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Energy Flow, Exergy Destruction, and Carbon Emission Accounting in Industrial Thermal Systems for Environmental, Social, and Governance Disclosure

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ABSTRACT

Global environmental, social, and governance disclosure frameworks have entered a phase of mandatory compliance, rendering accurate, traceable, and auditable carbon emission quantification a core requirement for low-carbon industrial governance and regulatory adherence. Industrial thermal systems constitute a primary source of carbon emissions within the industrial sector. Conventional carbon accounting methods, which rely heavily on static emission factors and aggregate estimation, suffer from inherent limitations, precluding compliance with the stringent demands of international sustainability standards for refined, dynamic, and physically interpretable carbon information. To address these challenges, a triply coupled accounting framework integrating energy flow, exergy flow, and carbon flow was constructed, specifically tailored for environmental, social, and governance disclosure in industrial thermal systems. An equipment-level exergy network topological model was established based on the second law of thermodynamics, enabling a detailed decomposition and quantitative characterization of system-wide exergy destruction. Leveraging the irreversible physical nature of exergy destruction, a network-based carbon responsibility allocation mechanism was developed, transcending the limitations of conventional black-box approaches and achieving equipment-level traceability of carbon liabilities. A thermodynamically interpretable dynamic correction model for emission factors was formulated, with real-time exergy efficiency serving as the core driving variable, effectively mitigating the substantial deviations inherent in static estimation under transient or variable operating scenarios. Furthermore, by integrating exergoeconomic principles, a multidimensional indicator system was constructed, encompassing exergy destruction rate, carbon emission intensity, and unit product carbon cost, thereby enabling the synergistic quantification of energy performance, carbon emissions, and carbon-related economic risks, precisely aligned with leading international environmental, social, and governance disclosure standards. This study advances the thermodynamic theoretical foundation for carbon accounting in industrial thermal systems, providing a scientifically robust and practically viable technical pathway for industrial enterprises to achieve refined carbon management, standardized environmental, social, and governance reporting, and low-carbon operational decision-making.

1. INTRODUCTION

The global climate governance system has been continuously strengthened, with the normalization and mandatory enforcement of low-carbon regulations and environmental information disclosure having become central binding constraints for the development of global industrial sectors [1, 2]. The implementation of the International Sustainability Standards Board (ISSB) framework and the EU Corporate Sustainability Reporting Directive (CSRD) has fundamentally reshaped the landscape of corporate environmental information disclosure, elevating carbon emission accounting and environmental, social, and governance reporting from voluntary industry initiatives to globally mandated compliance requirements [3, 4]. Existing international disclosure standards have established stringent criteria for the traceability, timeliness, and auditability of industrial carbon emission data, compelling the industrial sector to develop refined, dynamic, and physically rigorous carbon accounting systems [5, 6]. As the primary energy-consuming and carbon-emitting units within industrial production systems, industrial thermal systems encompass critical equipment such as boilers, heat exchanger networks, steam transmission networks, and waste heat recovery units, constituting the major source of greenhouse gas emissions in the industrial domain [7, 8]. At present, carbon emission accounting for industrial thermal systems is predominantly conducted using conventional emission factor methods and material balance approaches. These methodologies treat the entire thermal system as a single accounting unit for aggregate estimation, suffering from significant theoretical and practical deficiencies [9, 10]. Existing accounting frameworks are incapable of disaggregating the spatial distribution characteristics of carbon emissions within the system, rendering it difficult to delineate emission reduction responsibilities across individual equipment components. Furthermore, the reliance on fixed static emission factors fails to accommodate the off-design and variable operating characteristics inherent in industrial production, resulting in substantial deviations in dynamic carbon emission accounting outcomes [11, 12]. More critically, conventional carbon accounting focuses exclusively on aggregate emission statistics, without establishing linkages to system-level energy utilization efficiency or production operating costs. This limitation precludes the synergistic disclosure of multi-dimensional environmental, economic, and governance indicators under environmental, social, and governance frameworks, thereby constraining its applicability to the evolving requirements of modern industrial low-carbon management and compliance reporting [13, 14].

Against this backdrop, exergy analysis, grounded in the second law of thermodynamics, provides the core theoretical foundation for overcoming the technical bottlenecks inherent in traditional carbon accounting methodologies [15, 16]. Exergy, as a fundamental physical quantity characterizing energy quality and available work potential, enables the precise quantification of irreversible losses occurring during energy conversion and transfer processes [17, 18]. The integration of exergy analysis techniques into carbon emission accounting and environmental, social, and governance disclosure systems facilitates a comprehensive upgrading of industrial carbon accounting across three critical dimensions: from energy quantity statistics to energy quality tracing, from static aggregate estimation to dynamic real-time measurement, and from single-indicator emission accounting to synergistic quantification of multidimensional environmental, social, and governance metrics. This integration carries significant theoretical value and engineering practical significance for advancing the theoretical framework of industrial low-carbon accounting, supporting compliant corporate disclosure, and guiding targeted emission reduction strategies in industrial thermal systems [19, 20]. Considerable research efforts have been devoted to energy efficiency optimization, exergy analysis, and carbon emission accounting for industrial thermal systems. Nevertheless, the existing research framework remains characterized by pronounced technical deficiencies and theoretical gaps that preclude compliance with the high-precision disclosure requirements of environmental, social, and governance frameworks [21, 22]. With respect to the coupling of exergy flow and carbon flow, existing studies have predominantly focused on the coupled modeling of regional integrated energy systems, achieving preliminary qualitative correlations between exergy parameters and carbon emission trajectories. However, these investigations have been conducted at the macro-scale of regional energy systems, without penetrating to the equipment-level granularity within industrial thermal systems. Consequently, the refined decomposition of individual equipment exergy destruction and the quantitative allocation of corresponding carbon responsibilities remain unattainable, and the intrinsic mechanism by which exergy destruction drives carbon emissions has yet to be quantitatively characterized [17, 18].

Regarding dynamic carbon emission factor modeling, current mainstream dynamic accounting models are heavily reliant on data-driven approaches, including statistical regression and machine learning techniques, which fit temporal variations in emission factors based on historical operational data. These models lack underlying thermodynamic mechanistic support and have failed to identify the core physical variables that govern real-time fluctuations in emission factors. As a result, such approaches exhibit poor generalizability and limited physical interpretability, rendering them inadequate for accurate carbon emission accounting in industrial thermal systems operating under complex and variable conditions [9, 10]. With respect to the integration of exergoeconomics and carbon accounting, existing studies have primarily applied exergoeconomic analysis tools to cost allocation and pricing optimization for industrial products, with a focus on terminal product-level carbon cost distribution. These investigations have not developed carbon liability attribution mechanisms at the equipment-component level within thermal systems, nor have they established standardized quantitative indicator systems aligned with international environmental, social, and governance disclosure standards. A fundamental misalignment therefore persists between the objectives of current research and the practical demands of environmental, social, and governance compliance reporting [19, 20]. A synthesis of the extant literature reveals that the quantitative mapping relationship between exergy destruction and carbon liability has not been established within the current research community. A thermodynamically grounded dynamic carbon emission accounting model remains absent, and an integrated environmental, social, and governance quantitative evaluation framework that synergistically incorporates exergy efficiency, carbon emissions, and economic costs has yet to be realized. These cumulative deficiencies preclude the support of high-accuracy, traceable, and dynamic environmental, social, and governance carbon emission disclosure for industrial thermal systems [16, 23].

To address the aforementioned research gaps and technical deficiencies, an accounting methodology for carbon emissions in industrial thermal systems, characterized by the triply coupled integration of energy flow, exergy flow, and carbon flow, is developed, thereby establishing a comprehensive technical framework aligned with environmental, social, and governance disclosure requirements. First, a component-level exergy network topological model for industrial thermal systems is constructed. Through the deployment of branch-level exergy destruction accounting, a refined allocation of system-wide carbon responsibilities is achieved, enabling the transition from black-box aggregate accounting to component-level traceability accounting. Second, with exergy efficiency serving as the core thermodynamic driving parameter, a dynamically corrected emission factor model is formulated, resolving the issue of insufficient accounting accuracy under static assumptions applied to variable operating scenarios. Third, through the integration of exergoeconomic principles, a tripartite environmental, social, and governance quantitative indicator system is established, encompassing energy efficiency performance, emission intensity, and carbon cost risk. These three innovations follow a progressive logical sequence—physical mechanism characterization, environmental quantification, and value assessment—with exergy parameters serving as the unifying metric throughout, thereby advancing the theoretical framework for low-carbon accounting and environmental, social, and governance evaluation in industrial thermal systems.

The overall research architecture is structured with clarity, with each chapter progressively building upon the preceding one to complete the full theoretical modeling and validation workflow. Chapter 2 presents the exergy flow network modeling and destruction analysis for industrial thermal systems, establishing the thermodynamic foundation for the entire study. Chapter 3 develops the network-based allocation methodology for exergy destruction and carbon responsibility. Chapter 4 establishes the dynamic carbon emission accounting model based on exergy efficiency. Chapter 5 completes the construction of the multidimensional environmental, social, and governance quantitative indicator system. Chapter 6 conducts multi-scenario case validation on a representative industrial thermal system, substantiating the scientific validity and superiority of the proposed methodology. Chapter 7 summarizes the research findings and outlines future directions for theoretical extension and engineering application.

2. EXERGY FLOW NETWORK MODELING AND BRANCH-LEVEL DESTRUCTION ANALYSIS FOR INDUSTRIAL THERMAL SYSTEMS

Differential degradation in energy quality serves as the core physical driver of carbon emission differentiation in industrial thermal systems. Conventional energy efficiency analyses, grounded solely in the first law of thermodynamics, conduct quantity-based energy consumption accounting without quantifying the irreversible degradation occurring during energy conversion and transfer processes. Exergy, as the fundamental physical quantity characterizing available work potential within thermodynamic systems, enables the unified quantification of quality differentials across diverse energy forms and provides an accurate characterization of energy destruction mechanisms throughout the entire industrial thermal system workflow. The overall triply coupled "energy flow–exergy flow–carbon flow" accounting framework proposed for environmental, social, and governance disclosure is illustrated in Figure 1. To achieve refined destruction analysis of industrial thermal systems and subsequent precise traceability of carbon responsibilities, a unified exergy calculation model for multi-form energy flows was first constructed based on thermodynamic equilibrium criteria. This model encompasses all energy flow forms present during industrial thermal system operation, including fuel chemical energy, thermal energy, mechanical energy, and working fluid energy. The total exergy at any arbitrary thermodynamic state of the system can be obtained through the combined formulation of physical exergy and chemical exergy:

$$E_x=(H-H_0)-T_0(S-S_0)+\sum_i(\mu_i-\mu_{i,0})n_i \tag{1}$$

where, H and S denote the enthalpy and entropy at the current system state, respectively; H_0 and S_0 denote the corresponding enthalpy and entropy parameters at the standard environmental reference state; T_0 denotes the ambient reference temperature; μ_i and $\mu_{i,0}$ denote the chemical potentials of the i-th component at the current state and at the environmental reference state, respectively; and n_i denotes the molar amount of the component. Based on this generalized model and in consideration of the characteristic energy flow features of industrial thermal systems, differentiated exergy calculation formulations were established separately. Fuel chemical exergy is calculated as:

$$\dot{E}_{x,fuel}=\dot{m}_{fuel}e^{ch}_{x,fuel} \tag{2}$$

where, $\dot{m}_{fuel}$ denotes the fuel mass flow rate, and $e^{ch}_{x,fuel}$ denotes the standard chemical exergy per unit mass of fuel. Thermal exergy is calculated as:

$$\dot{E}_{x,Q}=\dot{Q}(1-T_0/T) \tag{3}$$

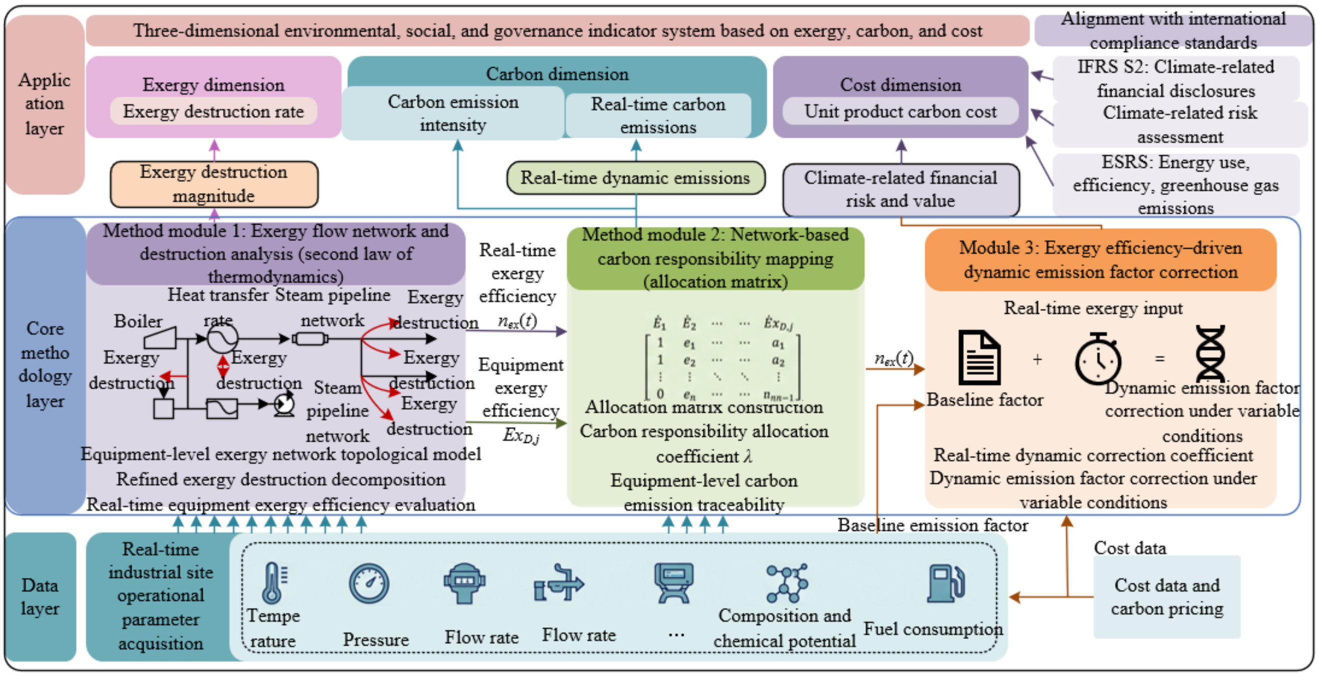


Figure 1. Overall triply coupled "energy flow–exergy flow–carbon flow" accounting framework for environmental, social, and governance disclosure

where, $\dot{Q}$ denotes the system heat flow rate and T denotes the real-time temperature of the heat source. The exergy values of mechanical energy and electrical energy are equal to their respective energy values, satisfying $\dot{E}_{x,W}=\dot{W}$. The exergy of a flowing working fluid is calculated as:

$$dotE_{x,flow}=\dot{m}[(h-h_0)-T_0(s-s_0)],\dot{m} \tag{4}$$

where, h and s denote the mass flow rate of the working fluid, and h_0 and s_0 denote the specific enthalpy and specific entropy of the working fluid at the real-time state and at the reference state, respectively.

To overcome the limitations of conventional single-device exergy analysis, which fails to characterize the coupling interrelationships within the system, a node-branch topological methodology was adopted for the network-based reconstruction of the industrial thermal system. Core equipment units—including boilers, heat exchangers, steam pipeline networks, and waste heat recovery devices—were abstracted as independent network nodes, and the energy transfer pathways between equipment units were uniformly defined as exergy branches, thereby enabling the structured decomposition of complex thermal systems. The overall system was assumed to contain N equipment nodes and M exergy transfer branches, and an $N\times M$ node-branch incidence matrix A was constructed. The matrix elements were defined according to the direction of energy flow transmission: an element was assigned a value of 1 when a branch flows into the corresponding node, −1 when a branch flows out of the corresponding node, and 0 when no energy association exists between the equipment and the branch. Based on the incidence matrix, a matrix-form exergy balance equation for the entire system can be established, enabling the simultaneous solution of exergy receipts and expenditures across all nodes:

$$A\dot{E}_x=\dot{E}_{x,D} \tag{5}$$

where, $\dot{E}_x$ denotes the M-dimensional branch exergy flow column vector, characterizing the real-time exergy transfer quantities along each energy pathway; and $\dot{E}_{x,D}$ denotes the N-dimensional node exergy destruction column vector, quantifying the irreversible exergy destruction at each equipment unit. This matrix-based modeling approach is adaptable to industrial thermal systems of arbitrary topological complexity, facilitating the upgrade from single-point equipment calculation to global network-coupled computation.

Based on the network topology, the exergy balance relationship of individual equipment units can be further decomposed, enabling precise quantification of the energy quality degradation level of each device. For the j-th equipment unit within the system, the total input exergy, total output exergy, and exergy destruction satisfy the steady-state thermodynamic balance relationship:

$$\sum_{i\in in,j}\dot{E}_{x,i}=\sum_{k\in out,j}\dot{E}_{x,k}+\dot{E}_{x,D,j} \tag{6}$$

where, $\Sigma_{i\in in,j}\dot{E}_{x,k}$ denotes the total input exergy of equipment j; $\Sigma_{k\in out,j}\dot{E}_{x,k}$ denotes the total effective output exergy of equipment j; and $\dot{E}_{x,D,j}$ denotes the irreversible exergy destruction generated during equipment operation. The system-wide total exergy destruction is obtained as the accumulation of destruction across all equipment units, calculated as:

$$\dot{E}_{x,D,total}=\sum_{j=1}^{N}\dot{E}_{x,D,j} \tag{7}$$

Through this hierarchical calculation logic, the precise decomposition of total system destruction into equipment-unit destruction can be achieved, and the spatial distribution characteristics of exergy destruction within the industrial thermal system can be clarified, thereby providing standardized physical parameters for the subsequent refined allocation of carbon responsibilities.

To quantitatively evaluate the energy quality utilization level of each equipment unit, a equipment-level exergy efficiency evaluation model was constructed based on the exergy receipt-expenditure relationship. Distinguished from conventional energy efficiency, which merely accounts for energy quantity utilization rates, this metric accurately reflects the degree of quality degradation caused by irreversible exergy destruction.

$$\eta_{x,j}=\frac{\Sigma_{k\in out,j}\dot{E}_{x,k}}{\Sigma_{i\in in,j}\dot{E}_{x,i}}=1-\frac{\dot{E}_{x,D,j}}{\Sigma_{i\in in,j}\dot{E}_{x,i}} \tag{8}$$

where, $\eta_{x,j}$ denotes the real-time exergy efficiency of equipment j. An efficiency value closer to unity indicates a higher level of energy quality utilization and lower irreversible destruction for the equipment. This parameter is capable of responding in real time to dynamic operational characteristics of the industrial system, including load fluctuations and operating condition transitions, thereby providing a core characterization variable for the subsequent development of an operating-condition-driven dynamic carbon emission accounting model.

The accuracy of the industrial thermal system network modeling directly determines the reliability of the subsequent carbon flow accounting and environmental, social, and governance indicator evaluation. During the modeling process, the system boundary must be rigorously defined, and complex energy flow structures—including splitting, mixing, and recirculation—must be precisely identified, ensuring that the topological relationships fully match the actual production operating conditions. Visualization of the system-wide exergy flow was accomplished through exergy Sankey diagrams, which intuitively display the exergy transfer patterns along each branch, the destruction proportions across equipment units, and clearly present the critical nodes of energy quality destruction within the industrial thermal system. The complete networked exergy modeling system achieves a structured, parameterized, and visualized representation of the energy flow mechanisms in industrial thermal systems, establishes a quantitative benchmark for equipment-level exergy destruction, and provides comprehensive thermodynamic theoretical support for the quantitative mapping between exergy destruction and carbon emissions, as well as for the dynamic correction of emission factors.

3. NETWORKED MAPPING METHOD FOR ALLOCATING CARBON RESPONSIBILITY FROM BRANCH EXERGY DESTRUCTION

Conventional carbon emission accounting frameworks for industrial thermal systems rely on fixed emission factors to compute total fuel-based carbon emissions, enabling only macroscopic statistical estimation of overall system emissions without supporting refined responsibility allocation or traceability analysis. The industry-standard accounting formula employs fuel consumption and corresponding static emission factors as the core calculation parameters, with total system carbon emissions obtained through superposition across fuel types:

$$C_{total}=\sum_{f}\left(\dot{m}_{fuel,f}\cdot EF_{f,static}\right) \tag{9}$$

where, $\dot{m}_{fuel,f}$ denotes the real-time consumption flow rate of the f-th fuel type, and $EF_{f,static}$ denotes the static carbon emission factor for the corresponding fuel. This accounting approach treats the industrial thermal system as an integral closed unit, neglecting the irreversible differences inherent in internal energy transfer and conversion processes, and consequently fails to distinguish the carbon emission contributions of individual equipment units. From the perspective of thermodynamic mechanisms, the additional fuel consumption incurred during industrial production processes is fundamentally attributable to the compensation of irreversible exergy destruction generated during the operation of various equipment units. Equipment units exhibiting more pronounced energy quality degradation necessitate greater compensatory fuel consumption, thereby generating correspondingly larger carbon emission volumes. Based on this physical mechanism, the intrinsic linkage between exergy destruction and carbon responsibility can be established, with quantified thermodynamic destruction parameters serving as the core basis for carbon responsibility allocation, thereby enabling the transition of carbon emission accounting from empirical statistics to mechanism-based analysis.

To achieve precise quantification of carbon responsibility at the equipment level, a standardized carbon responsibility allocation coefficient was constructed based on the system-wide exergy destruction distribution pattern, establishing a one-to-one correspondence between destruction weight and emission share. The node-branch exergy network topology abstraction and carbon responsibility mapping mechanism for industrial thermal systems are illustrated in Figure 2. Through the ratio of individual equipment exergy destruction to total system exergy destruction, the contribution weight of each equipment unit to overall carbon emissions is characterized. The equipment allocation coefficient is calculated as follows:

$$\alpha_j=\frac{\dot{E}_{x,D,j}}{\dot{E}_{x,D,total}}=\frac{\dot{E}_{x,D,j}}{\sum_{j=1}^{N}\dot{E}_{x,D,j}} \tag{10}$$

where, α_j denotes the carbon responsibility allocation coefficient for the j-th equipment unit, $\dot{E}_{x,D,j}$ denotes the real-time exergy destruction of the corresponding equipment, and $\dot{E}_{x,D,total}$ denotes the global total exergy destruction of the industrial thermal system. Given the determined total system carbon emissions, the actual carbon responsibility allocated to each equipment unit can be obtained through linear scaling using the allocation coefficients:

$$C_j=\alpha_j\cdot C_{total}=\frac{\dot{E}_{x,D,j}}{\dot{E}_{x,D,total}}\cdot C_{total} \tag{11}$$

where, C_j denotes the carbon emission amount allocated to the j-th equipment unit. This calculation approach is fundamentally grounded in the second law of thermodynamics, with responsibility allocation entirely based on the objective physical characteristics of system irreversibility, thereby circumventing the subjective biases inherent in empirical methods such as equal-proportion allocation or energy-consumption-proportional allocation.

To accommodate the complex topological characteristics of industrial thermal systems featuring multiple nodes and multiple branches, the equipment-level allocation model was extended into a matrix-based solution form, enabling the simultaneous and unified computation of carbon responsibility across the entire system. An N-dimensional equipment carbon responsibility coefficient vector α and an exergy destruction vector $\dot{E}_{x,D}$ were defined, and an N-dimensional all-ones column vector was introduced for normalization processing, yielding the matrix-based allocation formula:

$$\alpha=\frac{\dot{E}_{x,D}}{1^{T}\cdot\dot{E}_{x,D}} \tag{12}$$

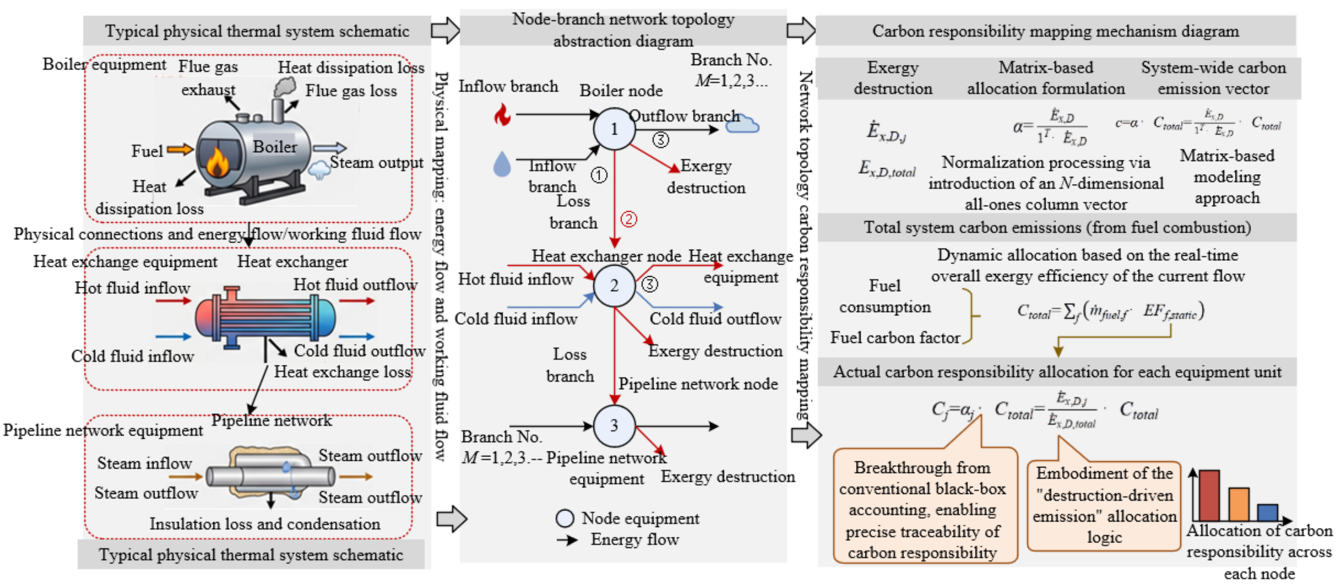


Figure 2. Node-branch exergy network topology abstraction and carbon responsibility mapping mechanism for industrial thermal systems

Based on this normalized coefficient vector, the carbon emission distribution across all equipment units can be solved simultaneously in a single operation, producing a systematic carbon emission vector:

$$c=\alpha\cdot C_{total}=\frac{\dot{E}_{x,D}}{1^T\cdot\dot{E}_{x,D}}\cdot C_{total} \tag{13}$$

where, c denotes the system-wide equipment carbon emission column vector, with each element sequentially corresponding to the carbon emission of each equipment unit. The matrix-based modeling approach eliminates the inefficiency of conventional iterative per-equipment computation and is adaptable to industrial thermal systems of arbitrary equipment scale and topological complexity, demonstrating strong generality and scalability.

To further enhance the refinement level of carbon emission traceability and transcend the granularity limitations of equipment-level accounting, a branch-level carbon emission intensity solution model was constructed based on the system topological incidence matrix, enabling carbon responsibility tracing along energy transmission pathways. Through the topological coupling relationships between nodes and branches, a system of linear equations was established to accomplish the quantitative solution of branch carbon emission intensities:

$$A^T\cdot\lambda=\gamma \tag{14}$$

where, A^T denotes the transpose of the system node-branch incidence matrix, λ denotes the M-dimensional branch carbon emission intensity vector, characterizing the carbon emission level per unit of exergy along each energy transfer branch, and γ denotes the carbon emission intensity vector per unit of effective exergy output from equipment units. This model bridges the carbon emission linkage between equipment destruction and branch transmission, enabling the precise identification of high-carbon-emission energy transmission segments and achieving full-chain carbon emission traceability for industrial thermal systems—from equipment units to energy flow branches.

The complete networked mapping system reconstructs the accounting logic for carbon emissions in industrial thermal systems, achieving objective allocation of carbon responsibilities grounded in the physical essence of exergy destruction. In contrast to conventional black-box accounting approaches, this methodology enables precise resolution of the spatial distribution characteristics of carbon emissions within the system and clarifies the responsibility boundaries for emission reduction across individual units and branches. Furthermore, the matrix-based modeling architecture is adaptable to topological variations and operational fluctuations in complex industrial thermal systems, and the accounting results exhibit rigorous physical interpretability. These attributes satisfy the core compliance requirements of environmental, social, and governance disclosure for traceable and auditable carbon emission data, providing robust technical support for refined carbon management and standardized disclosure in industrial enterprises.

4. REAL-TIME ACCOUNTING METHOD FOR CARBON EMISSION FACTORS BASED ON EXERGY EFFICIENCY DYNAMIC CORRECTION

The networked carbon responsibility allocation model constructed in the preceding section has effectively addressed the spatial stratification problem in carbon emission accounting for industrial thermal systems, achieving precise allocation of emission responsibilities at the equipment level. However, the baseline total carbon emissions within this accounting framework remain calculated using fixed static emission factors, rendering the accounting accuracy significantly constrained by the dynamic operating conditions of the industrial process. In actual production practice, industrial thermal systems are continuously subjected to dynamic variations, including load adjustments, operating condition transitions, and equipment performance degradation. The irreversible degree of internal energy conversion consequently fluctuates in real time, and the exergy efficiency exhibits pronounced nonlinear dynamic characteristics. Fixed static emission factors are incapable of matching the energy efficiency destruction differentials induced by changing operating conditions, and neglect the driving effect of energy quality degradation on carbon emission increments, thereby resulting in significant deviations in carbon emission accounting outcomes under variable scenarios. Existing engineering practice and literature indicate that conventional static-factor accounting methods can yield calculation errors of up to 50% under off-design operating conditions, substantially compromising the authenticity and credibility of carbon emission data and rendering them insufficient to meet the stringent requirements of environmental, social, and governance disclosure for accounting result accuracy and stability. Consequently, the construction of a dynamically corrected emission factor mechanism grounded in thermodynamic principles constitutes the central imperative for achieving high-accuracy real-time carbon accounting in industrial thermal systems.

To quantify the intrinsic influence of operating condition fluctuations on carbon emission levels, a dynamic adaptive correction mechanism for emission factors was established, with equipment exergy efficiency serving as the core thermodynamic driving parameter. The correlation diagram of the dynamic emission factor correction mechanism based on exergy efficiency variation is presented in Figure 3. Exergy efficiency objectively characterizes the energy quality utilization capability of equipment at any given moment, directly reflecting the degree of irreversible destruction inherent in energy conversion processes, and its dynamic evolution pattern is highly coupled with the carbon emission level per unit of effective output from the equipment. Based on the exergy efficiency differential between the baseline design operating condition and the real-time operating condition, a dimensionless exergy efficiency correction coefficient was constructed to quantitatively characterize the carbon emission increment effect induced by operating condition deviations:

$$\beta_j(t)=\frac{\eta_{x,j,ref}}{\eta_{x,j}(t)} \tag{15}$$

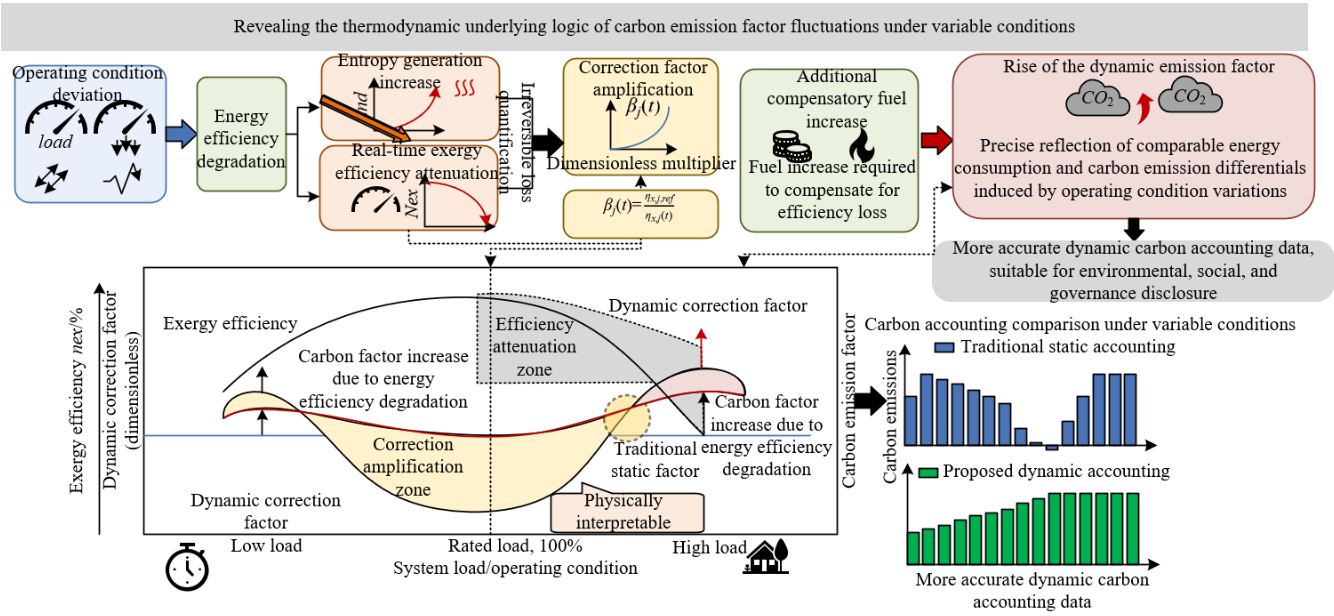


Figure 3. Correlation diagram of the dynamic emission factor correction mechanism based on exergy efficiency variation

where, $\beta_j(t)$ denotes the exergy efficiency correction coefficient for the j-th equipment unit at time t; $\eta_{x,j,ref}$ denotes the baseline exergy efficiency under the equipment rated design condition; and $\eta_{x,j}(t)$ denotes the real-time operational exergy efficiency of the equipment. On this basis, the correction coefficient was coupled with the conventional static emission factor to construct a real-time emission factor model fully adapted to dynamic operating conditions:

$$EF_j(t)=EF_{j,static}\cdot\beta_j(t)=EF_{j,static}\cdot\frac{\eta_{x,j,ref}}{\eta_{x,j}(t)} \tag{16}$$

where, $EF_j(t)$ denotes the real-time dynamic carbon emission factor of the equipment, and $EF_{j,static}$ denotes the conventional static emission factor corresponding to the fuel. When the equipment operating condition deviates from the rated state and the exergy efficiency decreases, the correction coefficient increases in magnitude, and the dynamic emission factor rises correspondingly, accurately reproducing the carbon emission increment induced by additional fuel consumption under low-efficiency operating conditions.

Based on the dynamic emission factor model, and in conjunction with the temporal variation characteristics of fuel consumption, precise integral accounting of equipment-level carbon emissions over continuous time domains can be achieved. Within any arbitrary accounting time duration Δt, the cumulative carbon emissions of equipment can be obtained through the time-domain integral formulation:

$$C_j(\Delta t)=\int_t^{t+\Delta t}\left[\dot{m}_{fuel,j}(\tau)\cdot EF_{j,static}\cdot\frac{\eta_{x,j,ref}}{\eta_{x,j}(\tau)}\right]d\tau \tag{17}$$

where, $\dot{m}_{fuel,j}(\tau)$ denotes the instantaneous fuel consumption flow rate of the equipment, and τ denotes the integral time-series variable. The total system-wide carbon emissions are obtained as the accumulation of the time-series carbon emissions across all equipment units:

$$C_{total}(\Delta t)=\sum_{j=1}^{N}C_j(\Delta t) \tag{18}$$

To accommodate the discrete data acquisition mode of industrial field online monitoring and enhance the engineering applicability of the model, the continuous integral formulation was subjected to discretized numerical processing. With a second-level time interval adopted as the minimum sampling period, iterative cumulative calculation of carbon emissions over the entire time horizon was performed:

$$C_j=\sum_k\left[\dot{m}_{fuel,j}(t_k)\cdot EF_{j,static}\cdot\frac{\eta_{x,j,ref}}{\eta_{x,j}(t_k)}\cdot\Delta\tau\right] \tag{19}$$

where, t_k denotes the discrete sampling time instant, and $\Delta\tau$ denotes the fixed sampling time step. This discretized computational approach can be directly interfaced with real-time monitoring data from industrial control systems, enabling second-level high-accuracy dynamic carbon emission accounting.

The dynamic factor correction model constructed in this study possesses complete thermodynamic physical interpretability, distinguishing it from conventional data-driven and statistically fitted dynamic accounting methodologies. The core driving variables of the model are derived from exergy efficiency parameters obtained through second-law thermodynamic derivation, without reliance on extensive historical operational data for training and fitting. The parameter variations are highly consistent with the physical mechanisms of equipment energy efficiency degradation and operating condition deviations. The real-time attenuation of equipment exergy efficiency directly corresponds to increased irreversible entropy generation within the system, quantifying the additional carbon emissions arising from ineffective energy losses during production processes, and fundamentally explaining, from the underlying physical mechanism, the intrinsic causes of carbon emission fluctuations under variable conditions. All model input parameters are routine operational measurements for industrial thermal systems—including temperature, pressure, and flow rate—which can be acquired locally through direct data collection, and the accounting process is reproducible, traceable, and auditable.

This dynamic correction system effectively compensates for the technical deficiencies of poor static factor adaptability and weak mechanistic interpretability of conventional dynamic models, complementing the equipment-level carbon responsibility allocation model presented in the preceding section. Together, these components constitute a spatiotemporally coupled refined carbon accounting framework. While preserving the advantages of thermodynamically objective quantification, this framework achieves the upgrade of carbon emission accounting from static fixed-value calculation to dynamic time-series evolutionary computation, providing reliable quantitative support for real-time environmental, social, and governance information disclosure, dynamic carbon emission control, and low-carbon operating condition optimization in industrial thermal systems.

5. EXERGY–CARBON–COST MULTI-OBJECTIVE COUPLED ENVIRONMENTAL, SOCIAL, AND GOVERNANCE QUANTITATIVE INDICATOR SYSTEM

Relying on the thermodynamic destruction analysis and dynamic carbon emission accounting framework established in the preceding sections, the energy quality degradation and carbon emission characteristics of industrial thermal systems can be quantified with high precision. However, physical and environmental parameters alone are insufficient to directly satisfy the multidimensional evaluation requirements of modern environmental, social, and governance information disclosure. Conventional environmental, social, and governance disclosure indicators tend to decouple the intrinsic relationships among energy efficiency, carbon emission levels, and climate-related financial risk, making it difficult to form a unified, traceable, and mechanistically consistent quantitative evaluation system. To address this issue, exergoeconomic theory was introduced to convert the physical scale of irreversible energy destruction into an economic value scale, establishing the correspondence between energy quality degradation and resource cost, and thereby laying the theoretical foundation for the coupled construction of multidimensional environmental, social, and governance indicators. The exergy–carbon–cost tripartite environmental, social, and governance quantitative evaluation pyramid model is presented in Figure 4. Exergoeconomics incorporates all effective energy carriers into the scope of economic accounting. The exergy destruction generated during system operation is essentially irreversible resource waste, the economic value of which can be uniformly quantified through the unit exergy cost:

$$c_{Ex}=\frac{P_{fuel}}{e_{x,fuel}^{ch}} \tag{20}$$

where, c_{Ex} denotes the unit exergy economic cost, P_{fuel} denotes the unit purchase price of fuel, and $e_{x,fuel}^{ch}$ denotes the standard chemical exergy of the fuel. This parameter achieves the normalization of fuel resource value and energy quality parameters, enabling the unified quantification of economic losses corresponding to different types of energy destruction, and establishing a bridging interface between thermodynamic analysis and economic evaluation.

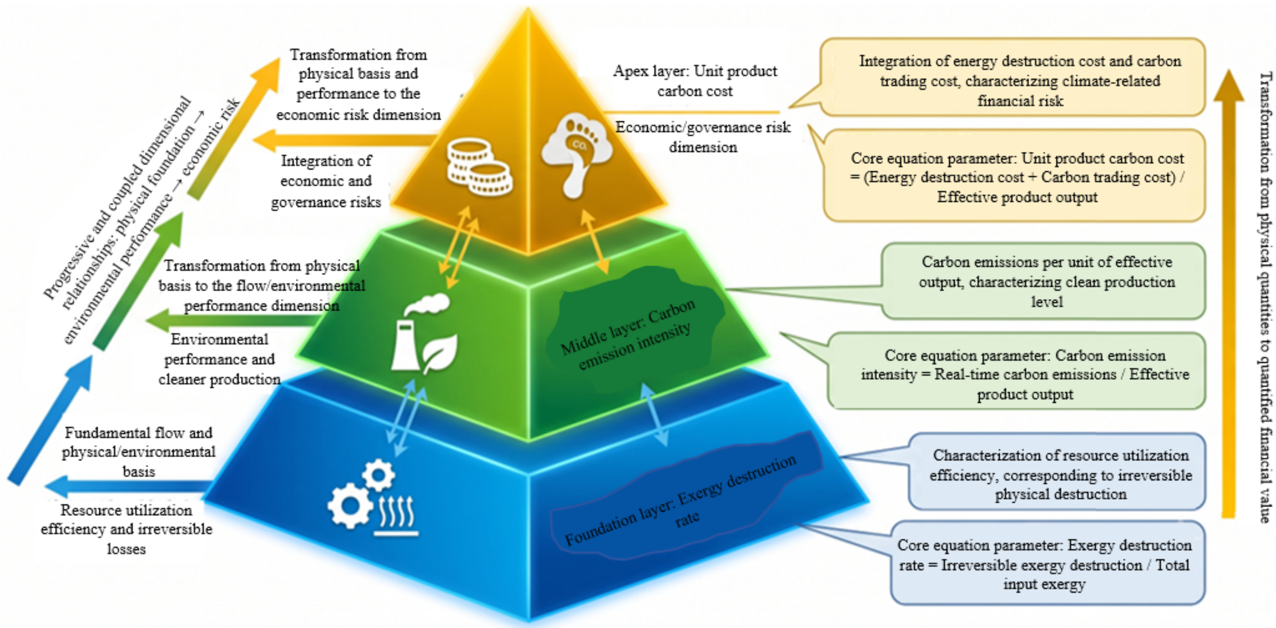


Figure 4. Exergy–carbon–cost tripartite environmental, social, and governance quantitative evaluation pyramid model

Based on the unit exergy cost and the dynamic carbon emission accounting results, the coupled calculation of system energy destruction cost and carbon emission cost can be performed simultaneously, achieving the integrated quantification of physical destruction, environmental emissions, and economic costs. The instantaneous exergy destruction cost of each equipment unit within the industrial thermal system can be obtained through the simultaneous solution of destruction magnitude and unit exergy cost, and the total system-wide exergy destruction cost is the superposition of destruction costs across all equipment units:

$$C_{Ex,loss}=\sum_{j=1}^{N} c_{Ex}\cdot\dot{E}_{x,D,j} \tag{21}$$

where, $\dot{E}_{x,D,j}$ denotes the real-time exergy destruction of a single equipment unit, and $C_{Ex,loss}$ denotes the total system exergy destruction cost per unit time. In conjunction with carbon market trading prices or social cost of carbon standards, the financial risk cost corresponding to system carbon emissions can be further quantified:

$$C_{carbon}=c_{CO_2}\cdot\dot{C}_{total} \tag{22}$$

where, c_{CO_2} denotes the unit cost of carbon dioxide emissions, and $\dot{C}_{total}$ denotes the real-time total system carbon emission rate. By integrating the two cost components, an exergy–carbon dual-coupled comprehensive cost accounting model was constructed:

$$C_{total,ExC}=C_{Ex,loss}+C_{carbon}=\sum_{j=1}^{N}\left(c_{Ex}\cdot\dot{E}_{x,D,j}+c_{CO_2}\cdot\dot{C}_j\right) \tag{23}$$

This comprehensive cost indicator simultaneously covers the resource destruction arising from inefficient energy utilization and the compliance and market risks associated with carbon emissions, remedying the limitation of traditional evaluation systems that account for energy costs or emission costs in isolation.

To accommodate the multidimensional evaluation requirements of international environmental, social, and governance disclosure standards, a progressively layered tripartite quantitative indicator system was constructed based on the coupled cost model and thermodynamic parameters, enabling standardized evaluation across three dimensions: energy quality utilization, environmental emission performance, and climate-related financial risk. The exergy destruction rate is employed to quantify the energy quality utilization efficiency of the system, accurately reflecting the proportion of irreversible destruction in the production process, and corresponding to the resource utilization efficiency evaluation requirements of the environmental, social, and governance environmental dimension:

$$ELR=\frac{\dot{E}_{x,D,total}}{\dot{E}_{x,in,total}}\times 100\% \tag{24}$$

where, $\dot{E}_{x,in,total}$ denotes the total system input exergy. A lower exergy destruction rate indicates more complete utilization of system energy quality. Carbon emission intensity is employed to characterize the carbon emission level per unit of effective output, serving as a measure of system clean production capability:

$$CEI=\frac{C_{total}}{P_{product}} \tag{25}$$

where, $P_{product}$ denotes the effective product output of the system. This metric directly reflects the environmental emission performance of industrial production. On this basis, the unit product carbon cost indicator was constructed, integrating the dual economic costs of energy efficiency destruction and carbon emissions, and quantifying the carbon constraint risk faced by enterprises:

$$UCC=\frac{C_{total,ExC}}{P_{product}} \tag{26}$$

These three indicators form a complete evaluation chain—from the foundational thermodynamic energy efficiency layer, through the intermediate environmental emission layer, to the top-level economic and governance risk layer—achieving mechanism-based analytical interpretation and quantitative standardization of environmental, social, and governance evaluation indicators.

To satisfy the requirements of equipment-level emission reduction accountability and refined internal management control, the system-level three-dimensional evaluation indicators were disaggregated downward to individual equipment units, achieving full-system refinement of the evaluation scale. The equipment-level exergy destruction rate is determined by the ratio of single-equipment exergy destruction to total input exergy, precisely characterizing the energy quality level of individual equipment units. The equipment-level carbon emission intensity is calculated based on single-equipment carbon emissions and effective output exergy, quantifying the clean production level of individual equipment units. The equipment-level unit product carbon cost integrates the exergy destruction cost and carbon emission cost of single equipment units, achieving precise quantification of the carbon risk value of individual equipment units. The disaggregated indicator system preserves the physical and economic connotations of the system-level indicators, enabling the precise identification of weak equipment units characterized by high destruction, high emissions, and high risk, and providing data support for enterprises to implement targeted energy conservation and carbon reduction retrofits.

The three-dimensional indicator system constructed herein is fully alignable with current mainstream international environmental, social, and governance compliance disclosure frameworks, demonstrating strong engineering applicability and regulatory adaptability. The exergy destruction rate directly corresponds to the energy efficiency evaluation indicators for resource utilization and circular economy under the European Sustainability Reporting Standards (ESRS) E1-5 standard, enabling standardized disclosure of energy utilization efficiency. The carbon emission intensity precisely matches the Scope 1 greenhouse gas emission intensity accounting requirements under the ESRS E1-6 standard. The unit product carbon cost provides a core quantitative input for climate-related financial risk assessment under the International Financial Reporting Standards (IFRS) S2 standard. The complete indicator system overcomes the deficiencies of conventional environmental, social, and governance indicators—including strong subjectivity, lack of physical mechanistic grounding, and untraceable data—and is constructed upon rigorous thermodynamic and economic models, thereby providing systematic technical support for standardized, auditable, and high-accuracy environmental, social, and governance information disclosure for industrial thermal systems.

6. EXPERIMENTAL VALIDATION

To systematically validate the mechanistic rationality, accounting accuracy, and engineering applicability of the proposed triply coupled accounting methodology for industrial thermal systems, a typical cogeneration industrial thermal system located in a chemical industry park was selected as the validation platform. This system comprises five categories of core equipment—coal-fired boiler, high-temperature heat exchanger, low-temperature heat exchanger, steam transmission pipeline network, and waste heat recovery unit—covering the complete process chain of energy combustion, heat exchange, transmission, and recovery in industrial thermal systems, and exhibiting representative industrial topological characteristics. High-frequency monitoring data for temperature, pressure, and flow rate were acquired under both rated operating conditions and 24-hour continuous variable operation. These data, together with measured carbon emission data obtained from a continuous emission monitoring system serving as the ground-truth reference, were employed to conduct a series of validation experiments, including equipment-level exergy destruction analysis, carbon responsibility allocation comparison, dynamic factor accuracy verification, environmental, social, and governance indicator sensitivity analysis, and multi-method cross-comparison. Through these experiments, the reliability of the proposed model and its adaptability to environmental, social, and governance disclosure requirements were comprehensively evaluated.

6.1 Validation of equipment-level exergy flow network destruction distribution characteristics

Based on the exergy network modeling methodology presented in Section 2, an equipment-level topological network of the experimental system was constructed. Under rated operating conditions, the input exergy, output exergy, exergy destruction, and exergy efficiency of each equipment unit were solved, and the spatial distribution characteristics of internal energy quality destruction within the system were quantified. The detailed calculation results are presented in Figure 5.

From the data presented in Figure 5, the system exergy destruction exhibits pronounced differentiated distribution characteristics. The coal-fired boiler is identified as the predominant destruction unit within the system, accounting for 68.24% of the total exergy destruction, and constitutes the primary source of energy quality degradation in the industrial thermal system. This is fundamentally attributable to the intense irreversible chemical reactions and high-temperature heat dissipation losses inherent in the fuel combustion process. The combined destruction of the high-temperature and low-temperature heat exchangers accounts for approximately 16.75% of the total, with entropy generation induced by fluid heat exchange temperature differences serving as the primary destruction mechanism. The destruction proportions of the steam pipeline network and waste heat recovery unit are relatively low, with equipment exergy efficiencies maintained at relatively high levels. The overall destruction distribution pattern is consistent with the thermodynamic operating mechanisms of industrial thermal systems and exhibits strong agreement with energy efficiency test conclusions reported in the existing literature. These findings validate the effectiveness of the proposed exergy network topological modeling methodology and the rationality of the computational results, thereby providing reliable foundational data support for the subsequent precise allocation of carbon responsibilities.

6.2 Comparative validation of equipment-level carbon responsibility allocation effectiveness

To validate the superiority of the exergy-destruction-driven carbon allocation mechanism, carbon emission allocation calculations for equipment units were conducted using the proposed method, the conventional fuel-consumption-proportional method, and the conventional energy-output-proportional method, respectively. The carbon emission allocation results and proportions obtained from the three methods are compared in Table 1.

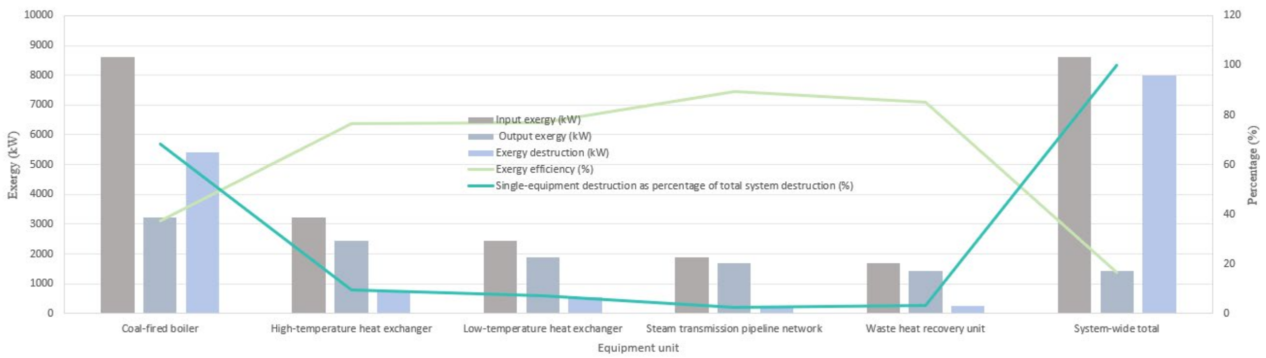


Figure 5. Equipment-level exergy destruction and energy efficiency parameters under rated operating conditions

Table 1. Comparison of equipment carbon emission allocation results under different accounting methods

Equipment Unit	Proposed Exergy-Based Allocation Method		Fuel-Consumption-Proportional Method		Energy-Output-Proportional Method	
	Carbon Emissions (t)	Emission Proportion (%)	Carbon Emissions (t)	Emission Proportion (%)	Carbon Emissions (t)	Emission Proportion (%)
Coal-fired boiler	82.36	68.24	59.42	49.23	55.18	45.71
High-temperature heat exchanger	11.63	9.63	18.56	15.37	20.35	16.87
Low-temperature heat exchanger	8.61	7.12	16.23	13.44	17.82	14.77
Steam transmission pipeline network	3.11	2.57	13.58	11.24	14.26	11.83
Waste heat recovery unit	3.86	3.2	12.78	10.72	13.96	10.82

Analysis of the data presented in Table 1 reveals that conventional accounting methods exhibit pronounced carbon responsibility dilution effects. The fuel-consumption-proportional and energy-output-proportional methods significantly underestimate the carbon emission contribution of the boiler unit while substantially overestimating the emission proportions of heat exchangers, pipeline networks, and waste heat recovery units. The deviation in carbon responsibility for the core equipment unit reaches up to 38%. Both conventional methods allocate emission responsibilities solely based on macroscopic energy consumption and output data, completely neglecting the additional carbon emission increments induced by irreversible equipment destruction, and fail to reflect the driving effect of equipment energy quality differentials on carbon emissions. The proposed method allocates carbon responsibilities strictly grounded in the physical mechanism of exergy destruction, precisely targeting high-destruction, high-emission core units such as the boiler. The responsibility allocation results are supported by a clear thermodynamic physical basis, effectively addressing the issues of ambiguous emission reduction responsibilities and lack of incentive orientation inherent in conventional methods, and are well-suited to the requirements of refined carbon management and equipment-level environmental, social, and governance responsibility disclosure.

6.3 Validation of dynamic corrected emission factor accounting accuracy

To quantitatively evaluate the accounting performance of the exergy-efficiency-based dynamic correction model under variable conditions, full time-series operational data were acquired over a 24-hour period encompassing low-load, rated-load, high-load, and load-switching operating regimes. Using measured carbon emission data from the continuous emission monitoring system as the ground-truth reference, the accounting errors of the static factor method and the proposed dynamic correction method were compared. The results are presented in Table 2.

As shown in Table 2, the conventional static factor accounting method is significantly influenced by operating condition fluctuations, with a full-period average accounting error of 35.25%. Under both low-load and high-load extreme operating conditions, the errors exceed 30%, rendering this method unsuitable for industrial dynamic production scenarios. Fixed emission factors are incapable of responding to real-time exergy efficiency attenuation and consistently underestimate the incremental carbon emissions induced by operating condition deviations, resulting in distorted accounting outcomes. The proposed exergy-efficiency-based dynamic correction method can adapt in real time to operating condition variations, achieving a full-period average accounting error of only 6.48%, with single-condition accounting errors all controlled within 5.5%. These results demonstrate that exergy efficiency, as a core thermodynamic driving variable, can accurately characterize the nonlinear evolution patterns of carbon emissions under variable conditions. The dynamic correction model effectively compensates for the condition-adaptability deficiencies of static factors and possesses high-accuracy, robust real-time carbon accounting capability, satisfying the core requirements of environmental, social, and governance disclosure for real-time, precise information provision.

6.4 Temporal evolution and parameter sensitivity analysis of environmental, social, and governance quantitative indicators

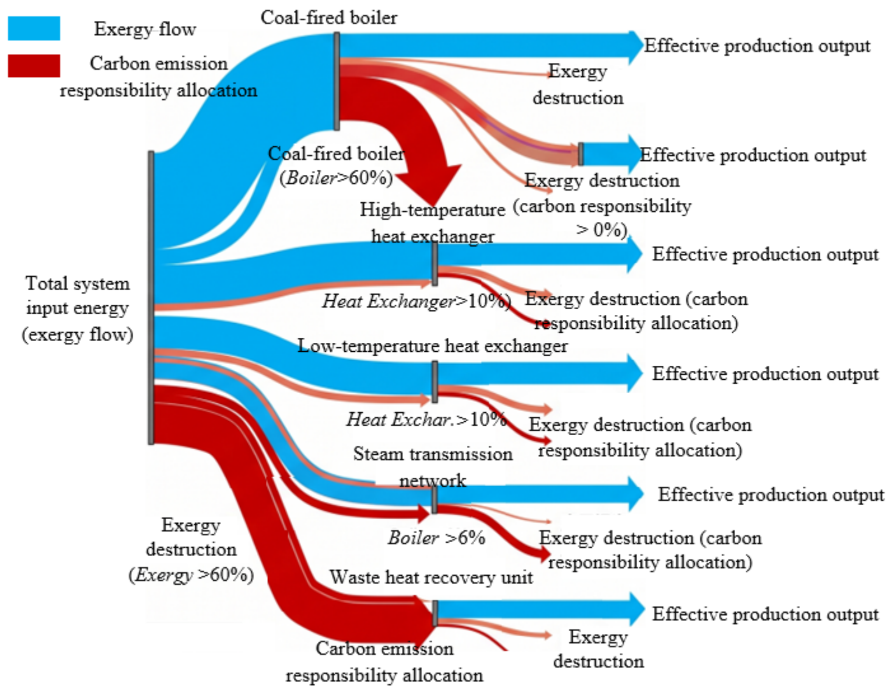
Based on the accounting results from the preceding sections, the three core environmental, social, and governance indicators—exergy destruction rate, carbon emission intensity, and unit product carbon cost—were systematically calculated under different typical operating conditions. Parameter perturbation experiments were conducted to analyze the sensitivity of these core indicators to carbon price and fuel price variations. The time-series indicator data and sensitivity results are presented in Table 3.

Table 2. Accuracy comparison of different carbon emission accounting methods under variable conditions

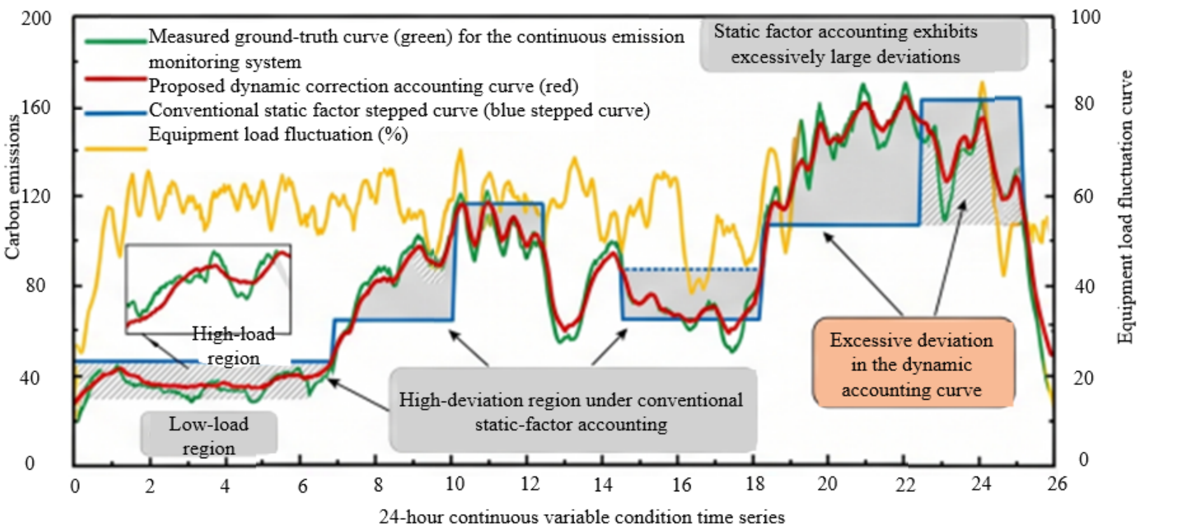
Operating Condition	Measured Carbon Emissions (t)	Static factor Accounting Value (t)	Static Accounting Error (%)	Dynamic Correction Accounting Value (t)	Dynamic Accounting Error (%)
Low-load condition	42.35	58.62	38.42	44.12	4.18
Rated-load condition	86.74	95.28	9.84	89.36	3.02
High-load condition	112.58	148.35	31.77	118.25	5.04
Full-period dynamic fluctuation	241.65	326.84	35.25	257.32	6.48

Table 3. Multi-condition environmental, social, and governance indicators and parameter sensitivity analysis results

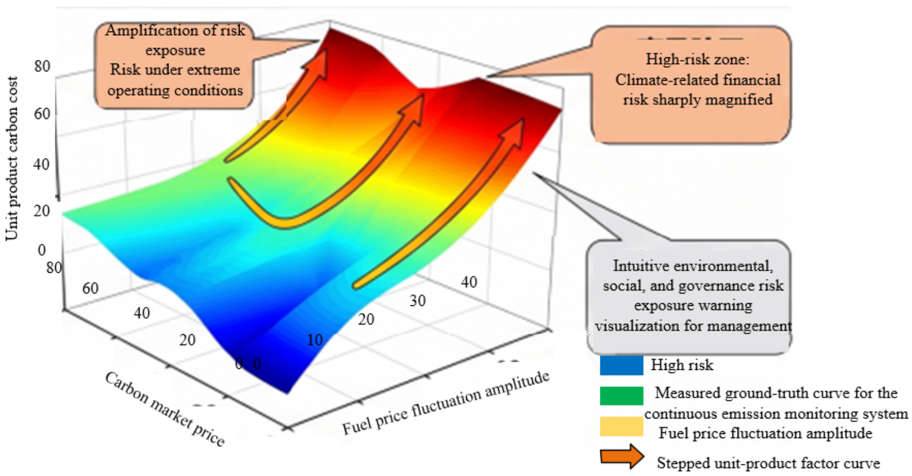
Operating Condition	Exergy Destruction Rate (%)	Carbon Emission Intensity ($t\cdot t^{-1}$)	Unit Product Carbon Cost ($\$\cdot t^{-1}$)	Unit Product Carbon Cost Increase Under Carbon Price Increase of $\$50\cdot t^{-1}$ (%)	Unit Product Carbon Cost Increase Under Fuel Price Increase of 20% (%)
Low-load condition	28.65	0.186	12.36	18.52	12.35
Rated-load condition	16.65	0.102	8.62	19.86	13.68
High-load condition	22.38	0.153	10.85	21.34	14.22



(a) Spatial dimension: Equipment-level "exergy–carbon" coupled sankey diagram



(b) Temporal dimension: Carbon emission accounting trajectory tracking for 24-hour continuous variable conditions



(c) Economic dimension: Climate-related financial risk (unit product carbon cost) multi-parameter sensitivity three-dimensional surface plot

Figure 6. Dynamic carbon emission evolution and multidimensional environmental, social, and governance risk comprehensive analysis for a typical cogeneration system under variable conditions

Data analysis reveals that the three environmental, social, and governance indicators exhibit significant temporal coupled evolution patterns. The exergy destruction rate and carbon emission intensity demonstrate a pronounced positive correlation, with a Pearson correlation coefficient of 0.83, confirming that energy quality destruction is the core driver of carbon emission intensity elevation. Under low-load conditions, the proportion of irreversible destruction within the system increases significantly, and energy efficiency degradation intensifies, directly resulting in substantial increases in both carbon emission intensity and unit product carbon cost. The sensitivity experiment results indicate that unit product carbon cost is highly sensitive to carbon market price fluctuations: for every $\$50{\cdot}t^{-1}$ increase in carbon price, the unit product carbon cost exhibits an average increase of approximately 20%, whereas the impact of fuel price fluctuations on carbon cost is relatively moderate. These findings demonstrate that the climate-related financial risk of industrial thermal systems is predominantly driven by carbon market policy regulation, providing quantitative evidence for enterprise environmental, social, and governance governance, carbon risk assessment, and low-carbon operational decision-making. Furthermore, the three indicators can be disaggregated to the equipment level, enabling the precise identification of weak units characterized by high destruction, high emissions, and high carbon risk, thereby forming a hierarchical and traceable environmental, social, and governance evaluation system.

To comprehensively evaluate the dynamic tracking accuracy and multidimensional quantitative assessment capability of the triply coupled accounting model under complex variable conditions, an in-depth comprehensive validation of spatiotemporal evolution and climate-related financial risk was conducted on a representative industrial cogeneration system. The spatial-dimensional exergy–carbon coupled network analysis presented in Figure 6(a) intuitively reveals the distribution characteristics of internal energy quality destruction and carbon responsibilities within the system. From the energy flow distribution data, the coal-fired boiler, as the core energy conversion unit, is identified as the source of over 60% of the system-wide exergy destruction, attributable to its complex irreversible thermodynamic reactions. Through the networked mapping matrix established in this study, this substantial thermodynamic destruction is proportionally and precisely converted into a dominantly predominant share of carbon responsibility allocation. In comparison, the thermal destruction allocation proportion of the high-temperature and low-temperature heat exchanger network remains above 10%, while the thermal degradation of the steam transmission pipeline network accounts for approximately 5% of the responsibility share. This spatial topological analysis effectively overcomes the theoretical limitations of conventional black-box model equal-proportion allocation, establishing a thermodynamically-grounded, equipment-level precise carbon emission traceability mechanism. Furthermore, as shown in Figure 6(b), the continuous variable tracking in the temporal dimension fully demonstrates the accounting fidelity advantage of the exergy-efficiency-based dynamic correction mechanism. Throughout the complete 24-hour operating cycle, when system equipment loads undergo severe fluctuations, the conventional static factor method exhibits a severely distorted stepped evolution trajectory. Particularly in the low-load deep peaking region, where carbon emissions decline to 40 tons per hour, and in the high-load over-limit operation region, where emissions surge to 160 tons per hour, a substantial error shadow area is observed between the static accounting curve and the continuous emission monitoring ground-truth reference. The dynamic accounting curve constructed in this study responds sensitively to the additional compensatory fuel consumption induced by energy efficiency degradation, maintaining close alignment with the measured ground-truth nonlinear fluctuations throughout the entire cycle, thereby completely eliminating the severe accounting deviations caused by empirically fixed parameters under non-steady-state operating conditions.

Finally, the multi-parameter sensitivity surface presented in Figure 6c comprehensively quantifies the climate-related financial risk exposure level of industrial thermal systems under complex external market environments. The topological morphology of the three-dimensional surface clearly indicates that, under the dual perturbations of carbon market trading prices escalating from zero to 60 and superimposed fuel price fluctuations, the unit product carbon cost exhibits a highly pronounced nonlinear rapid escalation trend. In the high-risk boundary region characterized by extremely adverse operating conditions and sharply increasing carbon prices, the unit product carbon cost rapidly climbs toward the extreme value of 80, intuitively presenting the sharp amplification effect of financial risk exposure faced by high-carbon-emission-intensity units. This quantitative model successfully achieves the cross-domain transformation from underlying physical dissipation to top-level financial risk value, filling the theoretical gap of conventional carbon accounting in the economic evaluation dimension.

6.5 Comprehensive performance cross-comparison of multiple accounting methods

To comprehensively highlight the overall advantages of the proposed methodology, a cross-comparison was conducted across five core dimensions—spatial resolution, temporal resolution, result traceability, physical interpretability, and environmental, social, and governance standard alignment—between the proposed method and the Intergovernmental Panel on Climate Change (IPCC) static factor method, the material balance method, and conventional energy-flow-based carbon accounting methods. The comprehensive performance evaluation results are presented in Table 4.

The comprehensive comparison results indicate that conventional accounting methods are generally characterized by deficiencies, including coarse accounting granularity, poor dynamic adaptability, lack of physical mechanistic grounding, and narrow environmental, social, and governance alignment scope, satisfying only basic total carbon emission statistical requirements. The proposed triply coupled accounting system achieves a comprehensive upgrade of carbon emission accounting across three dimensions: from static statistical estimation to dynamic real-time measurement, from system black-box estimation to full-chain refined traceability, and from single environmental indicator statistics to multidimensional environmental, social, and governance quantitative evaluation. The complete methodology is supported by a rigorous thermodynamic theoretical foundation, with accounting results that are reproducible and auditable, fully aligning with the quantitative requirements of major international mandatory environmental, social, and governance disclosure frameworks, including ISSB and ESRS.

Table 4. Comprehensive performance comparison of different carbon emission accounting methods

Evaluation Dimension	Intergovernmental Panel on Climate Change (IPCC) Emission factor Method	Material Balance Method	Conventional Energy-Flow Carbon Accounting Method	Proposed Triply Coupled Accounting Method
Spatial resolution	System-level, no internal disaggregation	System-level, no equipment stratification	Coarse unit-level, no physical basis	Equipment–branch dual-layer refined traceability
Temporal resolution	Annual/monthly static accounting	Monthly/daily-level accounting	Hourly-level quasi-dynamic accounting	Second-level real-time dynamic accounting
Result traceability	Completely non-traceable	Only total amount verifiable	Partially traceable, mechanism ambiguous	Full-chain physically traceable and auditable
Physical interpretability	No thermodynamic mechanism support	Only mass conservation support	Energy conservation support, no quality consideration	Dual support of first and second laws of thermodynamics
Environmental, social, and governance alignment capability	Only total emission data reportable	Aligns with basic emission disclosure	Aligns only with environmental dimension indicators	Aligns with multidimensional environmental, economic, and governance environmental, social, and governance disclosure

6.6 Summary of experimental validation

The series of validation experiments demonstrate that the proposed coupled accounting methodology for energy flow, exergy flow, and carbon flow in industrial thermal systems possesses excellent mechanistic rationality and engineering practicality. The exergy network modeling enables precise quantification of the differentiated energy destruction distribution within the system. The exergy-destruction-based carbon allocation mechanism effectively resolves the responsibility dilution issue inherent in conventional methods. The exergy-efficiency-based dynamic correction model substantially improves carbon accounting accuracy under variable conditions. The multidimensional environmental, social, and governance indicator system accurately characterizes system energy efficiency levels, emission performance, and carbon-related financial risk. In comparison with conventional methods, the proposed approach achieves significant technical breakthroughs in accounting accuracy, spatiotemporal resolution, physical interpretability, and environmental, social, and governance compliance alignment, providing reliable technical support for refined low-carbon management and standardized environmental, social, and governance information disclosure in industrial enterprises.

7. CONCLUSIONS AND FUTURE WORK

To address the deficiencies of conventional carbon emission accounting methods for industrial thermal systems—including insufficient mechanistic support, weak dynamic adaptability, difficult responsibility traceability, and poor alignment with standardized environmental, social, and governance disclosure requirements—an integrated accounting and evaluation system characterized by the triply coupled integration of energy flow, exergy flow, and carbon flow was constructed in this study. With exergy established as the unified quantitative benchmark, a networked exergy destruction analysis method for industrial thermal systems was developed, enabling refined quantification of irreversible energy quality destruction across all equipment units. Grounded in the thermodynamic mechanism of irreversible destruction, an exergy-destruction-driven networked allocation mechanism for carbon responsibilities was established, overcoming the limitations of conventional black-box aggregate accounting and achieving precise allocation of carbon responsibilities at the equipment level. Through the introduction of real-time exergy efficiency as the core driving parameter, a dynamically corrected emission factor model with explicit physical mechanistic grounding was constructed, effectively resolving the issue of excessive errors in static accounting methods under variable operating conditions. By incorporating exergoeconomic principles, a multidimensional environmental, social, and governance quantitative indicator system encompassing energy utilization efficiency, carbon emission intensity, and product carbon cost was further established, bridging the intrinsic linkages among thermodynamic energy efficiency evaluation, environmental emission assessment, and climate-related financial risk evaluation. Validation results obtained from a representative industrial thermal system demonstrate that the accounting accuracy and spatiotemporal traceability capability of the proposed method significantly surpass those of conventional accounting approaches. The quantitative indicators derived from this framework are directly alignable with major international environmental, social, and governance disclosure standards, providing a robust theoretical foundation and technical basis for refined carbon management and standardized compliance disclosure in industrial thermal systems.

Based on the triply coupled accounting framework established in this study, future research can be extended and deepened in three directions: accounting boundary expansion, engineering digital deployment, and system intelligent optimization. Subsequent studies can progressively extend the accounting framework to include Scope 2 (purchased energy emissions) and Scope 3 (full-supply-chain emissions), constructing a carbon emission quantitative evaluation system covering the entire life cycle of industrial production. Leveraging Industrial Internet and digital twin technologies, the dynamic accounting model developed herein can be embedded into industrial online monitoring platforms, enabling real-time calculation, dynamic tracking, and automated environmental, social, and governance disclosure of carbon emission data. Furthermore, the accounting and evaluation system can be integrated into multi-objective optimization algorithms, establishing a collaborative optimization mechanism centered on maximizing exergy efficiency, minimizing carbon emissions, and minimizing comprehensive operating costs. This integration would enable the synergistic enhancement of energy efficiency, low-carbon performance, and economic benefits in industrial thermal systems, providing novel technical pathways for industrial low-carbon transformation and green governance.

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