Solar collectors provide the basic heat source for heat loads, forming a complement with combined cooling, heating, and power (CCHP) devices. The latter recovers waste heat for heating or to drive absorption chillers for cooling while generating electricity, realizing the cascade utilization of "electricity-heat-cooling". In addition, electric boilers, gas boilers, and electric chillers act as auxiliary equipment, supplementing the energy supply when the renewable energy output is insufficient, ensuring system supply-demand balance. Figure 1 shows the basic structure of the hybrid energy system containing renewable energy generation.

Further, this paper constructs the energy coupling relationship matrix of hybrid energy systems containing renewable energy generation, that is, taking the equipment units in the system architecture as nodes, and using the input-output relationships of energy flows as links, by sorting out the energy conversion and transmission paths between equipment, a mathematical representation framework of multi-energy flow coupling is established. First, the composition of system nodes is clarified, including renewable energy equipment, energy conversion devices, energy storage equipment, and load ends. Then, the energy input and output types of each node are defined, such as the input of wind turbines is wind energy and the output is electric energy; the input of power-to-gas devices is electric energy and the output is synthetic gas; the input of CCHP units is natural gas and the outputs are electric energy, waste heat, etc. On this basis, the coupling relationship between nodes is described in matrix form: matrix rows represent energy input nodes and types, columns represent energy output nodes and types, and matrix elements represent the energy conversion efficiency or transmission coefficient from a specific input node to an output node. For example, the coupling relationship between photovoltaics and power-to-gas devices corresponds to the conversion efficiency of “photovoltaic electricity → power-to-gas synthetic gas,” and the coupling relationship between solar collectors and absorption chillers corresponds to the transmission coefficient of “collector thermal energy → chiller cooling energy.” Through this structured expression, it is possible to clearly present how renewable energy generation devices form a multi-dimensional energy interaction network with energy storage equipment, conversion devices, and load ends through the output of electric energy and thermal energy. Specifically, suppose the load matrix is represented by M, the coupling coefficient matrix by Z, the power matrix by O; if the storage matrix is represented by O_T, then the energy coupling relationship matrix of the entire system is:

$$M = ZO + O_T \tag{1}$$

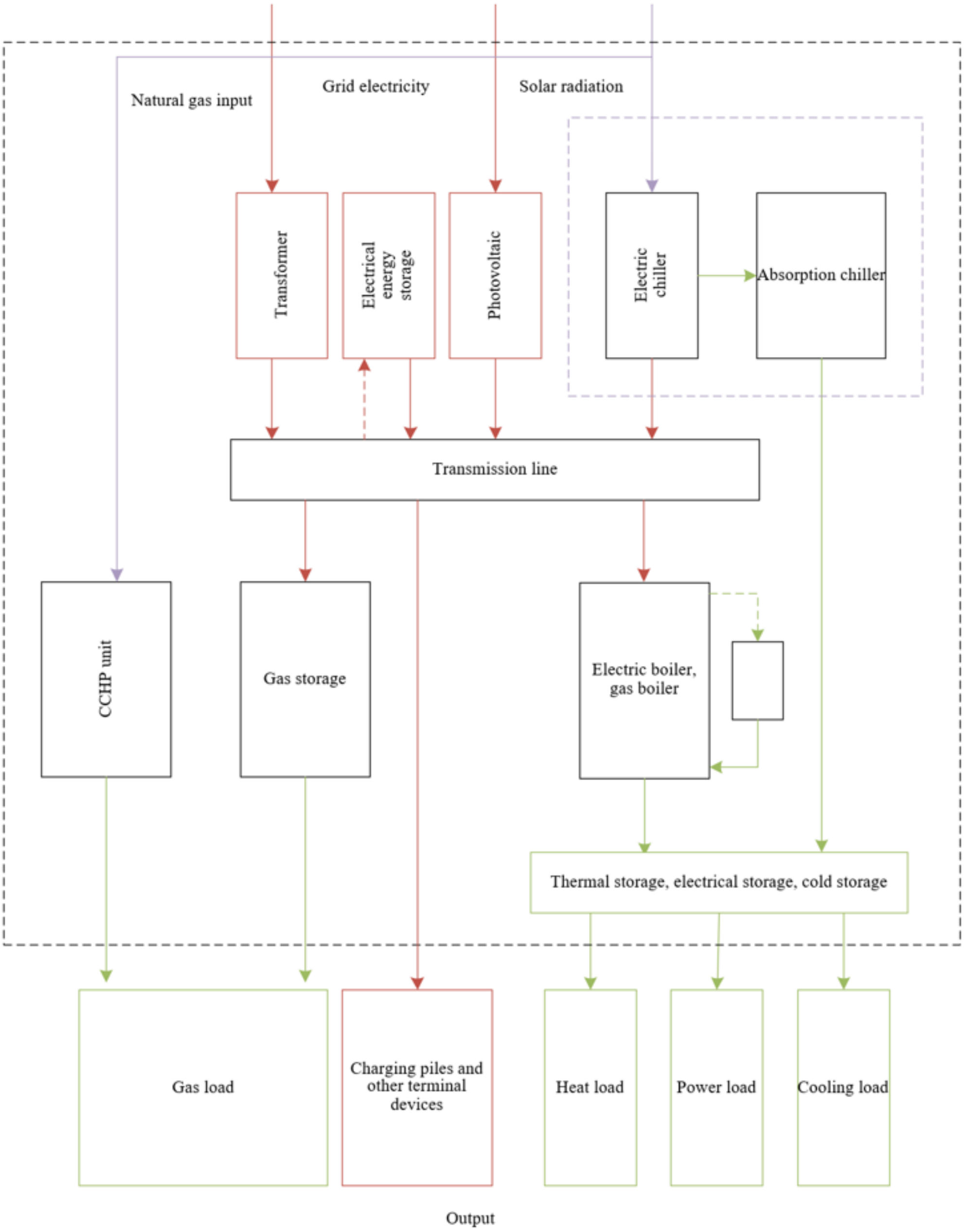

Figure 1. Basic structure of hybrid energy system containing renewable energy generation

Assuming the input power of electricity, natural gas, and thermal energy are represented by O^{EL}, O^{GA}, and O^{HE}, respectively; the electric power of wind turbines and photovoltaics are represented by $O^{EL}{}_{QS}$ and $O^{EL}{}_{ON}$, respectively; the externally purchased electricity power and the amount of purchased natural gas are denoted by $O^{EL}{}_{BU}$ and $O^{GA}{}_{BU}$; and the thermal power provided by solar thermal collectors is represented $O^{HE}{}_{TSZ}$, then the power matrix expression is:

$$O = \begin{bmatrix} O^{EL} \\ O^{GA} \\ O^{HE} \end{bmatrix} = \begin{bmatrix} O_{QS}^{EL} + O_{ON}^{EL} + O_{BU}^{EL} \\ O_{BU}^{GA} \\ O_{TSZ}^{HE} \end{bmatrix} \tag{2}$$

Assuming the electric, gas, thermal, and cooling loads are represented by M^{EL}, M^{GA}, M^{HE}, and M^{CO}, respectively; the proportion of electricity distributed to the power-to-gas device, electric boiler, and electric chiller over the total input electricity is represented by β, α, and ε; the gas conversion efficiency of the power-to-gas device is represented by $\lambda^{GA}{}_{OsH}$; the thermal production efficiency of the electric boiler and gas boiler are denoted by $\lambda^{HE}{}_{RY}$ and $\lambda^{HE}{}_{HY}$; the cooling efficiency of the absorption chiller and electric chiller are denoted by $\lambda^{CO}{}_{RZ}$ and $\lambda^{CO}{}_{XZ}$; the proportions of natural gas allocated to the CCHP device and the gas boiler over the total input natural gas are represented by γ and σ; the electricity, heat, and cooling conversion efficiencies of the CCHP device are denoted by $\lambda^{EL}{}_{ZZGO}$, $\lambda^{HE}{}_{ZZGO}$, and $\lambda^{CO}{}_{ZZGO}$; the proportion of heat allocated to the absorption chiller is represented by ϕ; the calorific value of natural gas is denoted by G^{GA}; and the charging/discharging power of electric, gas, thermal, and cooling energy storage devices are represented by $O^{EL}{}_{ts}$, $O^{GA}{}_{ts}$, $O^{HE}{}_{ts}$, and $P^{CO}{}_{ts}$, respectively, then the expression is:

$$\begin{bmatrix} M^{EL} \\ M^{GA} \\ M^{HE} \\ M^{CO} \end{bmatrix} = \begin{bmatrix} 1-\beta-\alpha-\varepsilon & \left(\varepsilon\lambda_{ZZGO}^{EL}\right)G^{GA} & 0 \\ \beta\lambda_{OsH}^{GA} / G^{GA} & 1-\gamma-\sigma & 0 \\ \alpha\lambda_{RY}^{HE} & \left(\gamma\lambda_{ZZGO}^{HE}+\sigma\lambda_{HY}^{HE}\right)G^{GA} & 1-\varphi \\ \varepsilon\lambda_{RZ}^{CO} & \gamma\lambda_{ZZGO}^{CO}G^{GA} & \varphi\lambda_{XZ}^{CO} \end{bmatrix} \cdot \begin{bmatrix} O^{EL} \\ O^{GA} \\ O^{HE} \end{bmatrix} + \begin{bmatrix} O_{ts}^{EL} \\ O_{ts}^{GA} \\ O_{ts}^{HA} \\ O_{ts}^{CO} \end{bmatrix} \tag{3}$$

2.2 Exergy analysis

The basic principle of exergy analysis for hybrid energy systems with renewable energy generation originates from the thermodynamic second law's quantitative evaluation of energy quality. Its core lies in attributing quality properties to different forms of energy through the energy quality coefficient method, thereby converting electricity, thermal energy, chemical energy, and other heterogeneous energy forms into a unified energy level to reveal the efficiency and loss patterns of "available energy" during energy conversion processes. Specifically, the system takes exergy flow as the object of analysis, defining the exergy input of equipment as the sum of external paid exergy and naturally endowed exergy. Since renewable energy generation equipment directly utilizes natural energy, its paid exergy can be regarded as zero, meaning its exergy efficiency can theoretically reach 100%. This indicates that the energy conversion process does not consume additional high-quality energy, but merely transforms the usable exergy from natural sources into usable energy within the system. In contrast, traditional energy equipment must consume high-grade energy to produce low-grade energy, with its exergy efficiency constrained by the degradation extent of energy quality. For example, electric chillers consume electricity with a quality coefficient of 1 to produce cooling energy with a quality coefficient of only 0.08, resulting in exergy efficiency far lower than energy utilization efficiency. However, absorption chillers use waste heat from the CCHP device to provide cooling, thus achieving higher exergy efficiency—highlighting how energy efficiency evaluation based on exergy analysis is sensitive to energy quality. This method overcomes the limitations of the first law of thermodynamics, which focuses only on energy quantity balance, and truly reflects the "quality efficiency" of energy conversion via exergy efficiency. It provides a scientific basis for identifying high exergy loss links in the system and optimizing equipment configuration.

At the thermodynamic functional level, renewable energy generation devices, due to their "zero paid exergy" characteristic, become net contributors of exergy flow in the system. Taking wind turbines and photovoltaics as examples, their input wind and solar exergy are directly converted into electrical exergy without consuming internally stored high-grade energy, thereby reducing exergy consumption at the source. Solar thermal collectors convert solar radiation exergy into thermal exergy and, together with waste heat utilization from the CCHP device, form a "low-grade thermal cascade utilization" model. The STC provides a basic thermal source, and the CCHP device recovers waste heat from natural gas engine power generation to drive the absorption chiller for cooling, thus avoiding the exergy loss of using high-grade electricity or natural gas for heating, and improving the system's overall exergy utilization efficiency. In addition, when the intermittency of renewable energy is adjusted through storage devices and power-to-gas units, although the exergy conversion of surplus electricity involves some exergy loss, since the initial electricity comes from zero paid exergy renewable energy, the system's reliance on traditional energy exergy inputs can still be significantly reduced. Through exergy analysis, the "exergy contribution" of renewable energy in the system can be quantitatively assessed: its zero paid exergy characteristic not only directly improves the system's exergy utilization efficiency but also indirectly reduces fossil energy exergy consumption via coupling with other equipment—thus thermodynamically embodying the core role of renewable energy in "quality improvement and efficiency enhancement" in hybrid energy systems.

3. DUAL-LEVEL DISPATCH FOR HYBRID RENEWABLES

This paper further develops an economic dispatch evaluation model for hybrid energy systems incorporating renewable power generation. Although the previous system architecture and exergy analysis clarified the energy efficiency parameters of equipment, the core issue of "how to achieve economic optimality through dispatch strategies during actual operation" remains unresolved. The construction of the economic dispatch evaluation model allows the energy quality parameters obtained from exergy analysis to be deeply coupled with economic variables, forming a dual-dimensional optimization framework of "energy efficiency – cost." For example, the zero marginal cost electricity from photovoltaics and wind turbines should be prioritized to meet the electrical load, and the economic performance of its surplus output when absorbed by power-to-gas or energy storage devices must be quantitatively assessed within the dispatch model to avoid neglecting economic costs in pursuit of mere energy balance. In addition, the operating costs of traditional energy equipment are directly related to their thermodynamic performance, requiring the dispatch model to develop differentiated output strategies to achieve coordinated control of thermodynamic optimization and economic cost.

To address the temporal and spatial scale differences between system planning and operational dispatch as well as the requirements for multi-objective optimization, this paper constructs a dual-level economic evaluation model for hybrid energy systems incorporating renewable power generation. The upper-level model focuses on capacity planning of equipment, solving the strategic question of "what to build and how much," while the lower-level model concentrates on optimizing operational dispatch, addressing the tactical question of "how to operate and adjust." The two models are coupled through decision variables and objective functions to form a unified framework. The core principle of this layered design lies in separating long-term investment decisions from short-term operational strategies, thereby avoiding the computational complexity caused by excessive variable dimensions in single-level models, while ensuring that the capacity configuration in the planning stage provides feasible boundaries for operational dispatch. Moreover, cost feedback from the operation stage provides data support for planning optimization, achieving coordinated improvement in economic performance and energy efficiency throughout the system's life cycle. Figure 2 shows the principle of the dual-level economic dispatch evaluation model for hybrid energy systems.

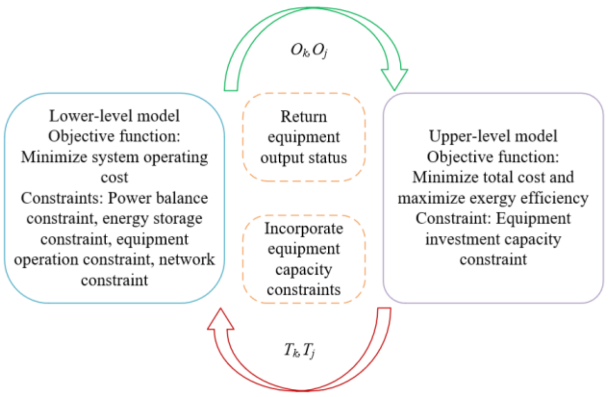

Figure 2. Dual-level economic dispatch evaluation model for hybrid energy systems

3.1 Upper-level model

The upper-level evaluation model takes the total life cycle cost and exergy efficiency of the system as dual objective functions. The modeling principle lies in balancing economic and thermodynamic performance through multi-objective optimization. The decision variables are the capacities of energy production equipment and energy storage equipment, essentially enabling the system's "hardware foundation" in terms of both thermodynamic and economic aspects: the capacity of renewable energy equipment directly determines the system's ability to absorb zero payment exergy energy, while the capacity of energy storage equipment influences the smoothing effect of renewable energy intermittency. Incorporating exergy efficiency into the objective function reflects a quantitative consideration of energy quality.

(1) System economic performance

The total cost Z_{TO} of the hybrid energy system incorporating renewable power generation includes the amortized initial investment cost Z_{IN} and the operational cost Z_{RU}. Assume that the unit capacity configuration cost and capacity of the k-th energy production device and the j-th energy storage device are denoted by $Z_{IN,k}$, T_k, $Z_{IN,j}$, and T_j, respectively. The discount rate is denoted by e, the planning horizon is V, and the number of days is F. The following equations provide the specific mathematical model of the objective function:

$$Z_{TO} = Z_{IN} + Z_{RU} \tag{4}$$

$$Z_{IN} = \frac{1}{F}\left(\sum_k Z_{IN,k}T_k + \sum_j Z_{IN,j}T_j\right)\frac{e(e+1)^V}{(e+1)^V - 1} \tag{5}$$

(2) System exergy efficiency

Assume that the u-th form of output and input energy are denoted by $R_{u,OUT}$ and $R_{u,IN}$, respectively. The sets of input and output energy forms are represented by Ψ_{IN} and Ψ_{OUT}. The exergy coefficient of the u-th form of energy is denoted by η_u, and the exergy coefficient of renewable energy is denoted by η_{er}. The overall exergy efficiency of the hybrid energy system incorporating renewable power generation is:

$$\begin{aligned} \lambda_{ra} &= \frac{Ra_{OUT}}{Ra_{IN}} = \frac{\sum_{u\in\Psi_{OUT}} R_{u,OUT}\eta_u}{\sum_{u\in\Psi_{IN}} R_{u,IN}\eta_u} \\ Ra_{OUT} &= \sum_{s=1}^{S}\begin{pmatrix} M_s^{EL}\eta_{EL} + M_s^{GA}\eta_{GA} \\ +M_s^{HE}\eta_{HE} + M_s^{CO}\eta_{CO}\end{pmatrix} \\ Ra_{IN} &= \sum_{s=1}^{S}\left(O_s^{EL}\eta_{EL} + O_s^{GA}\eta_{GA} + O_{er,s}\eta_{er}\right) \end{aligned} \tag{6}$$

3.2 Lower-level model

The lower-level evaluation model aims to minimize operating costs by introducing maintenance costs Z_{po}, energy consumption costs Z_{rz}, and carbon emission costs Z_{zr}, constructing a dynamic optimization model that includes real-time output of equipment and storage state. The core principle is to achieve real-time matching of “energy flow – cost flow” through dispatch strategies under the established equipment capacity constraints: maintenance costs are related to the equipment’s operating duration and output intensity, reflecting the reliability cost during the equipment's life cycle; energy consumption costs focus on the economic differences between fossil energy and renewable energy, reducing operating expenses by prioritizing the dispatch of zero marginal cost renewable energy; carbon emission costs internalize environmental externalities, guiding the system to reduce the use of fossil energy through economic leverage. The output distribution of equipment in the decision variables must satisfy the energy balance constraint, while the optimization of the energy storage charge and discharge power must consider the renewable energy forecast output and load fluctuations.

$$\begin{cases} D_{1.1} = MINZ_{TO} \\ D_{1.2} = MAX\,\lambda_{ra} \end{cases} \tag{7}$$

$$D_2 = MINZ_{RU} \tag{8}$$

The coupling between the lower-level and upper-level models is reflected in: The equipment capacity planned in the upper-level model setting the boundaries for lower-level dispatch, while the cost data accumulated during lower-level operation feeds back into the upper-level model, forming a "planning – dispatch – feedback optimization" closed loop. This ultimately achieves a multidimensional balance of economic performance, energy efficiency, and environmental benefits for the hybrid energy system.

3.3 Constraints

The construction of constraint conditions for the dual-level economic evaluation model of hybrid energy systems incorporating renewable power generation follows the principle of "layered design and coupling." It constructs constraint systems that are both physically feasible and economically reasonable, addressing the different decision objects and objectives of the upper-level planning and lower-level dispatch. The constraint conditions for the upper-level model focus on the boundary limits of equipment investment capacity, primarily quantifying the technical-economic constraints on the system hardware configuration. These include: (1) upper and lower capacity limits of equipment, such as the maximum installation capacity of wind turbines and photovoltaics being limited by available land area and natural conditions, and the minimum capacity of energy storage equipment needing to meet the basic peak-shaving requirements of the system to avoid excessive dependence on traditional energy; (2) budget constraints, where the total initial investment cost must not exceed the project budget limit, ensuring the economic feasibility of the planning scheme; (3) multi-energy flow coupling constraints, such as the capacity of power-to-gas devices needing to match the maximum surplus output of renewable energy generation equipment, avoiding inefficient configurations like “having electricity without storage” or “having storage without electricity,” and the area of solar thermal collectors needing to match heat load demands and the heat recovery capacity of combined heat and power (CHP) units, ensuring preliminary balance of heat supply and demand at the planning level. These constraints, by limiting the feasible domain of decision variables, integrate technical feasibility and economic rationality into the upper-level planning, providing realistic hardware boundaries for lower-level dispatch.

The constraint conditions for the lower-level model focus on energy flow and system interaction in the operational dispatch, constructing a constraint set centered on energy balance and considering the transmission and equipment characteristics. The first constraint is the multi-energy flow balance constraint, including supply and demand balance equations for electric, thermal, and cooling loads. Next, there are equipment operation characteristic constraints, such as the power generation and waste heat output of CHP units needing to meet a fixed proportional relationship, the cooling capacity of electric refrigerators and absorption chillers being limited by input energy and efficiency, and the charge/discharge power of energy storage devices not exceeding their rated power, with the state of charge required to stay within a safe range. Additionally, the transmission constraints for the power grid and natural gas grid must consider upper and lower limits of power or flow, such as the interactive power with the external grid needing to meet the maximum purchase/sale power specified in the grid access agreement, and the input flow of natural gas pipelines must not exceed the maximum flow rate allowed by the pipe diameter, avoiding network overload or blockage. These constraints, by describing the real-time relationship between equipment output and energy flow, ensure that the dispatch strategy is executable at the physical level, while also linking with the capacity configuration of the upper-level model. Specifically, the upper and lower limits of the capacity configuration for the *k*-th energy production device and the *j*-th energy storage device are represented by $T_{k,MAX}$, $T_{j,MAX}$, $T_{k,MIN}$, and $T_{j,MIN}$, which results in the following inequality:

$$\begin{cases} T_{k,MIN} \le T_k \le T_{k,MAX} \\ T_{j,MIN} \le T_j \le T_{j,MAX} \end{cases} \tag{9}$$

The following provides a detailed explanation of the core constraints of the system model.

(1) Energy supply and demand balance constraint

The energy supply and demand balance constraint is the core physical constraint of the two-layer model, aiming to ensure dynamic multi-energy flow balance during both the planning and scheduling phases. In the upper-layer capacity planning model, this constraint manifests as the total matching of long-term supply and demand: the minimum capacity configuration of renewable energy devices, traditional energy devices, and storage devices needs to be determined based on historical load data and future predictions, ensuring that their total capacity is no less than the peak demand for electricity, heat, and cooling, avoiding systemic energy shortages. In the lower-layer operational scheduling model, this constraint is refined into a real-time balance equation: the electrical load should equal the sum of wind turbine power generation, photovoltaic power generation, CHP generation, storage discharges, and purchased electricity from the grid. The thermal load should equal the sum of heat supplied by solar collectors, residual heat from CHP devices, heat from electric and gas boilers, and heat losses. The cooling load should equal the sum of cooling power from absorption chillers and electric chillers. Furthermore, the energy conversion in the power-to-gas device must meet input-output balance, forming a cross-energy domain balance network of "electricity-gas-heat-cooling" to ensure that there is no net energy accumulation or shortage in the system at any given moment. Assume that the natural gas consumed by CHP devices, and the electricity, heat, and cooling power they provide are denoted by $O^{GA}{}_{ZZGO,s}$, $O^{EL}{}_{ZZGO,s}$, $O^{HE}{}_{ZZGO,s}$, $O^{ZO}{}_{ZZGO,s}$, the electricity consumed by the power-to-gas device, electric boiler, and electric chiller is denoted by $O^{EL}{}_{OsH,s}$, $O^{EL}{}_{RY,s}$, $O_{RZ,s}{}^{EL}$, the natural gas provided by the power-to-gas device is denoted by $O^{GA}{}_{OsH,s}$, the natural gas consumed by the gas boiler is denoted by $O^{GA}{}_{HY,s}$, and the heat power provided by the electric boiler and gas boiler is denoted by $O^{HE}{}_{RY,s}$, $O^{HE}{}_{HY,s}$, the heat consumed by the absorption chiller is denoted by $O^{HE}{}_{XZ,s}$, and the cooling power provided by the absorption chiller and electric chiller is denoted by $O^{CO}{}_{XZ,s}$, $O^{CO}{}_{RZ,s}$. Then the equation is:

$$\begin{cases} O_{QS,s}^{EL} + O_{ON,s}^{EL} + O_{BU,s}^{EL} + O_{ZZGO,s}^{EL} + O_{DIS,s}^{EL} \\ = M_s^{EL} + O_{CHA,s}^{EL} + O_{OsH,s}^{EL} + O_{RY,s}^{EL} + O_{RZ,s}^{EL} \\ O_{OsH,s}^{GA} + O_{BU,s}^{GA} + O_{DIS,s}^{GA} \\ = M_s^{GA} + O_{CHA,s}^{GA} + O_{HY,s}^{GA} + O_{ZZGO,s}^{GA} \\ O_{TSZ,s}^{HE} + O_{ZZGO,s}^{HE} + O_{RY,s}^{HE} + O_{HY,s}^{HE} + O_{DIS,s}^{HE} \\ = M_s^{HE} + O_{CHA,s}^{HE} + O_{XZ,s}^{HE} \\ O_{ZZGO,s}^{CO} + O_{XZ,s}^{CO} + O_{RZ,s}^{CO} + O_{DIS,s}^{CO} \\ = M_s^{CO} + O_{CHA,s}^{CO} \end{cases} \tag{10}$$

(2) Unit output and ramp rate constraints

Unit output and ramp rate constraints focus on the technical feasibility of equipment operation, differentiating between the characteristics of renewable and traditional energy devices. In the upper-layer planning model, equipment output constraints manifest as the upper and lower limits of capacity configuration, while ramp rate constraints are indirectly reflected through equipment selection parameters. In the lower-layer scheduling model, output constraints are further refined into real-time operational boundaries: the output of renewable energy devices is limited by real-time meteorological conditions, the output of traditional energy devices must be between the minimum technical output and maximum rated power, and the power generation and residual heat output of CHP units must meet fixed coupling relationships. Ramp rate constraints limit the minute-level changes in equipment output. These constraints ensure that the scheduling strategy is executable at the technical level while interacting with the upper-layer planned equipment capacities. Assume that the upper and lower limits of unit operating power are denoted by $O_{k,MAX}$, $O_{k,MIN}$, and the upper and lower limits of unit ramp rate capabilities are denoted by $O_{k,UP}$, $O_{k,DO}$. Then the inequality is:

$$\begin{cases} O_{k,MIN} \le O_{k,s} \le O_{k,MAX} \\ O_{k,MIN} \le O_{k,s-1} - O_{k,s} \le O_{k,UP} \end{cases} \tag{11}$$

(3) Renewable energy constraints

Renewable energy constraints focus on its intermittency, uncertainty, and policy consumption targets, extending throughout the planning and scheduling stages of the two-layer model. In the upper-layer planning, renewable energy devices' reasonable installation scale must be determined through resource assessment, and the "minimum renewable energy penetration rate" constraint must be set to implement the high renewable energy access target. Additionally, the capacity of power-to-gas devices and storage devices must match the maximum excess output of renewable energy to avoid excessive curtailment of electricity due to insufficient absorption capacity. In the lower-layer scheduling, renewable energy constraints are reflected in real-time output predictions and flexible adjustment: based on short-term weather forecasts, the upper and lower fluctuation limits of device outputs are set, and renewable energy is prioritized for scheduling. Furthermore, the "curtailment rate constraint" is introduced: when renewable energy output exceeds immediate load and storage absorption capacity, some curtailment is allowed, but the environmental cost must be accounted for, pressuring the upper-layer planning to optimize the capacity configuration of storage and conversion devices. Assume the power of wind turbines, photovoltaics, and solar collectors is denoted by $O_{QS,s}$, $O_{ON,s}$, $O_{TSZ,s}$, and the corresponding upper and lower limits of power are denoted by $O_{QS,MIN}$, $O_{QS,MAX}$, $O_{ON,MIN}$, $O_{ON,MAX}$, $O_{TSZ,MIN}$, $O_{TSZ,MAX}$. Then the inequality is:

$$\begin{cases} O_{QS,MIN} \le O_{QS,s} \le O_{QS,MAX} \\ O_{ON,MIN} \le O_{ON,s} \le O_{ON,MAX} \\ O_{TSZ,MIN} \le O_{TSZ,s} \le O_{TSZ,MAX} \end{cases} \tag{12}$$

(4) Energy storage device constraints

The energy storage device constraints cover capacity configuration, operational status, and charge/discharge strategies, serving as the key bridge between the upper-level planning and lower-level scheduling. In the upper-level model, the capacity of energy storage devices must meet the dual goals of "peak-valley difference balance" and "renewable energy smoothing": the battery capacity must at least satisfy 50% of the system's maximum peak-valley electric load difference, and the gas storage device capacity must match the maximum daily conversion capacity of the power-to-gas device and the peak-valley fluctuation of the natural gas load. Meanwhile, the power parameters of energy storage devices must align with the instantaneous output of renewable energy devices and load peaks. In the lower-level scheduling, energy storage constraints are further refined into real-time operational boundaries: the state of charge must be maintained within a safe range to avoid overcharging and overdischarging that could impact lifespan; charge/discharge power must not exceed the rated value; cross-period energy storage must satisfy time scale matching. Additionally, the charging and discharging strategy of energy storage devices must interact with the renewable energy output, load curve, and electricity price signals. The constraint conditions are embedded in the scheduling model through differential or difference equations to ensure the energy storage system achieves a balance between economic feasibility and reliability. Let the charge and discharge power of the j-th energy storage device be denoted by $O^j_{CHA,j}$ and $O^j_{DIS,s}$, respectively; the upper limits of the charge and discharge power be $O^j_{CHA,MAX}$ and $O^j_{DIS,MAX}$; the efficiencies of charge and discharge be λ^j_{CHA} and λ^j_{DIS}; the scheduling time step be $\triangle s$; then the equations and inequalities are as follows:

$$\begin{cases} T_{j,s+1} = T_{j,s} + \left[O^j_{CHA,s} \lambda^j_{CHA} - O^j_{DIS,s} / \lambda^j_{DIS} \right] \Delta s \\ 0 \le O^j_{CHA,s} \le O^j_{CHA,MAX} \\ 0 \le O^j_{DIS,s} \le O^j_{DIS,MAX} \\ T^j_{ts}(0) = T^j_{ts}(24) \end{cases} \tag{13}$$

To ensure that charging and discharging cannot occur simultaneously, set $\vartheta_{CHA,MAX}{}^j$, $\vartheta_{DIS,MAX}{}^j \in \{0,1\}$. $\vartheta_{CHA}{}^j$ and $\vartheta_{DIS}{}^j$ are the charge and discharge states of the j-th energy storage device, respectively, thus:

$$\begin{cases} 0 \le \vartheta^j_{CHA} + \vartheta^j_{DIS} \le 1 \\ 0 \le O^j_{CHA,s} \le \vartheta^j_{CHA} O^j_{CHA,MAX} \\ 0 \le O^j_{DIS,s} \le \vartheta^j_{DIS} O_{DIS,MAX} \end{cases} \tag{14}$$

(5) Network constraints

Network constraints focus on the interaction boundaries between the system and the external electricity grid and gas network, as well as internal transmission limits, ensuring the safety and compliance of energy flow. In the upper-level planning, the maximum allowable power at the grid connection point and the maximum input flow of the gas pipeline need to be defined, based on which the capacity configuration of related devices is constrained. Internal network constraints are reflected indirectly through efficiency coefficients, influencing the capacity configuration decisions of the upper-level model. In the lower-level scheduling, network constraints manifest as real-time interactive power limits: the purchased/sold power with the external grid must not exceed the capacity of the connection point and must meet the power factor requirements; the interaction flow with the gas network must stay within the allowable range of the pipeline to avoid network congestion. Furthermore, the node balance constraint of the internal multi-energy flow network must clarify the energy flow direction to prevent logical "energy islands" or unreasonable couplings. By constructing network constraints, the model ensures the system complies with technical specifications when interacting with external energy networks and follows physical transmission laws during internal energy scheduling, achieving coordinated operation of the "source-grid-load-storage." Let the upper and lower limits of energy purchased from the electricity grid and gas network, as well as the constraints for power transmission and gas pipeline transmission, be denoted by $O^{EL}{}_{BU,MAX}$, $O^{GA}{}_{BU,MAX}$, $O^{EL}{}_{BU,MIN}$, $O^{GA}{}_{BU,MIN}$, then the inequality is:

$$\begin{cases} O_{BU,MIN}^{EL} \leq O_{BU,s}^{EL} + O_{BU,MAX}^{EL} \\ O_{BU,MIN}^{GA} \leq O_{BU,s}^{GA} + O_{BU,MAX}^{GA} \end{cases} \tag{15}$$

Figure 3 shows the solution flowchart for the dual-layer economic scheduling evaluation model of the hybrid energy system.

4. EXPERIMENTAL FINDINGS

Figure 4 shows the energy utilization efficiency and exergy efficiency of each energy production device in the hybrid energy system with renewable energy generation. Wind turbines and photovoltaics, due to their direct conversion of natural energy, exhibit high exergy efficiency, reflecting their advantage of low exergy loss under the zero-paid exergy characteristic. The solar thermal collector has lower exergy efficiency due to the quality limitation of the collected thermal energy. The CCHP unit improves energy utilization efficiency through multi-energy supply, but its exergy efficiency has certain losses due to the conversion characteristics of the equipment. Gas boilers and electric boilers incur large exergy losses in energy conversion, resulting in low exergy efficiency. The power-to-gas device has significantly lower exergy efficiency due to the degradation of energy quality in the conversion from electricity to gas. The absorption chiller relies on thermal energy input, and its exergy efficiency is limited, while the electric chiller has higher energy utilization efficiency but shows evident exergy loss in the conversion from electric energy to cooling energy, resulting in lower exergy efficiency. These data intuitively present the thermodynamic performance of each component, providing support for the analysis of exergy flow characteristics and exergy loss distribution in the system architecture. They also offer key parameters for the economic scheduling evaluation model, helping to reveal the impact of device energy efficiency on operating costs, thereby balancing thermodynamic performance and economic cost during scheduling optimization to promote the coordinated improvement of economic performance and energy efficiency in different scenarios.

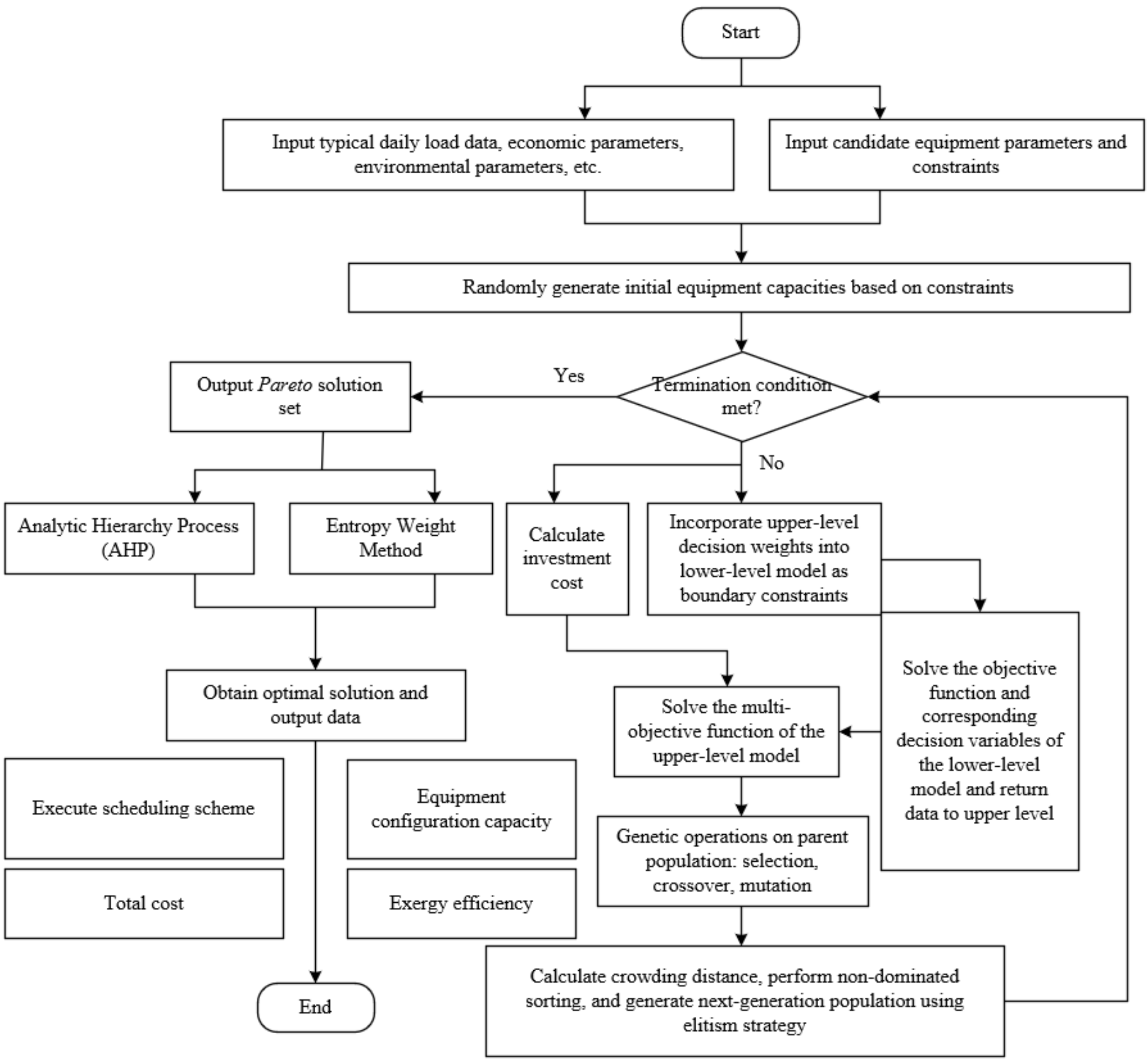

Figure 3. Solution flowchart for the dual-layer economic scheduling evaluation model of the hybrid energy system

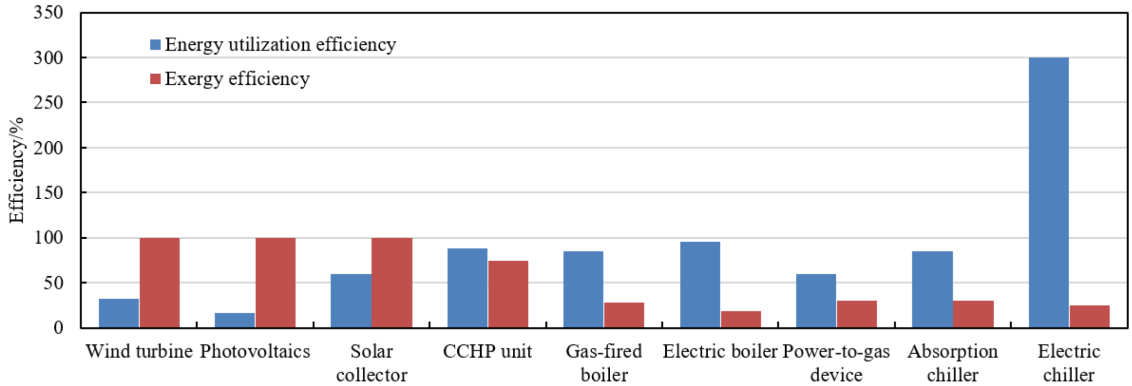

Figure 4. Energy and exergy efficiency of hybrid renewable systems

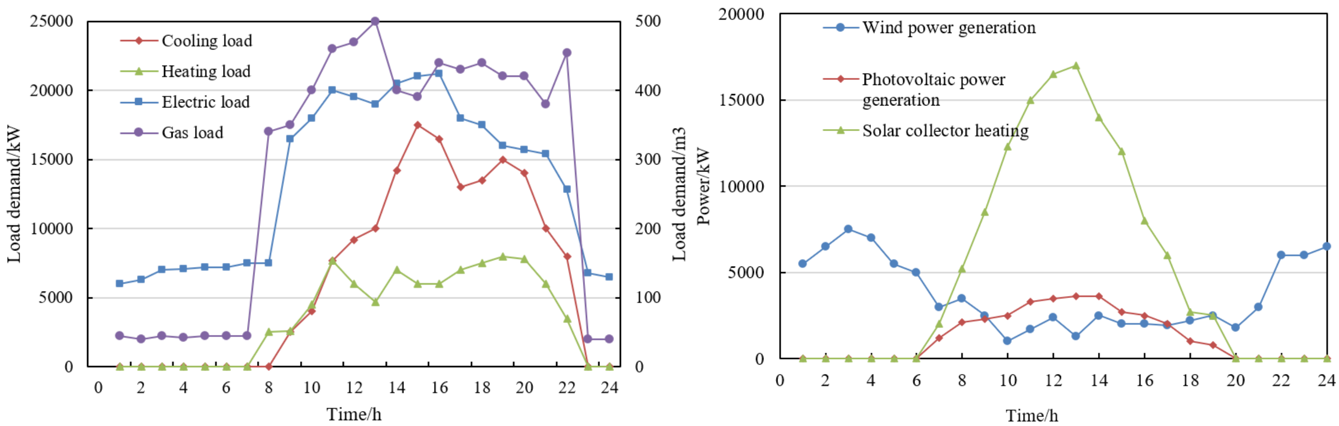

Figure 5. Load and renewable output curve of hybrid energy systems

Figure 5 presents the time-varying curves of load demand and renewable energy output in the hybrid energy system with renewable energy generation. In the upper figure, the cooling load is higher during daytime periods, reflecting the large daytime cooling demand. The thermal load shows certain fluctuations and has significant demand during some periods. The electric load also peaks during the daytime, which is consistent with the regular pattern of electricity usage for production and living. The gas load rises significantly during specific periods. In the lower figure, wind power generation exhibits irregular fluctuations and is significantly affected by wind speed. Photovoltaic power generation mainly occurs during daylight periods with sunshine, reflecting its dependence on sunlight. The solar thermal collector's heat supply also shows higher output during daytime, related to solar irradiance intensity.

Table 1. Price parameters

Parameter	Price (Unit)	Time Period
Electricity (yuan/(kW·h))	1.12	10:00-14:00 19:00-22:00
	0.326	00:00-7:00 23:00-24:00
	0.62	Other
Natural gas (yuan/m³)	2.24	00:00-24:00
Carbon tax (yuan/(kgCO₂))	0.22	00:00-24:00

Table 1 presents the price parameters from the experimental model's basic data, specifying the pricing standards for different energy types and environmental costs. The electricity price adopts a time-of-use pricing model, set at 1.12 yuan/(kW·h) during peak electricity demand periods, and drops to 0.326 yuan/(kW·h) during off-peak periods. Other time periods are not separately listed. This time-of-use pricing mechanism provides a price signal for economic scheduling, guiding the system to reduce electricity usage or utilize alternative energy sources during peak periods and store energy reasonably during off-peak periods. The natural gas price is set at 2.24 yuan/m³, directly affecting the operating cost of gas equipment, and should be comprehensively considered in the scheduling model in comparison with the costs of other energy sources. The carbon tax is set at 0.22 yuan/kgCO₂, incorporating environmental cost into economic evaluation, constraining the use of fossil energy, and promoting the system to prioritize the use of renewable energy to reduce carbon emissions. These data intuitively present the time distribution characteristics of load demand and the intermittency and fluctuation of renewable energy output. They not only provide basic data of actual operation scenarios for the system architecture and exergy analysis in the first part, helping to deeply analyze the exergy flow characteristics and exergy loss distribution of each component under different load and energy output conditions, but also provide key inputs for constructing the economic scheduling evaluation model in the second part, facilitating the formulation of scientific and reasonable scheduling strategies considering multiple cost factors and the uncertainty of renewable energy output.

Figure 6 shows the Pareto optimal solution set of the dual-level economic dispatch evaluation model of the hybrid energy system with renewable power generation. The horizontal axis represents exergy efficiency values, and the vertical axis represents the total cost. The data points exhibit an obvious trend: as the exergy efficiency increases from approximately -

68 to -65, the total cost gradually decreases from nearly 394,000 yuan to about 384,000 yuan, indicating a significant negative correlation between exergy efficiency and total cost, i.e., the higher the exergy efficiency, the lower the total system cost. This trend suggests that improving exergy efficiency can effectively reduce the total cost of the system in a hybrid energy system with renewable power generation. This is because higher exergy efficiency implies more efficient energy utilization, reducing energy waste and exergy loss, thereby lowering energy consumption cost, equipment maintenance cost, and other economic expenditures. This result reflects the effectiveness of the dual-level economic dispatch evaluation model, which achieves a coordinated balance between thermodynamic performance and economic cost through the integrated optimization of equipment capacity configuration and operation scheduling strategies.

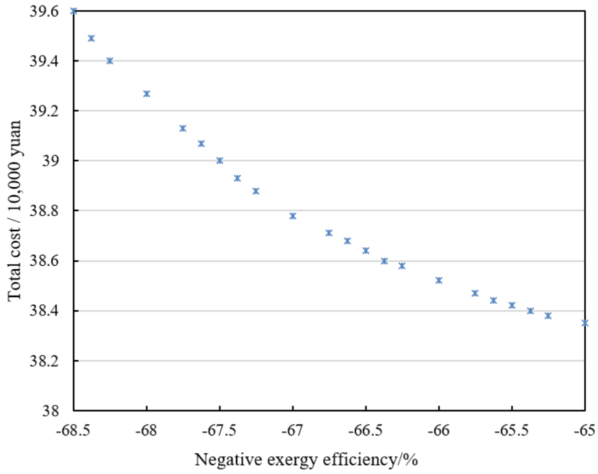

Figure 6. Pareto front of hybrid dispatch model

Table 2. Equipment capacity configuration of the hybrid energy system with renewable power generation under different scenarios

Equipment	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CCHP unit	0	8251	25415	14589
Gas boiler	22356	18	0	16523
Electric boiler	25	589	277	457
Power-to-gas device	1789	135	153	462
Absorption chiller	13256	6458	12548	11248
Electric chiller	118	14589	14265	1256

Table 2 presents the equipment capacity configuration of the hybrid energy system with renewable power generation under four scenarios. The CCHP unit has a capacity of 0 in Scenario 1, increases to 8251 in Scenario 2, further rises to 25415 in Scenario 3, and then drops to 14589 in Scenario 4. The gas boiler capacity is 22356 in Scenario 1, drastically reduces to 18 in Scenario 2, drops to 0 in Scenario 3, and then increases significantly to 16523 in Scenario 4. Other devices, such as electric boilers, power-to-gas devices, absorption chillers, and electric chillers, show significant fluctuations across different scenarios. For example, the electric chiller capacity is as high as 14589 in Scenario 2, only 118 in Scenario 1, and falls to 1256 in Scenario 4. These data intuitively reflect the significant differences in equipment capacity configuration under different scenarios, indicating the system's characteristic of dynamically adjusting equipment configuration based on actual operating conditions. Experimental results show that the capacity of the CCHP unit and the gas boiler exhibit a negative correlation, indicating that the CCHP unit, due to its higher exergy efficiency and advantages in integrated energy utilization, can effectively replace the gas boiler, reducing dependence on traditional high-energy-consumption and high-pollution equipment, thereby improving system economy. In Scenario 3, the CCHP unit has the highest capacity while the gas boiler is at 0, indicating that this configuration maximizes the use of high-efficiency equipment and reduces energy and environmental costs, verifying the positive effect of thermodynamic performance optimization on economic improvement. The dynamic adjustment of equipment capacities under each scenario reflects that the dual-level economic dispatch evaluation model can comprehensively consider multiple cost factors and operational scenarios, and optimize equipment capacity configuration to achieve system economic optimization. For example, the high capacity configuration of the electric chiller in Scenario 2 may be an adaptive adjustment based on the electricity load or cooling load demand in that scenario, combined with time-of-use electricity pricing and other factors. Overall, the model dynamically balances the thermodynamic performance and economic cost of equipment, providing a scientific basis for energy system planning under different scenarios, ensuring that the system meets load demands while achieving optimal life-cycle economy, and fully demonstrating the theoretical and practical effectiveness of the dual-level model in the research.

By observing the three groups of dispatch result figures (Figure 7), in terms of electricity dispatch, photovoltaic, and wind turbines actively output during daytime to directly meet part of the electricity load, energy storage devices dynamically charge and discharge based on renewable energy output and load demand, and the electricity consumption of devices such as the CCHP unit, power-to-gas device, electric boiler, and electric chiller changes orderly over time, reflecting their response to time-of-use electricity pricing and energy supply-demand conditions. In thermal dispatch, solar collectors dominate heat supply during daytime, with thermal storage devices cooperating in charging and discharging; gas boilers and electric boilers assist in heat supply when renewable energy is insufficient. In cooling dispatch, absorption chillers and electric chillers collaboratively supply cooling, with cooling storage devices assisting in adjustment during certain periods to meet cooling load demand.

Overall, each device operates in close coordination during different time periods, demonstrating the system's adaptability to the intermittency of renewable energy and the coordinated control of multi-energy flows. The scheduling results indicate that the system effectively reduces the usage frequency of conventional energy sources by giving priority to renewable energy, directly decreasing energy consumption cost and carbon emission cost. The flexible charge-discharge strategy of energy storage devices improves the absorption rate of renewable energy, avoids power curtailment and energy waste, and indirectly reduces system operating cost. The CCHP unit, with its high-efficiency cascade utilization of energy, reduces exergy loss, improves the comprehensive energy utilization rate, and further optimizes economic performance. Through the scheduling evaluation model, the system realizes accurate matching of multi-energy flows and coordinated optimization of equipment under the consideration of time-of-use electricity price, equipment operation cost, and environmental cost, verifying the model's effectiveness in balancing energy supply and demand and reducing total system cost under different operating scenarios. It provides a scientific scheduling scheme that considers both thermodynamic performance and economic cost for hybrid energy systems with renewable energy generation, promoting the realization of optimal economic performance in practical operation.

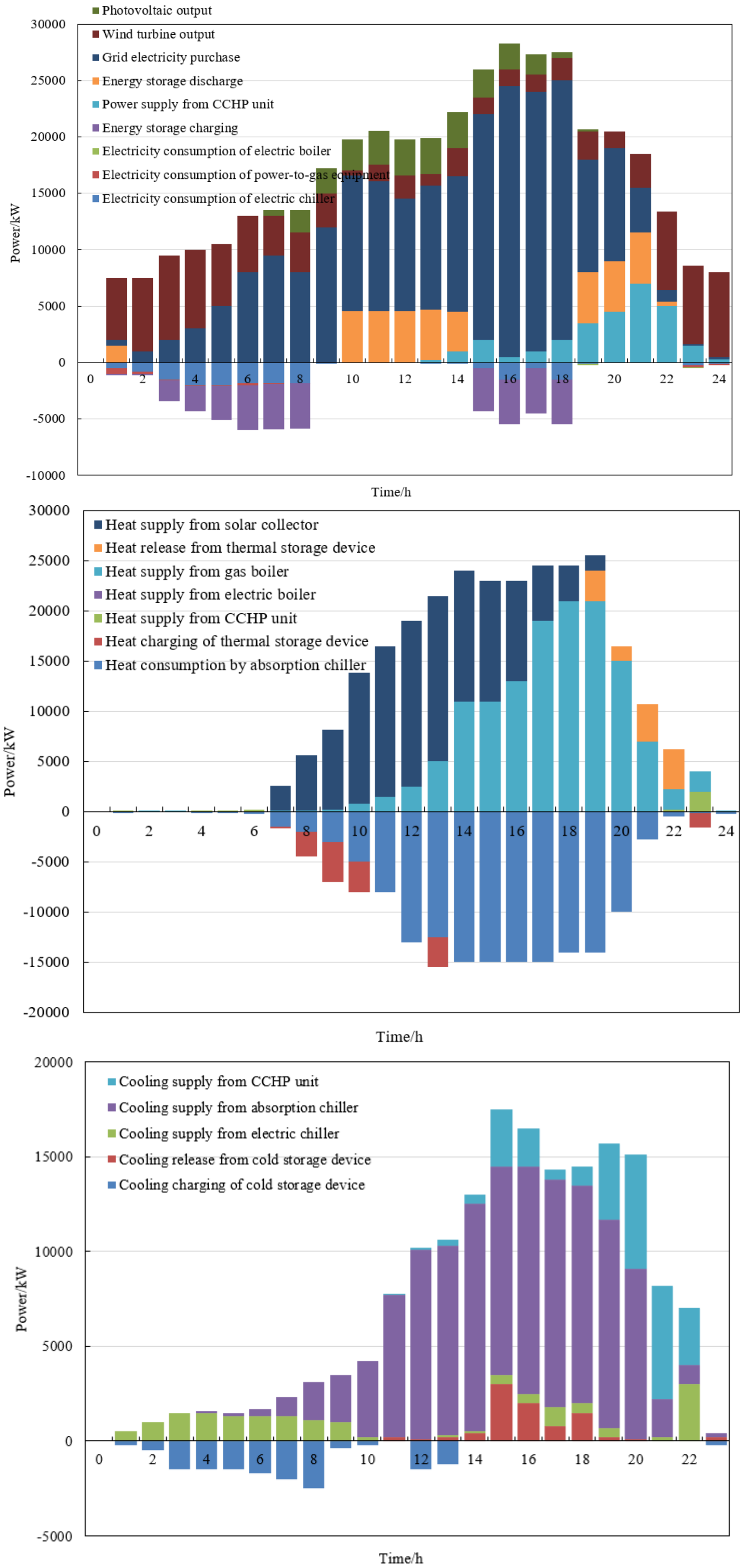

Figure 7. Scheduling results of hybrid energy system with renewable energy generation

5. CONCLUSION

This paper focused on the hybrid energy system with renewable energy generation and forms two core contents: First, through system architecture construction and exergy analysis, the exergy flow characteristics and exergy loss distribution of each component were clarified, revealing the key influencing factors of thermodynamic performance and laying a theoretical foundation for system energy efficiency optimization; Second, an economic scheduling evaluation model was constructed, which comprehensively considers cost factors and the uncertainty of renewable energy to achieve economic optimization under multiple scenarios. The research results show that efficient equipment such as the CCHP unit can significantly replace traditional high-energy-consuming equipment, and the coordinated scheduling of energy storage and renewable energy can effectively improve the energy absorption rate, reduce total system cost and environmental cost. The value of this study lies in providing a "thermodynamic-economic" dual-dimensional analysis framework for the planning, design and operation scheduling of hybrid energy systems, supporting the integration of a high proportion of renewable energy, and promoting the energy system towards high efficiency, economy, and low carbon.

However, the study still has certain limitations: the model does not fully consider the complex factors in actual operation, and some assumptions in the multi-objective optimization process simplify real scenarios, which may affect the model's generalizability. At the same time, the model has high computational complexity, and its computational efficiency for large-scale systems needs to be improved. Future research can focus on introducing more accurate real-time prediction models, exploring lightweight and efficient algorithms, and deepening multi-objective coordination mechanisms to further expand the model's adaptability to complex scenarios. In addition, new energy storage technologies or innovative system architectures can be integrated to continuously explore the potential for improving the economic performance and energy efficiency of hybrid energy systems, promoting theoretical research towards more practically instructive directions.

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