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# A Thermodynamics-Based Carbon Accounting Model for Carbon Emissions: A Multi-Objective Coupling Analysis of Energy Conservation and Cost Accounting

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## ABSTRACT

In the context of global "dual carbon" goals and the growing demand for low-carbon transitions in enterprises, traditional carbon emission accounting methods fall short in high energy-consuming industries due to their neglect of energy quality differences and cost coupling relationships. Existing studies typically rely on the first law of thermodynamics or focus solely on economic costs, lacking sufficient analysis of the energy-carbon-cost nexus and a comprehensive multi-objective coordination mechanism. This paper focuses on the coupling relationships among energy flow, carbon emissions, and cost control within enterprise production systems, and proposes a thermodynamics-based carbon accounting model tailored for carbon accounting purposes. Through interdisciplinary integration, six key areas of research are developed: revealing the intrinsic linkages among energy, carbon, and cost based on exergy analysis; quantifying energy quality differences via energy quality coefficients; constructing subsystem models grounded in exergoeconomics to analyze coupling mechanisms; designing multi-objective evaluation indicators; establishing component models and constraints; and developing a carbon accounting method suitable for complex industrial processes. This research breaks through the limitations of traditional single-dimensional accounting by, for the first time, deeply integrating the thermodynamic principle of energy conservation with the cost accounting framework of managerial accounting. It provides a theoretical tool for enterprises to accurately identify high-carbon and inefficient processes, balance carbon reduction costs and benefits, and supports the implementation of "dual carbon" goals in the industrial sector with significant methodological value.

## 1. INTRODUCTION

Driven by the global "dual carbon" goals, enterprise carbon emission accounting [1, 2], as a core component of the carbon accounting system, is facing the transformational challenge from single-dimensional emission measurement to multi-dimensional coupling analysis of "energy-carbon-cost". Traditional carbon emission accounting methods are mostly based on the Intergovernmental Panel on Climate Change (IPCC) inventory method or input-output models [3-6]. Although they can realize the quantification of carbon emissions, they fail to accurately portray the thermodynamic essence of energy conversion and the economic correlation of cost accounting in production systems. With the development of enterprise low-carbon management towards refinement and scientific approaches [7, 8], it is urgent to construct a new model integrating the thermodynamic principle of energy conservation with the accounting framework of cost accounting, to solve the problem of coordinated optimization of energy flow, carbon emissions, and cost control in high energy-consuming industries.

Introducing thermodynamic theory into the field of carbon accounting and analyzing the energy-carbon conversion mechanism in enterprise production processes through the law of energy conservation can not only break through the limitation of traditional accounting methods assuming "energy homogeneity" [9], but also provide a scientific basis at the physical level for the quantification of carbon cost [10]. Specifically, constructing a carbon emission accounting model from the thermodynamic perspective can realize two core values: First, accurately identify the energy efficiency defects of high carbon emission links from the dimension of energy quality, and provide targeted paths for process improvement, second, perform coupling analysis of the environmental cost of carbon emissions and production costs, assisting enterprises in balancing short-term cost input and long-term environmental benefits in carbon reduction decisions, promoting the coordinated optimization of “carbon reduction” and “cost reduction”. This interdisciplinary research not only enriches the methodological system of carbon accounting but also has practical guiding significance for the low-carbon transformation of high energy-consuming industries.

In existing studies, some scholars have attempted to apply thermodynamic methods to carbon emission accounting [11-14], but generally suffer from insufficient coupling of “energy-cost”. For example, literature [15] constructed an industrial system carbon emission model, which achieved carbon flow calculation under energy conservation, but did not include the impact of energy quality differences on cost, resulting in a disconnect between accounting results and actual enterprise cost control needs. The carbon cost accounting framework proposed in literature [16] integrated financial data, but relied on empirical coefficients for the conversion between energy and carbon emissions, ignoring the real driving effect of exergy loss during equipment operation on carbon emissions, making the model limited in applicability to complex processes. In addition, traditional studies mostly focus on single objectives and lack systematic analysis of the coupling relationship between the two, which is difficult to meet the multi-objective decision-making needs of enterprises [17, 18].

This paper conducts six aspects of research around the "energy-carbon-cost" coupling system: 1) construct the theoretical basis of exergy analysis of the energy-carbon-cost coupling system based on thermodynamics, revealing the intrinsic relationship among energy quality (exergy), carbon emissions, and cost, 2) propose an energy quality coefficient accounting method for the energy-carbon-cost coupling system, quantifying the exergy value and carbon intensity of different forms of energy, 3) construct subsystem models based on exergoeconomics to analyze the coupling mechanism of exergy cost and carbon emissions in the energy conversion process of production, 4) design comprehensive evaluation indicators for multi-objective coupling analysis to realize the coordinated evaluation of carbon reduction efficiency and cost effectiveness, 5) establish component models and constraints for the system to provide a theoretical framework for modular accounting of complex industrial systems, 6) develop a carbon emission accounting method suitable for high energy-consuming industries to realize cross-dimensional integration from energy conservation analysis to cost accounting. This paper, for the first time, combines exergy analysis theory with carbon accounting, and constructs a multi-objective coupling model with both physical accuracy and economic practicality, which not only makes up for the shortcomings of traditional methods in energy quality analysis and cost integration, but also provides enterprises with a practical “energy-carbon-cost” coordinated management tool, helping them to achieve a win-win situation in environmental and economic benefits under the carbon neutrality target.

## 2. CONSTRUCTION OF A THERMODYNAMIC-BASED CARBON EMISSION ACCOUNTING MODEL FOR CARBON ACCOUNTING

### 2.1 Exergy analysis theoretical basis of the energy-carbon-cost coupling system based on thermodynamics

The exergy analysis theoretical basis of the energy-carbon-cost coupling system based on thermodynamics is essentially to construct a cross-dimensional bridge connecting the physical properties of energy, carbon emission intensity, and cost accounting through the quantitative analysis of energy quality—exergy. As the core indicator for measuring the usable value of energy, exergy's "exergy balance method" can accurately identify exergy losses in the energy transfer and conversion process of production systems. Such exergy losses not only indicate the inefficiency of energy utilization but also inherently align with the generation of carbon emissions. High exergy loss segments are often accompanied by inefficient energy conversion, leading to excessive fossil energy consumption and additional carbon emissions. For carbon accounting, the introduction of exergy analysis theory can break through the limitations of the “energy homogenization” assumption in traditional accounting by reconstructing the coupling relationship of "energy-carbon-cost" from the perspective of energy quality differences: on the one hand, the exergy value quantifies the actual working capacity of different forms of energy, providing a more production-realistic physical basis for carbon emission accounting, on the other hand, it maps exergy losses to environmental and production costs, enabling carbon accounting to identify implicit carbon costs caused by energy quality degradation. This provides a theoretical basis for enterprises to incorporate the environmental impact of energy quality into cost accounting.

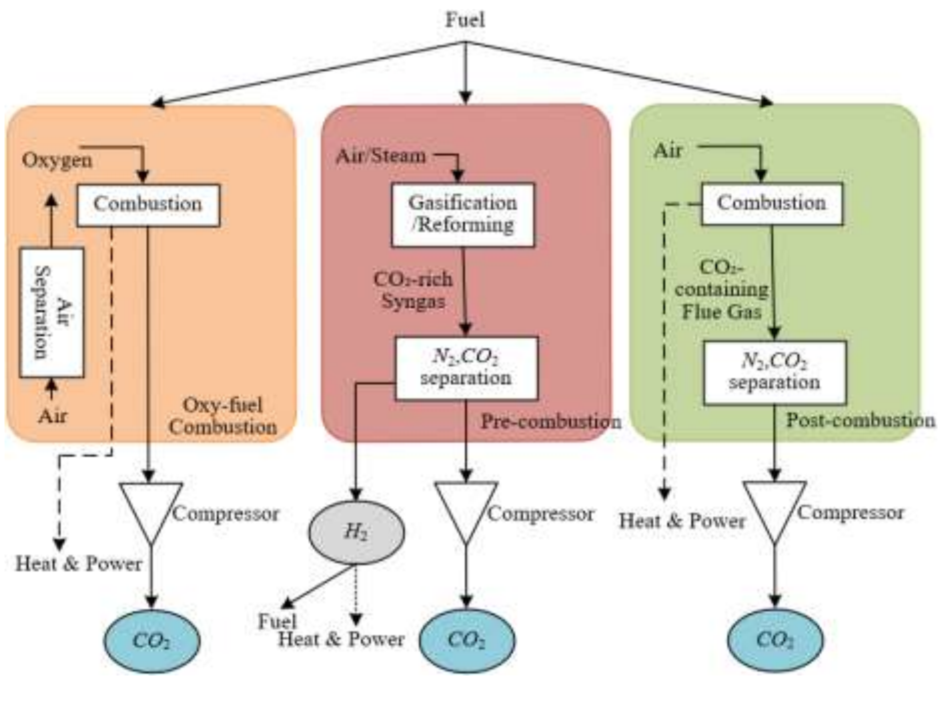


**Figure 1.** Common carbon emission capture processes and flows

## 2.2 Exergy coefficient accounting of the energy-carbon-cost coupling system

Figure 1 shows common carbon emission capture processes and flows. Traditional carbon accounting methods mostly rely on the quantity of energy to calculate carbon emissions, ignoring the essential differences in working capacity among different forms of energy such as electrical energy, thermal energy, and mechanical energy. For example, the exergy value of 1 kWh of electricity is much higher than that of 1 kWh of steam thermal energy, but their carbon emission intensities may differ significantly due to different energy sources. The accounting of exergy coefficients introduces thermodynamic exergy analysis theory, integrating both the "quantity" and "quality" of energy into the accounting system. This allows carbon accounting to accurately identify the high-efficiency utilization potential of high-exergy energy during conversion processes and the recovery value of low-exergy energy. This kind of accounting not only provides a quality benchmark more aligned with real production processes for the physical measurement of carbon emissions, but also enables carbon accounting to convert the cost of exergy loss during energy quality degradation into quantifiable environmental and economic costs, thus realistically reflecting the distribution of carbon costs caused by differences in energy utilization efficiency in financial statements.

Meanwhile, from the multi-objective coupling requirement of the research, the accounting of exergy coefficients is also the bridge for cross-dimensional integration of "energy conservation analysis" and "cost accounting." One of the core tasks of carbon accounting is to provide cost-benefit analysis for corporate carbon reduction decisions, and the carbon conversion efficiency and cost input corresponding to different energy qualities vary significantly. For example, improving the utilization efficiency of high-exergy energy may bring higher carbon reduction benefits and long-term cost savings, while traditional accounting methods that ignore energy quality often fail to accurately measure such differences. Through the quantification of exergy coefficients, carbon accounting can establish a three-dimensional correlation model of "energy quality–carbon emission intensity–cost input," coupling indicators such as exergy efficiency in thermodynamics, carbon emissions per unit value in carbon accounting, and energy cost ratios in accounting into a unified analysis system. This enables enterprises to accurately assess the marginal benefits of "carbon reduction–cost" for different segments based on exergy coefficients when formulating reduction strategies, avoiding decision deviations caused by the lack of energy quality accounting.

Specifically, based on thermodynamic exergy theory, exergy coefficients for different energy forms such as electricity, natural gas, hydrogen, thermal energy, and cooling energy are calculated according to their differences in working capacity:

•Electrical energy, as high-quality energy, has its exergy coefficient $\eta_r$ directly defined as 1, since it can theoretically be 100% converted into mechanical work or other forms of energy under ideal conditions, and its exergy value equals its energy quantity.

•Fuel energies such as natural gas and hydrogen require calculation of $\eta$ values using the chemical reaction exergy formula, based on their calorific value and reversible working capacity under environmental benchmarks, reflecting the theoretical limit of converting chemical energy into effective work.

•The exergy coefficients $\eta_g$ and $\eta_z$ of thermal and cooling energy are closely related to temperature. Based on the Carnot cycle principle, their quality is quantified by Eq. (3) and Eq. (4). The $\eta_g$ of high-temperature thermal energy approaches 1, while the $\eta_z$ of low-temperature cooling energy may be below 0.5. Carbon accounting, through this step, upgrades energy from "quantity measurement" to "quality–quantity dual-dimensional accounting," establishing a unified physical benchmark for subsequent coupling analysis of carbon emissions and costs.

Specifically, the steady-state exergy in the system can be expressed as the product of $\eta$ and power $O$:

$$r = \eta O \tag{1}$$

Assuming the environmental temperature is represented by $S_0$, and the complete combustion temperature of the fuel is represented by $S$, the formula for calculating the exergy coefficients of natural gas and hydrogen is:

$$\eta_h = 1 - \frac{S_0}{S - S_0} LN \frac{S}{S_0} \tag{2}$$

Assuming the temperatures of thermal and cooling loads are represented by $S_g$ and $S_z$, the calculation formulas for $\eta_g$ and $\eta_z$ are:

$$\eta_g = 1 - \frac{S_0}{S_z} \tag{3}$$

$$\eta_z = \frac{S_0}{S_z} - 1 \tag{4}$$

Further, for each type of energy, match its corresponding carbon emission factor based on the energy quality coefficient, to calculate the unit exergy-based carbon emission. For thermal energy conversion equipment, through the exergy loss–carbon emission coupling model, the exergy loss during equipment operation is converted into equivalent carbon emissions. For example, for an industrial furnace, every 10% reduction in exergy efficiency means that additional consumption of high exergy-value fuels will generate incremental carbon emissions. Carbon accounting can, through the energy quality coefficient as a hidden emission cost, avoid the one-sidedness of traditional accounting that only calculates carbon emissions based on fuel consumption. To achieve final energy procurement cost allocation, based on the energy quality coefficient of different energies, procurement costs are allocated to effective exergy value and exergy loss cost. For instance, the procurement cost of natural gas can be split into the effective energy cost corresponding to the exergy value and the environmental cost unrelated to exergy value, allowing carbon accounting to distinguish between the effective cost used for performing work and the ineffective cost ultimately converted into carbon emissions. In the depreciation and maintenance cost of fixed assets, introduce the exergy efficiency loss cost quantified by energy quality coefficient of equipment. For example, an electric motor with an exergy efficiency of 60%, the additional electricity consumption caused by exergy loss each year can be converted into a specific cost item through an energy quality coefficient of $\eta_r$=1, included in the full-cycle carbon cost assessment of the equipment, avoiding the defect of traditional accounting that only calculates initial investment and apparent energy consumption. Finally, through energy quality coefficient, link carbon pricing with energy quality, and establish the unit exergy-based carbon price. High-$\eta$ value energy has a lower unit exergy-based carbon price, while low-$\eta$ value energy's carbon price allocation needs to be combined with its actual exergy contribution, guiding enterprises to prioritize the use of high-exergy, low-carbon energy, achieving unified decision-making of carbon reduction and cost reduction.

### 2.3 Construction of subsystem model for energy-carbon-cost coupled system based on exergy economics

Figure 2 shows the energy-carbon-cost coupled system model under the carbon accounting framework. Further, under the model framework, subsystem models are constructed. Firstly, the enterprise production system is decomposed into several independent subsystems according to functional units, and exergy flow is taken as the core link of energy interaction between subsystems.

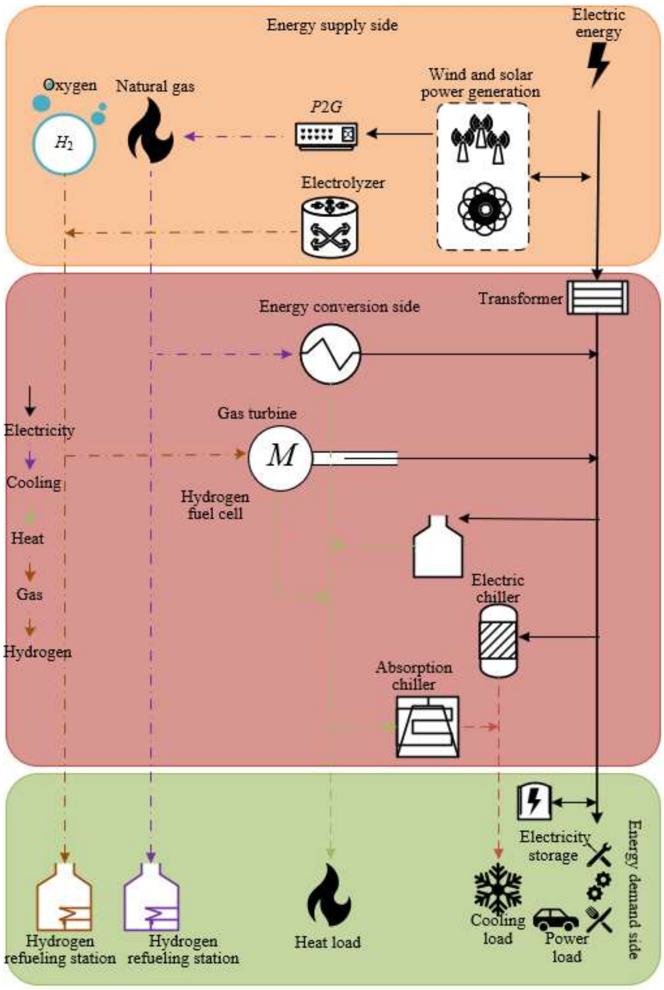


**Figure 2.** Energy-carbon-cost coupled system model under the carbon accounting framework

By establishing an event matrix, clearly mark the association between each subsystem and different exergy flows: if a certain exergy flow enters the subsystem, mark it as 1, if it flows out of the subsystem, mark it as -1, if there is no direct relation, mark it as 0. For example, for the blast furnace ironmaking subsystem of a steel plant, its input exergy flows include coke chemical exergy and blast kinetic exergy, output exergy flows include molten iron exergy and blast furnace gas exergy, while the electric energy exergy flow unrelated to the plant lighting system is marked as 0. The matrix description provides a visualized energy flow map for carbon accounting, enabling precise identification of key subsystems with high exergy flow input and output, and identification of potential high energy consumption and high carbon emission links, laying the groundwork for targeted cost accounting. Specifically, the system is divided into $l$ subsystems interrelated by $v$ types of exergy flows, and the event matrix $X(u\times k)$ indicates the relation between subsystem $u$ and exergy flow $k$. Suppose $v$ types of exergy flows are represented by matrix $Ra(v\times v)$, the unit exergy economic cost of exergy flow is denoted by matrix $z(v\times 1)$, and the non-energy cost of subsystem is denoted by matrix $C(l\times 1)$. The cost equation is:

$$X \times Ra \times z + C = 0 \quad (5)$$

Each subsystem needs to meet the exergy flow cost balance principle, that is, the total cost of input exergy flows should equal the total cost of output exergy flows, internal energy loss cost of the subsystem, and environmental cost of carbon emissions. However, due to the fact that the types of exergy flows in actual production systems usually exceed the number of subsystems, the subsystem's own cost balance equations alone cannot form a complete solvable system. Traditional cost accounting often ignores the implicit losses caused by energy quality differences, while this study incorporates such exergy loss costs and carbon emission costs uniformly into the accounting framework, forming a multi-dimensional cost balance relationship. At this point, the core task of carbon accounting is transformed into identifying equation gaps — that is, which exergy flows' unit costs still need to be further determined through external conditions or internal rules, clarifying the direction for the establishment of subsequent supplementary equations.

To solve the problem of the open system of equations, carbon accounting needs to establish supplementary equations through exergy flows with known external prices. For energy purchased from outside, its unit exergy cost can directly adopt the market price as a known condition, forming an independent pricing anchor point. For example, the energy quality coefficient of purchased electricity is the highest, and its unit exergy cost can directly be equal to the electricity price without additional calculation. For internally generated exergy flows without explicit market prices in the system, the opportunity cost method is used for pricing, i.e., the cost of substituting unrecovered waste heat by purchased energy is taken as its implicit value. Suppose there are $a$ exergy flows entering the system, and the input exergy flow matrix is denoted as $X_1(a\times v)$, then the expression of the exergy flow cost supplementary equation is:

$$X_1 \times Ra \times z = Z_A \quad (6)$$

On the basis of a closed system of equations, carbon accounting needs to reasonably allocate the costs of subsystems in multi-output scenarios according to energy quality. For example, when a power subsystem simultaneously outputs high-quality mechanical energy and low-quality waste heat exergy, the input total cost should be allocated based on the energy quality difference of the two. Mechanical energy with a high energy quality coefficient bears a higher proportion of the effective cost, while waste heat with a low energy quality coefficient corresponds to a lower cost allocation. Meanwhile, carbon emission costs should be allocated based on the actual carbon intensity of each output exergy flow, to ensure that low-carbon high-exergy output flows are not unreasonably allocated excessive environmental costs. The cost allocation equation is:

$$\frac{z_1^{'}}{\eta_1}=\frac{z_2^{'}}{\eta_2}=\ldots=\frac{z_j^{'}}{\eta_j} \tag{7}$$

Suppose the energy quality coefficient matrix of the output exergy flows is represented by $X_2(e\times v)$, the matrix expression of the cost allocation equation is:

$$X_2\times Ra\times z=0 \tag{8}$$

Arranging the above three formulas into a unified form yields:

$$X'\times Ra\times z+C'=0 \tag{9}$$

where,

$$A'(n\times n)=\begin{pmatrix}A\\A_1\\A_2\end{pmatrix},Z'(n\times 1)=\begin{pmatrix}Z\\-C\\0\end{pmatrix}$$

$$X'(v\times v)=\begin{pmatrix}X\\X_1\\X_2\end{pmatrix},C'(v\times 1)=\begin{pmatrix}C\\-Z\\0\end{pmatrix}$$

### 2.4 Comprehensive evaluation indicators for energy-carbon-cost systems

(1) Exergy loss: A quantitative measure of energy quality degradation and a hidden driving indicator of carbon cost

Under the carbon accounting framework, exergy loss is defined as the permanent loss of the ability to do work due to irreversible factors during energy transmission and conversion processes. In essence, it is the degradation of high-quality energy into low-quality energy. For the energy-carbon-cost coupled system, exergy loss not only reflects the physical defect of energy utilization efficiency, but also directly relates to the incremental cost of carbon emissions. Each unit of exergy loss means that the system needs to consume additional high-exergy-value energy to make up for the insufficient work capacity, thus producing extra $CO_2$ emissions. By tracking the exergy loss of each subsystem, key links of energy quality cliff-type degradation can be accurately located, and the exergy loss amount of these links can be converted into equivalent carbon costs, making the energy quality degradation costs that are ignored in traditional accounting visible, providing dual support for cost allocation and emission reduction decisions. Suppose the system's exergy loss is denoted by $Ra_{LOSS}$, the input exergy flow by $\Sigma Ra_{IN}$, and the output exergy flow by $\Sigma Ra_{OUT}$, the calculation formula for exergy loss is:

$$Ra_{LOSS}=\sum Ra_{IN}-\sum Ra_{OUT} \tag{10}$$

(2) Exergy efficiency: Coupled evaluation index of energy utilization effectiveness and low-carbon potential

Exergy efficiency, as the ratio of the actual work potential of the system to the theoretical maximum work potential, is the core index connecting thermodynamic performance and carbon accounting goals. In the energy-carbon-cost coupled system, the economic significance of exergy efficiency goes beyond mere energy utilization rate. High exergy efficiency means that the system achieves the same production goal with less high-quality energy input, directly reducing fossil energy consumption and carbon emissions. For example, for an industrial motor, every 5% increase in exergy efficiency not only reduces electricity consumption but also decreases the indirect carbon emissions generated by power production. This energy efficiency-carbon efficiency synergy can be quantified in carbon accounting as the reduction in carbon cost corresponding to per unit exergy efficiency improvement. Enterprises can use the exergy efficiency index to predict the comprehensive benefits of energy-carbon-cost during equipment selection and process design stages, thus avoiding the shortcomings of traditional efficiency indicators which only focus on energy quantity and ignore quality differences. The formula for calculating exergy efficiency is as follows:

$$\lambda_{Ra}=\frac{\sum Ra_{OUT}}{\sum Ra_{IN}} \tag{11}$$

(3) Exergy loss cost: Economic monetization measurement of energy quality degradation

Exergy loss cost is a key index that converts exergy loss from a thermodynamic physical quantity into an accounting monetary value. It is defined as the additional economic cost borne by the system due to the degradation of energy quality, including two parts: (1) Direct energy compensation cost: additional energy purchase expenditure due to exergy loss, (2) Environmental external cost: carbon emission cost corresponding to the additional energy consumption. Carbon accounting establishes an exergy loss–price factor conversion model to incorporate the exergy losses of subsystems into the cost accounting system. This index allows carbon accounting to embed thermodynamic analysis results directly into financial reports, presenting to management the transmission path of low energy efficiency → increased costs → profit erosion. Assuming the exergy loss cost of the system is denoted by $Z_{LOSS}$, and the economic cost of unit exergy loss in a subsystem is denoted by $Z_{LOSS}$, then the calculation formula of exergy loss cost is:

$$Z_{LOSS}=Ra_{LOSS}z_{LOSS} \tag{12}$$

(4) Exergy economic coefficient: Dynamic evaluation metric of system energy saving and carbon reduction potential

The exergy economic coefficient is defined as the ratio of unit exergy loss cost to unit product output value, used to measure the potential improvement space per unit economic output in energy quality management. This index integrates both thermodynamic efficiency and economic benefit dimensions: a low exergy economic coefficient indicates a low proportion of exergy loss cost and small potential for energy saving and carbon reduction, a high exergy economic coefficient indicates significant deficiencies in energy quality management, and by reducing exergy loss, higher cost savings and marginal carbon reduction benefits can be obtained.

Carbon accounting uses the exergy economic coefficient to achieve differentiated evaluations of various subsystems. For example, in the sintering and cold rolling processes of a steel plant, if the exergy economic coefficient of the former is three times that of the latter, the sintering process is prioritized for energy-saving transformation, as each reduction of 1 unit exergy loss brings higher value-cost ratio optimization. This index provides enterprises with a multi-objective decision-making tool from the input-output perspective, shifting carbon reduction actions from policy-driven to value-driven, ensuring that limited resources are invested in links with the most significant energy efficiency improvements and cost savings. The following formula gives the exergy economic coefficient:

$$d_{Ra} = \frac{C}{z_{LOSS} Ra_{LOSS} + C} \tag{13}$$

**2.5 Energy-carbon-cost coupled system component model and constraint conditions**

(1) Component model and constraint conditions of P2G device

As the core unit for converting electric energy into chemical energy, the energy-carbon-cost coupled model of the P2G device needs to describe the one-way conversion process from electrical exergy input → syngas exergy output. On the input side is high-exergy electric energy generated from the grid or renewable energy sources, which is converted into syngas through electrolysis, methanation, and other processes. The syngas exergy flow on the output side enters the subsequent energy utilization stages. Carbon accounting needs to simultaneously track two types of cost flows: one is the electricity purchase cost and corresponding carbon emission cost, the other is the exergy loss cost during equipment operation. Specifically, assuming the input power and output natural gas volume of the P2G device are represented by $O^{IN}{}_{P2G}$ and $O^{OUT}{}_{P2G}$ respectively, the component model expression is:

$$O_{P2G}^{PUT} = \lambda_{P2G} O_{P2G}^{IN} \tag{14}$$

Constraint conditions of the P2G device component model:

*Energy conversion unidirectionality*: the device only allows electric exergy flow input, reverse input of syngas exergy flow is prohibited,

*Exergy efficiency threshold constraint*: a minimum ratio of syngas exergy output to electric exergy input is set, and cost warnings are triggered when below the threshold,

*Carbon intensity linkage constraint*: if the input electric energy is generated from fossil energy, then the carbon emission per unit exergy value of the syngas must be calculated in real time based on the electricity carbon intensity/syngas energy-quality coefficient, ensuring accurate association of carbon emission accounting in downstream usage with upstream energy attributes.

(2) Component model and constraint conditions of electrolyzer device

The electrolyzer device generates hydrogen and oxygen by driving water decomposition through electric energy. Its model focuses on the conversion link from electric exergy to hydrogen exergy. The input side is direct current electricity, and the output side is high-pressure hydrogen exergy flow, accompanied by the discharge of low-exergy waste heat. Carbon accounting needs to couple the energy consumption cost of the electrolyzer with the exergy value benefit of hydrogen, and simultaneously quantify the implicit exergy loss cost caused by unrecovered waste heat. Specifically, assuming the input power and output hydrogen volume of the electrolyzer are represented by $O_{Rs}{}^{IN}$ and $O_{Rs}{}^{OUT}$ respectively, the component model expression is:

$$O_{Rs}^{IN} = \eta_{Rs} O_{Rs}^{OUT} \tag{15}$$

Constraint conditions of the electrolyzer device component model:

*Operational mode exclusivity*: at any moment, the device can only be in electrolysis mode or shutdown mode, reverse electric energy flow is prohibited,

*Current density boundary condition*: upper and lower limits are set for the working current of the electrolyzer, and when exceeded, the operating power is automatically adjusted to ensure the exergy efficiency remains in the economic interval,

*Hydrogen-carbon balance constraint*: every 1 kg of hydrogen produced must match the corresponding electricity carbon footprint, and this carbon emission amount is pre-allocated to the subsequent usage stage of hydrogen, realizing full-chain carbon cost tracing from electricity to hydrogen.

(3) Component model and constraint conditions of energy storage device

As a spatial-temporal energy allocation unit, the energy storage device model needs to describe the dynamic of exergy flow in both directions: energy input and storage → energy release and output. During the charging stage, high-exergy electric energy from the grid or renewable energy is received, with self-discharge or evaporation during storage leading to exergy loss, during the discharging stage, the stored energy is released and converted into usable exergy flow, accompanied by efficiency loss in the conversion process. Carbon accounting needs to establish the relationship among storage medium exergy value, storage duration, and cost amortization. For example, in battery energy storage, each cycle of charging and discharging exergy loss corresponds to the allocation of equipment depreciation cost and additional energy consumption cost. The change in energy storage amount of the energy storage system from time period $s$ to $s+\Delta s$ is described as follows. Assuming the energy storage amount at time $s+\Delta s$ and $s$ are represented by $R^{a+\Delta s}{}_{a}$ and $R^{s}{}_{a}$ respectively, the charging power and discharging power at time $s$ are represented by $O^{s}{}_{a,z}$ and $O^{s}{}_{a,f}$ respectively, and the charging and discharging efficiencies are denoted by $\lambda_{a,z}$ and $\lambda_{a,f}$, then the component model expression is:

$$R_a^{a+\Delta s} = R_a^s + \left( O_{a,z}^s \lambda_{a,z} - \frac{O_{a,f}^s}{\lambda_{a,f}} \right) \Delta s \tag{16}$$

Constraint conditions of energy storage device component model:

*Mutual exclusivity of charging and discharging states*: Only charging or discharging can be performed at the same moment, bidirectional flow is prohibited.

*Power and capacity boundary limitation*: Set upper limits of charging/discharging power to avoid overcharge/discharge-induced lifetime degradation, and set minimum remaining capacity to ensure the system's peak-shaving capability.

*Exergy loss cost allocation*: Set differentiated exergy loss sharing rules according to storage technology type. For example, the self-discharge exergy loss of lithium batteries is accounted into operation cost based on storage duration × unit capacity exergy value × self-discharge rate, for hydrogen storage tanks, the evaporation loss needs additional accounting of carbon emission cost from hydrogen production.

Assuming that the maximum charging and discharging powers are represented by $O_{a,z}^{MAX}$ and $O_{a,f}^{MAX}$ respectively, the constraint inequality is as follows:

$$\begin{cases} 0 \le O_{a,z}^{s} \le i_a^s O_{a,z}^{MAX} \\ 0 \le O_{a,f}^{s} \le \left(1 - i_a^s\right) O_{a,f}^{MAX} \end{cases} \tag{17}$$

### 2.6 Carbon emission accounting method of the energy-carbon-cost coupled system

The carbon emission accounting of the energy-carbon-cost coupled system is based on the law of thermodynamic energy conservation. By identifying the physical correlation paths of energy-carbon flows, the total carbon emissions are deconstructed into three core modules: Direct emissions, indirect emissions, and carbon absorption, for accurate measurement:

*Gas turbine direct emission*: Focuses on $CO_2$ emissions generated by fossil fuel combustion due to chemical energy conversion. A mapping relationship is established based on the exergy value and carbon intensity of the fuel. For example, the higher heating value exergy of natural gas is directly related to its carbon-hydrogen ratio. Carbon accounting should calculate the theoretical emission as fuel input exergy flow × fuel carbon intensity, and correct the actual emission through device exergy efficiency.

*Grid indirect emission*: For implicit carbon emissions of purchased electricity, link the electricity's exergy quality coefficient with the grid's mixed carbon intensity. Use electric exergy input × grid carbon intensity as the basis for indirect emission accounting, avoiding the defect of traditional accounting that only measures enterprise-owned emissions and ignores upstream energy production carbon footprints.

*P2G equipment carbon absorption*: As a negative emission module, it accounts for the carbon fixation amount through capturing $CO_2$ and converting it to syngas. Quantified as carbon capture efficiency × input $CO_2$ flow, it directly offsets the system's total emissions, reflecting the contribution of the carbon utilization process to the carbon neutrality goal.

This classification-based quantification method incorporates various forms of energy-carbon flows into a unified accounting system through exergy flow tracing, enabling carbon accounting to penetrate production processes, identify high-carbon segments and low-carbon advantages, and provide accurate physical basis for cost aggregation. Assuming the grid carbon emission factor is denoted by $\omega_r$, the gas turbine $CO_2$ emission coefficient is denoted by $\omega_{hs}$, and the $CO_2$ absorption coefficient of P2G equipment is denoted by $\omega_{P2G}$. The specific expressions are as follows:

$$Zx_{TA} = Zx_{DI} + Zx_{IN} - Zx_{P2G} \tag{18}$$

$$\begin{cases} Zx_{DI} = \omega_{hs} O_{hs}^{OUT} \\ Zx_{IN} = \omega_r O_{IN} \\ Zx_{AB} = \omega_{P2G} O_{P2G}^{OUT} \end{cases} \tag{19}$$

Assuming the lower heating value of natural gas is represented by MGN, and the efficiency of P2G equipment is represented by $\lambda_{P2G}$. The relationship between the amount of methane $N_{CH4}$ produced by P2G and the power consumption $O_{P2G}$ can be expressed as:

$$O_{o2h} = \frac{1}{3.6} \frac{MGN}{\lambda_{P2G}} N_{CH_4} \tag{20}$$

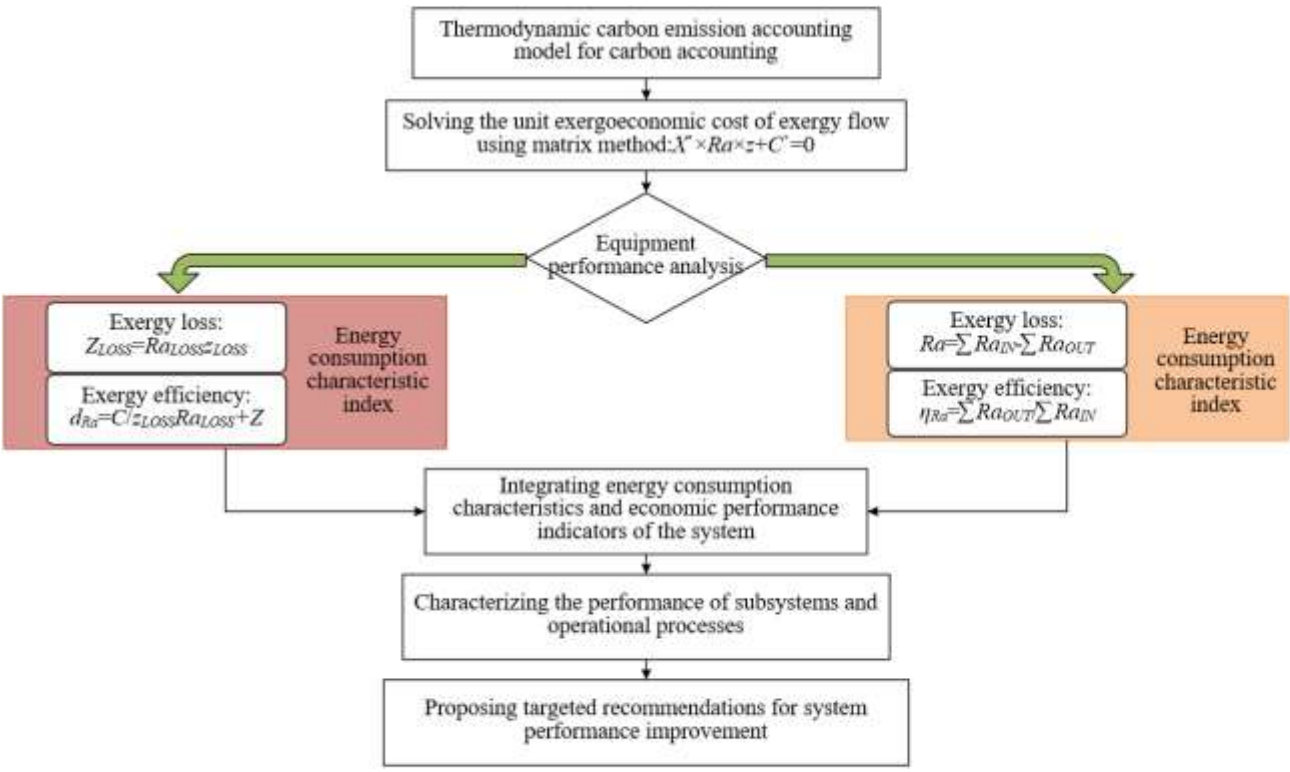


**Figure 3.** Solving flowchart of the energy-carbon-cost coupled system model under the carbon accounting framework

Assuming the molar volume of methane and the molar mass of $CO_2$ are represented by $N^l_{CH4}$ and $L^l_{CO2}$ respectively. When a certain volume of $N_{CH4}$ is generated, the fixed $CO_2$ can be expressed as:

$$L_{CO_2} = \frac{N_{CH_4}}{N^l_{CH_4}} L^l_{CO_2} \tag{21}$$

As the core parameter linking carbon emission physical quantity and economic cost, carbon price plays a value benchmark role in accounting. The classified direct emission, indirect emission, and net emission are multiplied by the carbon price respectively, and converted into environmental cost that can be included in the income statement. Through linkage analysis of carbon price – exergy quality coefficient – cost, carbon accounting can evaluate the cost-effectiveness of different emission reduction measures. For example, increasing gas turbine exergy efficiency by 1% can reduce fuel consumption by 5,000 tons and correspondingly reduce $CO_2$ emissions by 15,000 tons, although extending the operating time of P2G equipment increases electricity procurement cost, its carbon absorption effect can reduce net emission cost. Enterprises can choose the optimal emission reduction path through marginal cost comparison. This principle breaks through the limitation of traditional carbon accounting that emphasizes measurement and ignores analysis, using carbon price as a bridge between thermodynamic analysis and cost accounting. It enables enterprises to quantify both emission reduction investment and cost saving simultaneously in energy system design, energy procurement, and carbon management, achieving a dynamic balance between environmental and economic benefits. Through this accounting method, carbon accounting evolves from a mere emission recorder to a decision enabler for multi-objective optimization, providing scientific quantitative tools for enterprise cost control and strategic transformation in the carbon-neutral era. Figure 3 shows the solving flowchart of the energy-carbon-cost coupled system model under the carbon accounting framework.

## 3. EXPERIMENTAL RESULTS AND ANALYSIS

Figures 4 and 5 show the variation curves of wind-solar power generation and the variation curves of load-side energy demand. In the wind-solar power variation curves, photovoltaic power shows obvious day-night characteristics. Power is zero from midnight to early morning, rises gradually with sunrise, fluctuates during the day, and returns to zero at night, reflecting the light-dependent nature of solar power. Wind power fluctuates sharply and irregularly without clear pattern in different time periods, reflecting the instability of wind resources. The variation curves of load-side energy demand show that: electric load rises gradually from midnight to morning and fluctuates during subsequent periods, cold load shows a rising then falling trend, peaking from afternoon to evening, heat load is relatively stable with small fluctuations, gas load and hydrogen load fluctuate slightly overall, with hydrogen load remaining at a low level. These curves collectively reveal the intermittency and volatility of energy supply, and the diversity and temporal variability of load-side demand, providing foundational data reflecting the dynamic characteristics of the system for building a thermodynamics-based energy-carbon-cost coupled system.

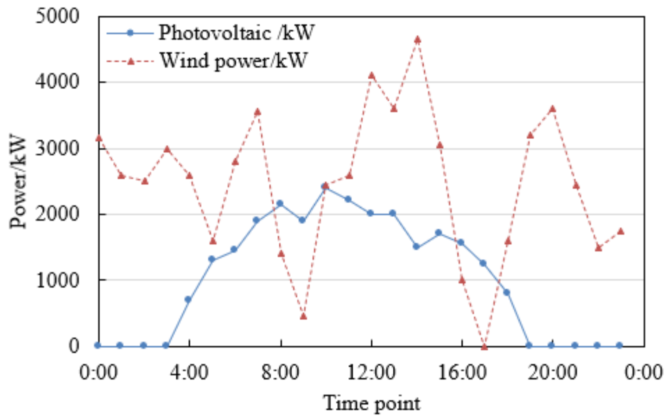


**Figure 4.** Thermodynamic carbon emission accounting model wind-solar power variation curve

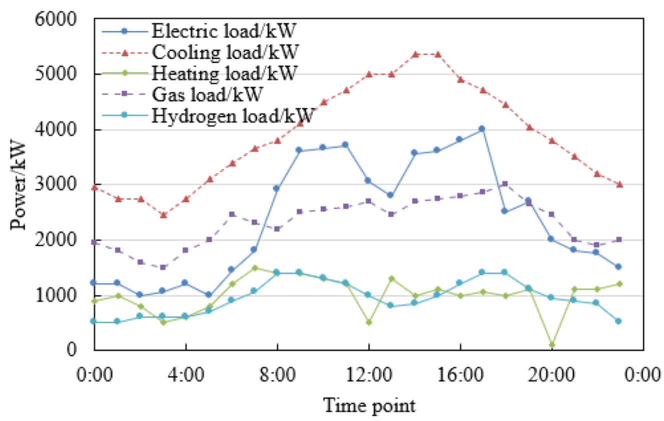


**Figure 5.** Thermodynamic carbon emission accounting model load-side energy demand variation curves

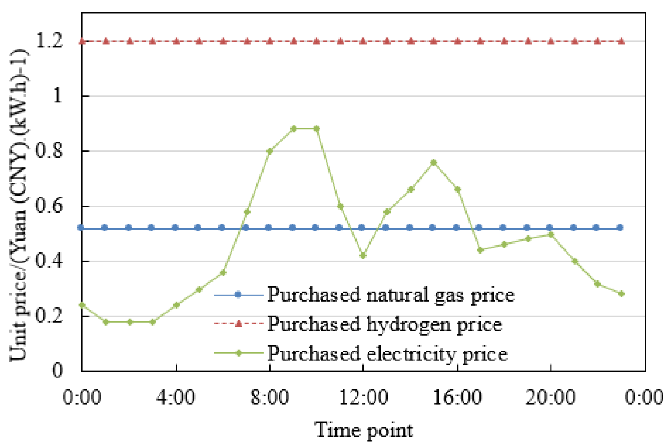


**Figure 6.** Energy price variation curve of thermodynamic carbon emission accounting model

Figure 6 shows the energy price variation curves. The price of purchased natural gas remains relatively stable, the price of purchased hydrogen remains constant, while the purchased electricity price shows significant fluctuations, reflecting the dynamic change characteristics of the electricity market. Figure 7 shows the carbon emission cost analysis chart, which displays the carbon emission costs and carbon fixation benefits of different segments. The carbon emission costs of the electricity side, gas side, and gas turbine show different fluctuation trends at different time periods, reflecting the dynamic costs of carbon emissions in each segment. The carbon fixation benefit of P2G is sometimes negative or positive in different periods, reflecting the impact of carbon fixation activities on cost-effectiveness. These data provide key support for analyzing the exergy cost and carbon emission coupling mechanism in energy conversion processes, quantifying carbon intensity, and enabling synergistic evaluation of emission reduction efficiency and cost-effectiveness.

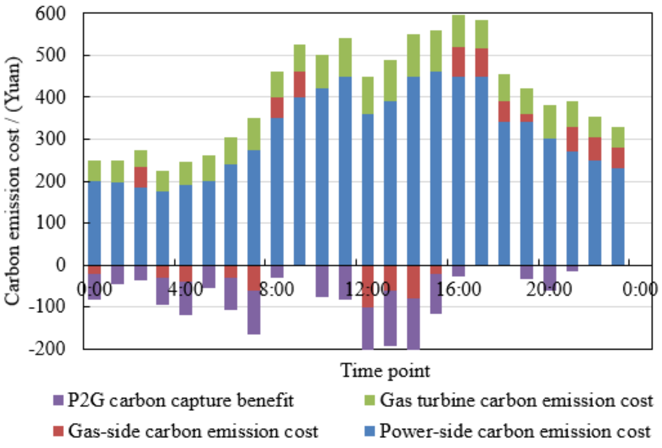


**Figure 7.** Carbon emission cost analysis of thermodynamic carbon emission accounting model

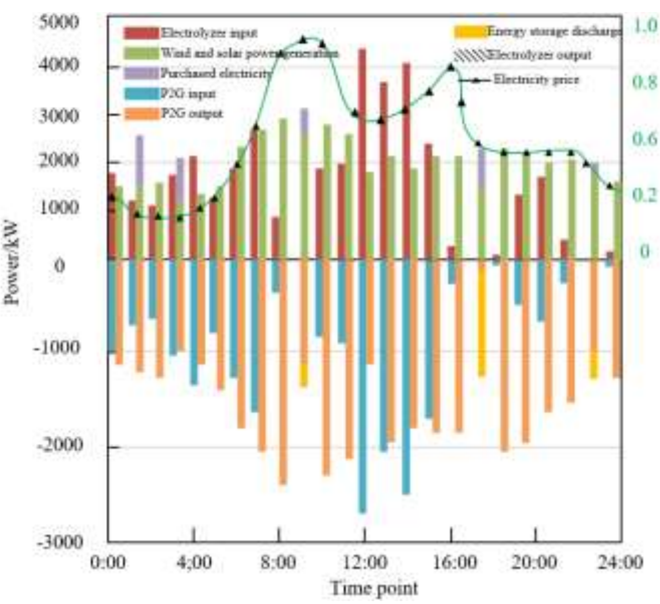


**Figure 8.** Output situation of supply-side equipment in thermodynamic carbon emission accounting model

Figure 8 shows the power variation of different devices and electricity price fluctuations within 24 hours: the horizontal axis represents time, and the vertical axis represents power/kW. Wind and solar power generation exhibit obvious periodicity, with higher power output during the daytime, aligning with natural light and wind conditions, reflecting the intermittent characteristics of renewable energy, electrolyzer input shows significantly increased power in some periods, indicating its concentrated demand for energy input during operation, purchased electricity input shows large fluctuations in power, reflecting the instability of dependence on external electricity, energy storage discharges show positive power in specific periods, indicating that it releases stored energy during peak electricity price or energy shortage, P2G output power has both positive and negative values, reflecting the bidirectional nature of energy conversion, i.e., it can either output energy to the system or absorb energy from the system, electricity price shows a fluctuating state, with higher prices during some daytime periods, forming a contrast with the high output of wind and solar power, reflecting a potential correlation between electricity price and renewable energy output. From the "energy-carbon" dimension, Figure 7 shows that wind and solar power have significantly higher output during the daytime. As low-carbon energy forms, their effective input can reduce reliance on high-carbon external electricity. The dynamic changes in outputs of devices such as electrolyzer input and P2G output reflect the process of energy conversion, and the switching and matching of different energy forms. From the "energy-cost" and multi-objective coupling dimension, the electricity price curve is closely related to the output of devices. For example, during periods of high electricity prices, the proportion of output from low-cost energy such as wind and solar power is relatively increased, which reflects the thermoeconomics model's consideration of cost-effectiveness. By analyzing the coupling mechanism of thermoeconomic cost and carbon emission in the energy conversion process, production process costs are optimized. The output fluctuations of energy storage discharge, external electricity input, and other equipment demonstrate that the system, under the principle of energy conservation, realizes the balance of cost and carbon emissions through the coordinated operation of multiple devices, verifying the feasibility of cross-dimensional integration from energy conservation analysis to cost accounting.

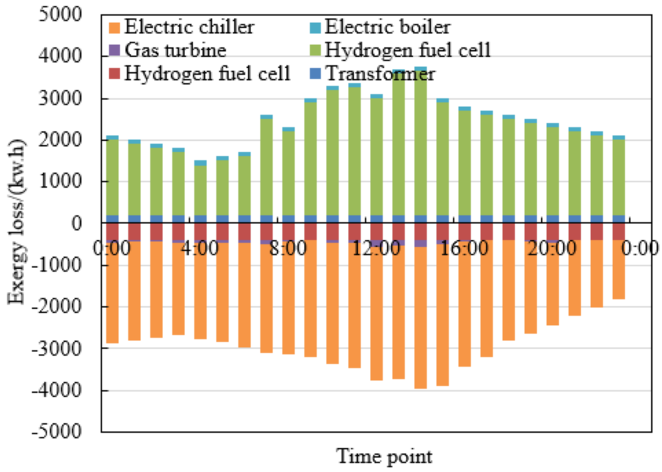


**Figure 9.** Energy loss and exergy loss of conversion-side equipment in thermodynamic carbon emission accounting model

As shown in Figure 9, different devices show unique exergy loss and efficiency characteristics due to differences in energy conversion mechanisms. The electric chiller converts high-quality electrical energy into low-quality cold energy, resulting in the highest exergy loss and exergy efficiency of only 8.1%, while the absorption chiller uses waste heat for cooling, the exergy efficiency rises to 42.1%, highlighting the importance of the exergy coefficient accounting method in quantifying the exergy value of different energy forms. Although the gas turbine has large energy losses during combustion and exhaust, due to its output of relatively high-quality energy forms, its exergy loss is relatively low, with an exergy efficiency of 33.8%, hydrogen fuel cells produce energy loss due to electrochemical reactions, but their exergy efficiency reaches 62.5%, reflecting the impact of energy conversion paths on exergy loss. The electric boiler shows significant exergy loss during resistance heating, with an exergy efficiency of 13.6%, the transformer has the least energy and exergy loss, with exergy efficiency as high as 97.9%. These differences provide empirical evidence for analyzing the coupling mechanism of exergy cost and carbon emission in energy conversion processes. Further comprehensive analysis reveals that although the transformer and electric boiler have relatively low energy loss, the electric boiler produces low-quality heat energy, resulting in high exergy loss, deeply reflecting the difference between energy quantity and energy quality in cost accounting and carbon emission correlation. Gas turbines and hydrogen fuel cells produce high-quality electricity, resulting in low exergy loss, highlighting the key impact of energy quality on exergy cost. The absorption chiller improves energy efficiency by utilizing waste heat, while the electric chiller incurs large exergy losses due to the conversion path from electricity to cooling energy.

Figure 10 shows the exergy flow and unit exergy economic cost variation in the absorption chiller cooling process of the thermodynamic carbon emission accounting model. During the input stage of the gas turbine, the exergy flow value is high, close to 2500 kW, and the unit exergy economic cost is relatively low, about 1.5 yuan/(kW·h), in the output stage of the gas turbine, exergy flow drops significantly to about 700 kW, and the unit exergy economic cost rises to about 3.5 yuan/(kW·h), during the gas turbine output/absorption chiller input stage, the exergy flow further decreases to about 200 kW, and the unit exergy economic cost fluctuates slightly, in the output stage of the absorption chiller, the exergy flow drops to the lowest, but the unit exergy economic cost soars to about 4.5 yuan/(kW·h), showing obvious characteristics of energy quality degradation and cost change. This figure intuitively presents the dynamic evolution of exergy flow and cost in the energy conversion chain. Starting from the exergy flow of fuel input to the gas turbine, through gas turbine output, absorption chiller input to final output, the quantity of exergy flow shows a decreasing trend. This phenomenon stems from the irreversibility of exergy transfer, leading to a continuous decline in energy quality. At the same time, unit economic cost continues to rise, reflecting the cumulative effect of non-energy costs in each link, highlighting the limitations of analyzing only exergy quantity, and further emphasizing the necessity of pricing exergy. The experimental results show that through pricing, the coupling mechanism of exergy cost and potential carbon emission in the energy conversion process can be accurately analyzed, supporting multi-objective coupling analysis and achieving coordinated evaluation of carbon reduction efficiency and cost-effectiveness, further verifying the scientificity of cross-dimensional integration from energy conservation to cost accounting proposed in this paper.

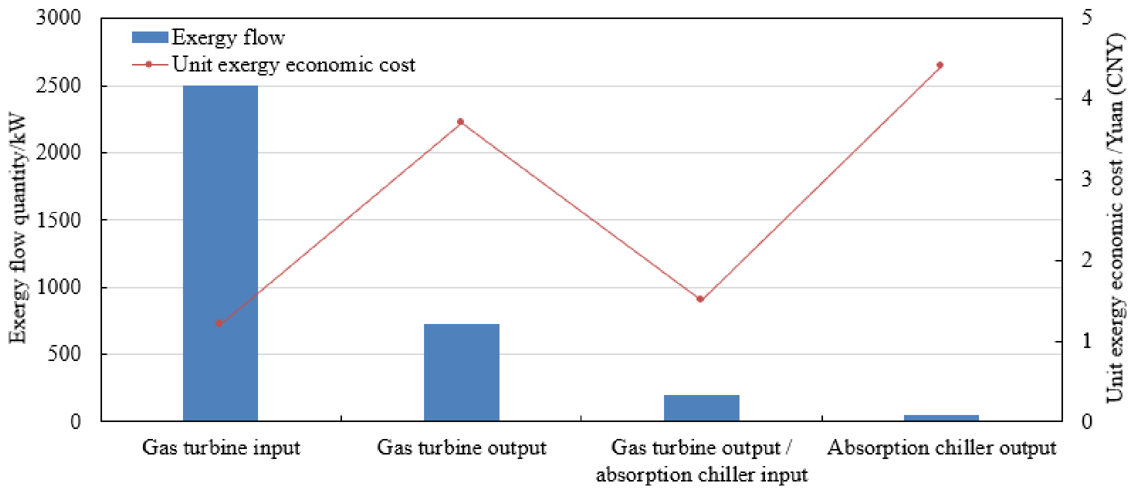


**Figure 10.** Exergy flow and exergy price variation in absorption chiller cooling process of thermodynamic carbon emission accounting model

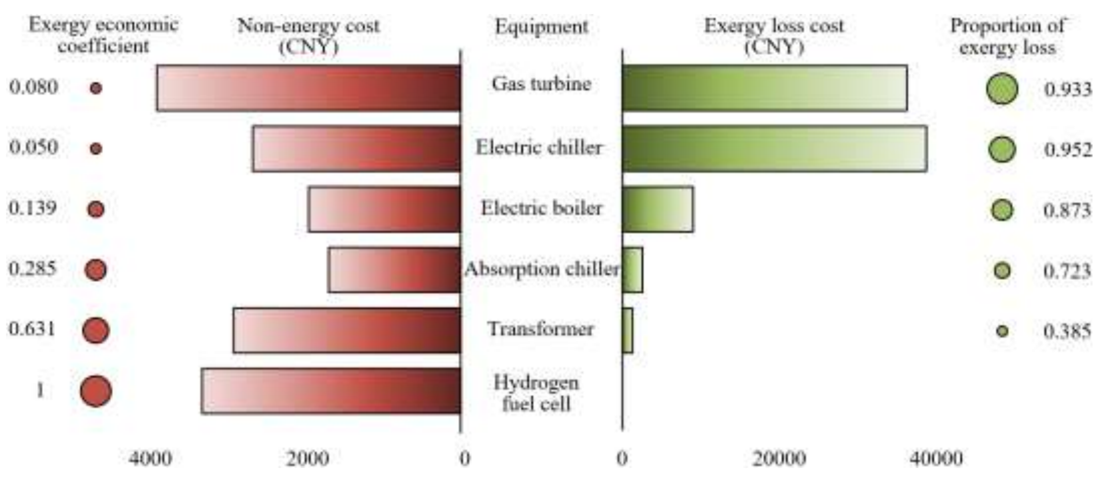


**Figure 11.** Economic characteristic parameter indicators of thermodynamic carbon emission accounting model

In the equipment economic characteristic experimental analysis, as shown in Figure 11, the hydrogen fuel cell has an energy unit price of zero and zero exergy loss cost due to hydrogen being provided by renewable energy such as wind and solar power, with the non-energy cost ratio approaching 100%, showing excellent overall economic performance. The electric chiller converts electric exergy into cooling exergy, the gas turbine converts natural gas into electric exergy and thermal exergy, and the electric boiler converts electric exergy into thermal exergy. These processes all show significant energy quality differences, leading to high exergy loss costs and low exergy economic coefficients, with poor economic performance, highlighting the key research point of the paper on the relationship between energy quality and cost—i.e., the direct impact of quality differences in energy conversion on exergy loss cost. The absorption chiller uses the thermal exergy generated by the gas turbine for cooling. Although its exergy loss quantity is lower than that of the transformer, due to the much higher unit exergy economic cost of cooling exergy than that of electric exergy, its exergy loss cost is higher, further verifying the importance of the quantification of exergy value of different energy forms proposed in the paper. The difference in exergy value of different energy forms directly affects cost accounting.

## 4. CONCLUSION

This paper conducted six aspects of research around the “energy-carbon-cost” coupling system, constructs a thermodynamics-based exergy analysis theory, proposed an exergy coefficient accounting method to quantify energy exergy value and carbon intensity, analyzed the coupling mechanism of exergy cost and carbon emissions in the energy conversion process based on thermoeconomics, designs multi-objective comprehensive evaluation indicators, established system component models and constraints, and developed a cross-dimensional carbon emission accounting method suitable for high-energy-consumption industries. This research combined exergy analysis theory with carbon accounting for the first time, constructing a multi-objective coupling model with both physical accuracy and economic practicality. It not only filled the gap of traditional methods in energy quality analysis and cost integration but also provided enterprises with a “energy-carbon-cost” collaborative management tool, helping enterprises achieve a unified environmental and economic benefit under the carbon neutrality goal, highlighting both theoretical innovation and practical application value.

However, there are still some limitations in this study: the model has a strong dependence on specific scenario data, and its universality and dynamic adaptability in complex and variable industrial environments need further verification, in addition, the model is relatively complex, and needs to be simplified and optimized to improve enterprise adaptability in practical promotion. Future research can expand to multi-industry applications, combine with artificial intelligence, big data, and other technologies to enhance the dynamic response ability and accuracy of the accounting model, deeply explore the “energy-carbon-cost” coupling mechanism under the integration of emerging energy technologies, further improve the theoretical system, and promote the implementation of the model in a wider range of fields, providing more solid theoretical and methodological support for the global carbon neutrality goal.


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