



Exergoeconomic Analysis of Thermodynamic Efficiency and Revenue Allocation Mechanisms for Waste-to-Energy PPP Projects Based on Extended Exergy Accounting

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ABSTRACT

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Waste-to-energy (WtE) incineration has become a core technology for the resource recovery and harmless treatment of municipal solid waste. The Public–Private Partnership (PPP) model is now the dominant implementation mode for the investment, construction, and operation of WtE projects in China. However, current engineering practice and theoretical research largely decouple thermodynamic efficiency optimization from the multi-stakeholder revenue allocation system. Conventional exergoeconomic analyses focus exclusively on equipment-level energy–cost accounting under a single operator framework; they fail to characterize the heterogeneous contributions of multiple stakeholders and cannot establish a quantitative link between thermodynamic performance improvement and incremental economic benefits. Consequently, they offer limited support for designing incentive-compatible mechanisms that ensure fairness and efficiency in PPP contracts. To address these gaps, this study constructs a multi-stakeholder exergoeconomic cost-sharing framework based on exergoeconomics and extended exergy accounting (EEA) theory, and develops a coupled quantitative model linking thermodynamic efficiency with revenue distribution. The transmission pathways and allocation rules through which system exergy destruction reduction converts into incremental stakeholder benefits are systematically revealed. A typical 750 t/d commercial WtE PPP project is adopted as a case study to perform a full-system exergy balance analysis and identify critical exergy-loss units. A multi-objective optimization is conducted using the Non-dominated Sorting Genetic Algorithm (NSGA-II) to achieve a trade-off between thermodynamic efficiency and revenue allocation fairness. Parametric perturbation analyses further examine the influence mechanisms of key factors including waste calorific value, electricity tariff policies, and waste treatment subsidies. The proposed integrated framework bridges the long-standing divide between technical thermodynamic optimization and economic benefit distribution. It provides a theoretical basis and quantitative decision-making tool for dynamic contract design, revenue mechanism optimization, and sustainable long-term operation of WtE PPP projects.

1. INTRODUCTION

The global generation of municipal solid waste continues to expand, with annual output projected to increase from 2.1 billion tonnes in 2023 to 3.8 billion tonnes by 2050 [1, 2]. Waste-to-energy (WtE) incineration enables significant volume reduction and energy recovery of solid waste and has become a key technological pathway in modern municipal solid waste treatment systems [3-5]. More than fifty countries have built and commissioned over one thousand incineration power plants worldwide. In China, the Public–Private Partnership (PPP) model is widely adopted for the investment, construction, and long-term operation of WtE projects, gradually forming a governance pattern involving government, social capital, and the public [6]. More broadly, sustainable energy projects increasingly require governance arrangements capable of reconciling operational efficiency, environmental performance, and the interests of multiple participating actors

[7]. Inherent conflicts exist during project operation, as the optimization objective of system thermodynamic performance lacks an internal connection with the revenue allocation rules among multiple stakeholders [8]. Irreversible reactions in the incineration process and finite temperature differences across heat-transfer processes generate substantial exergy destruction, directly constraining power-generation performance and the associated revenue potential [9, 10]. Energy and exergy analyses of power-generation systems have similarly demonstrated the importance of locating thermodynamic losses and examining operating parameters when system efficiency is optimized [11, 12]. Current revenue allocation rules are formulated based on pre-signed commercial agreements and do not incorporate a dynamic adjustment mechanism linked to real-time thermodynamic operating performance. Quantitative criteria are lacking for attributing incremental costs and incremental revenues generated by efficiency improvements to relevant parties [13, 14].

Exergoeconomics establishes a theoretical bridge between thermodynamic analysis and economic accounting and has been widely applied to cost optimization studies of WtE systems [15, 16]; however, existing methods assume a single operating entity and are difficult to adapt to multi-participant project models [17, 18]. The extended exergy accounting (EEA) method can convert non-energy inputs such as capital, labor, and environmental governance into unified thermodynamic indicators, providing a feasible path for measuring the comprehensive input level of different stakeholders [19, 20]. This paper attempts to construct a complete quantitative analytical framework that integrates exergy accounting, exergoeconomic allocation, revenue modeling, and multi-objective optimization into a unified analysis system, connecting system thermodynamic efficiency and multi-party revenue distribution to provide thermodynamic-level theoretical support for the design of incentive-compatible mechanisms in PPP projects [21, 22].

A review of existing relevant studies reveals three notable limitations in the current research system. Most studies conduct exergy analysis of WtE systems or financial economic evaluation independently; the two analytical paths remain separate, and a quantitative relationship between thermodynamic performance changes and revenue distribution patterns has not yet been established [9, 10]. Existing work lacks a complete analytical chain and cannot quantify how value-added benefits brought by reduced equipment exergy loss should be allocated among different stakeholders [13, 14]. Mainstream exergoeconomic analysis tools take equipment units and energy flows as accounting objects; the typical Specific Exergy Costing (SPECO) method can only complete product cost allocation within the system and does not consider the multi-stakeholder participation characteristics of projects [15, 16]. In waste incineration PPP projects, funding sources and operation–maintenance responsibilities differ across equipment items, while traditional methods cannot realize precise attribution of the economic costs corresponding to exergy destruction to each participating entity [5, 7]. Conventional exergy accounting frameworks only consider energy and capital inputs while neglecting various non-energy elements in project operation processes [19, 20]. Governmental regulatory efforts, operational team labor inputs, and environmental risks borne by the public all profoundly affect the sustainable operation status of projects [7, 8]. Although EEA has been trialed in facility siting and energy system assessment, it has not yet been applied to solving multi-stakeholder revenue allocation problems [23, 24]. These shortcomings collectively restrict existing theories from guiding the design of long-term mechanisms for waste incineration PPP projects.

To address the above research gaps, this paper carries out four systematic research tasks. First, a multi-stakeholder exergoeconomic cost allocation model adapted to PPP projects is constructed to establish the correspondence among energy flow, equipment ownership, and stakeholder revenue, realizing stakeholder attribution of exergy destruction costs. Second, EEA is introduced to quantify various non-energy inputs and calculate the thermodynamic contribution level of each participant, serving as a benchmark for judging the rationality of revenue allocation. Third, a coupled model of thermodynamic efficiency and revenue allocation is established, defining an exergoeconomic efficiency coefficient to reveal the transmission law between system performance improvement and stakeholder incremental

revenue. Fourth, dual-objective optimization is implemented using the Non-dominated Sorting Genetic Algorithm (NSGA-II) to simultaneously seek solutions for improving system exergy efficiency and revenue allocation fairness, and the impact of external condition fluctuations is analyzed.

The overall structure of this paper comprises six chapters. Chapter 2 builds a whole-process thermodynamic model of waste incineration power generation and conducts exergy balance analysis. Chapter 3 completes multi-stakeholder exergoeconomic allocation modeling and EEA. Chapter 4 constructs the coupling model of thermodynamic efficiency and revenue allocation. Chapter 5 performs multi-objective optimization calculations and parameter sensitivity analysis. Chapter 6 summarizes the main research conclusions and proposes policy implications.

2. THERMODYNAMIC MODEL AND EXERGY ANALYSIS

This paper takes a typical domestic 750 t/d municipal waste incineration PPP project as the research object. The unit is equipped with an incineration boiler and a steam turbine generator set with parameters of 4 MPa and 400 °C. According to functional differences in energy conversion, material handling, and pollutant control, the overall thermal system is divided into four major subsystems: incinerator, waste heat boiler, steam turbine generator set, and flue gas treatment system. Municipal solid waste is fed into the grate through the feeding unit for complete combustion. High-temperature flue gas generates high-quality superheated steam via radiation and convection heat transfer, driving the steam turbine generator set to complete power generation. End-of-pipe flue gas is purified by multi-stage environmental protection equipment before being discharged up to standard. To eliminate calculation deviations caused by unsteady conditions and ambiguous boundary conditions, standardized modeling assumptions are uniformly set for the study. Steady-state operating conditions are adopted throughout. Waste composition and thermodynamic parameters are fixed. The standard environmental state is selected as the thermodynamic reference. The exergy contribution of low-grade energy forms is ignored, and heat leakage losses between subsystems are excluded, so as to construct a unified and standardized modeling boundary for whole-process refined exergy accounting and subsequent multi-stakeholder coupling analysis. Figure 1 shows the exergy flow topology and node distribution diagram of the PPP waste incineration power generation system.

Municipal solid waste chemical exergy constitutes the core component of primary energy input, and its calculation accuracy directly determines the reliability of overall thermodynamic analysis. Municipal solid waste has complex components and exhibits significant spatiotemporal variation, making traditional heating value conversion methods inadequate for accurately characterizing its energy quality. This paper adopts the Szargut calculation method based on elemental analysis to quantify the exergy value of waste fuel. The core calculation formula is as follows:

$$Ex_{fuel} = LHV \times \psi \quad (1)$$

where, Ex_{fuel} is the specific chemical exergy per unit mass of waste, LHV is the lower heating value of municipal solid waste,

and ψ is the fuel exergy correction factor. The exergy correction factor can be quantitatively solved from the elemental composition ratio of waste:

$$\psi = 1.0064 + 0.1519 \frac{H}{C} + 0.0616 \frac{O}{C} + 0.0429 \frac{N}{C} \quad (2)$$

where, C , H , O , and N are the mass fractions of carbon,

hydrogen, oxygen, and nitrogen in waste, respectively. Typical measured domestic municipal solid waste component parameters are used for calculation. The final results show that the lower heating value is 7500 kJ/kg, the exergy correction factor is 0.904, and the specific chemical exergy of waste is 6780 kJ/kg, effectively avoiding systematic errors caused by conventional constant-value estimation.

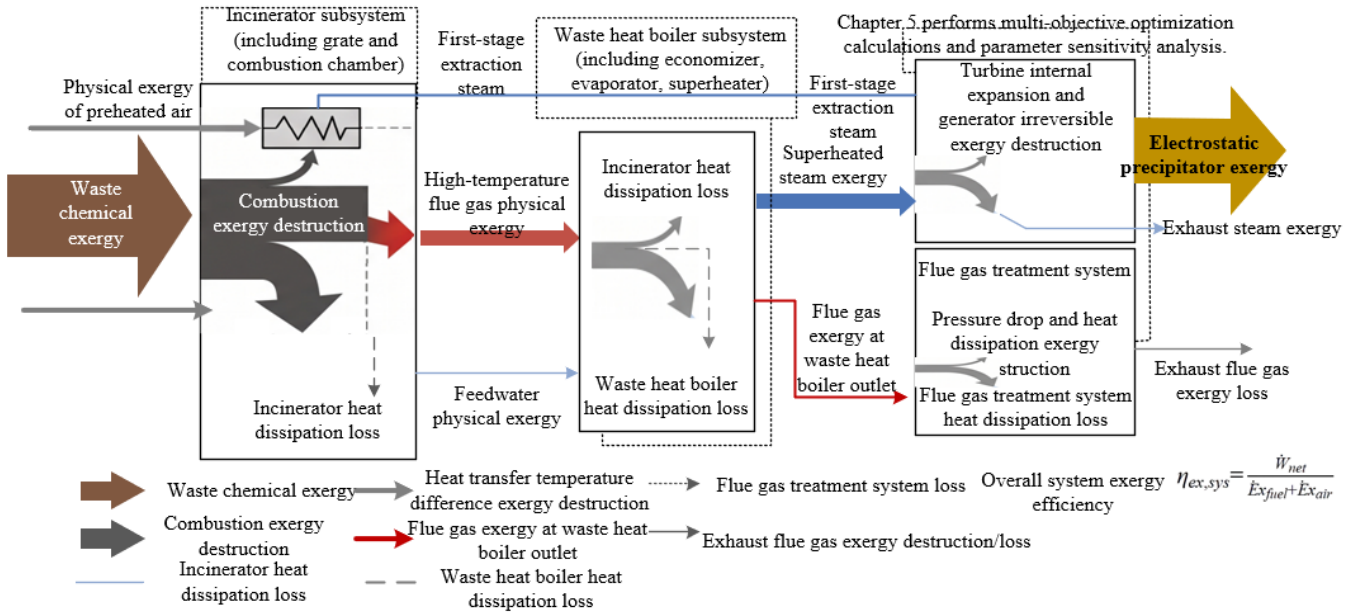


Figure 1. Exergy flow topology and node distribution diagram of the Public–Private Partnership (PPP) Waste-to-energy (WtE) system

The system operation involves working fluids of multiple types, and the thermodynamic properties of different fluids vary significantly. A single accounting model cannot meet the exergy-solving requirements of the whole process. This paper establishes a hierarchical and differentiated physical exergy accounting system. The general expression for physical exergy calculation is:

$$Ex = \dot{m}[(h - h_0) - T_0(s - s_0)] \quad (3)$$

where, Ex is the physical exergy of the stream, $\dot{m}$ is the mass flow rate, h and s are the specific enthalpy and specific entropy under actual working conditions, h_0 and s_0 are the specific enthalpy and specific entropy under standard environmental conditions, and T_0 is the reference ambient temperature. For ideal gas mixtures such as air and flue gas, the component superposition method is used to solve physical exergy:

$$Ex_{physical} = \sum_i \dot{m}_i \left[c_{p,i} (T - T_0) - T_0 c_{p,i} \ln \frac{T}{T_0} + R_i T_0 \ln \frac{P}{P_0} \right] \quad (4)$$

where, $\dot{m}_i$ is the mass flow rate of a single component, $c_{p,i}$ is the constant-pressure specific heat of the component, R_i is the individual gas constant, and T and P are the actual working temperature and pressure, respectively. For real working fluids such as water/steam, the IAPWS-IF97 international standard property database is used to obtain accurate thermodynamic parameters. Meanwhile, the proportion and preheating condition of primary air components are specified, enabling refined solution of exergy parameters for all streams in the whole system.

To accurately trace the equipment-level source of

irreversible losses in the system, standardized exergy balance equations are established for the four subsystems respectively, unifying the whole-process accounting paradigm. The core exergy balance relation is:

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \sum \dot{E}x_{dest} + \sum \dot{E}x_{loss} \quad (5)$$

where, $\dot{E}x_{in}$ and $\dot{E}x_{out}$ are the inlet and outlet exergy rates of the subsystem, $\dot{E}x_{dest}$ is the exergy destruction rate caused by internal irreversible processes, and $\dot{E}x_{loss}$ is the exergy loss rate directly emitted to the environment. Considering the differentiated characteristics of energy conversion mechanisms of each unit, exclusive balance equations and efficiency evaluation indicators are constructed respectively. The incinerator focuses on irreversible losses of combustion reactions, evaluating combustion performance by the ratio of effective flue gas exergy output to total input exergy. The waste heat boiler concentrates on heat transfer temperature difference losses between hot and cold media, characterizing heat exchange efficiency by net exergy gain of the working fluid. The steam turbine generator set quantifies exergy losses during steam expansion and work extraction, taking net electrical exergy output as the core evaluation basis. The flue gas treatment system accounts for fluid pressure drop and heat dissipation losses, fully covering the exergy loss mechanism and quantification features of all equipment.

On the basis of refined exergy balance calculations for each subsystem, this paper constructs a system total exergy efficiency indicator capable of representing the overall energy utilization level of the unit, establishing a quantitative link between primary energy input and electrical output. The

calculation formula is:

$$\eta_{ex,sys} = \frac{\dot{W}_{net}}{\dot{E}x_{fuel} + \dot{E}x_{air}} \quad (6)$$

where, $\eta_{ex,sys}$ is the overall system exergy efficiency, $\dot{W}_{net}$ is the net electrical exergy output after deducting auxiliary power consumption, $\dot{E}x_{fuel}$ and $\dot{E}x_{air}$ are the input exergy rates of waste fuel and preheated air, respectively. Operating condition accounting results show that the physical exergy input of preheated air accounts for only 2%–5% of the total system exergy input, having limited impact on overall efficiency evaluation. Based on this engineering feature, reasonable simplification is made to the calculation formula, streamlining the accounting process while ensuring rigor of thermodynamic evaluation, thus forming a hierarchical, high-precision energy efficiency evaluation system ranging from equipment units to the whole system.

3. MULTI-STAKEHOLDER EXERGoeconomic COST ALLOCATION AND EXTENDED EXERGY ACCOUNTING

3.1 Multi-stakeholder exergoeconomic cost allocation model

Traditional exergoeconomic analysis systems take the SPECO method as the core to realize quantitative system cost allocation. This method relies on the correspondence between fuel and product exergy flows of equipment to construct a standardized cost balance relation for solving the exergy cost level of unit equipment. The cost balance expression for a single equipment is as follows:

$$\sum_{out} \dot{C}_{out,k} = \sum_{in} \dot{C}_{in,k} + \dot{Z}_k \quad (7)$$

where, $\dot{C}_{out,k}$ and $\dot{C}_{in,k}$ represent the output and input exergy flow cost rates of equipment k , respectively, and $\dot{Z}_k$ represents the annualized capital cost rate of equipment k after depreciation. The analysis boundary of this accounting framework is limited to equipment units and energy flow processes and is only applicable to single-operator energy system cost evaluation scenarios. WtE PPP projects involve multiple independent stakeholders. Investment responsibility, operation–maintenance obligations, and risk-bearing levels differ significantly among stakeholders. Traditional methods cannot attribute economic costs and revenue

rights/responsibilities corresponding to thermodynamic losses to the relevant entities, making it difficult to support quantitative design of project revenue allocation mechanisms.

To break through the dimensional limitation of traditional accounting frameworks, this paper establishes a three-tier mapping accounting system coupling exergy flow characteristics, equipment ownership attributes, and stakeholder revenue rights, realizing precise transmission of thermodynamic performance into stakeholder-level economic benefits. Figure 2 shows the framework of multi-stakeholder EEA and the three-tier cost–revenue mapping. The study first completes a full deconstruction of the PPP project revenue structure and clarifies the compositional dimensions of distributable project revenue. The total revenue calculation is as follows:

$$R_{total} = R_{elec} + R_{tip} + R_{subsidy} \quad (8)$$

where, R_{total} is the annual total revenue of the project, R_{elec} is the electricity sales revenue from grid-connected power generation, R_{tip} is the revenue from municipal waste treatment services, and $R_{subsidy}$ is the government viability gap funding revenue. On this basis, integrating equipment investment cost, operation–maintenance cost, and fuel consumption cost, a refined equipment-level exergoeconomic cost model is established:

$$c_{ex,k} = \frac{\dot{Z}_k + \dot{C}_{fuel,k} + \dot{C}_{O\&M,k}}{\dot{E}x_{out,k}} \quad (9)$$

where, $c_{ex,k}$ is the unit exergoeconomic cost of equipment k , $\dot{C}_{fuel,k}$ is the allocated cost rate of waste pretreatment and fuel consumption for equipment k , $\dot{C}_{O\&M,k}$ is the annual operation–maintenance cost rate of equipment k , and $\dot{E}x_{out,k}$ is the exergy output rate under steady-state operation. The annualized fixed investment cost of equipment is converted over the full life cycle through the capital recovery factor:

$$\dot{Z}_k = Z_k \times \frac{i(1+i)^n}{(1+i)^n - 1} \quad (10)$$

where, Z_k is the total initial construction investment of equipment k , i is the industry benchmark discount rate, and n is the designed service life of equipment. This calculation mode avoids the one-sidedness of static investment accounting and can precisely characterize the real economic cost corresponding to the thermodynamic performance of different equipment.

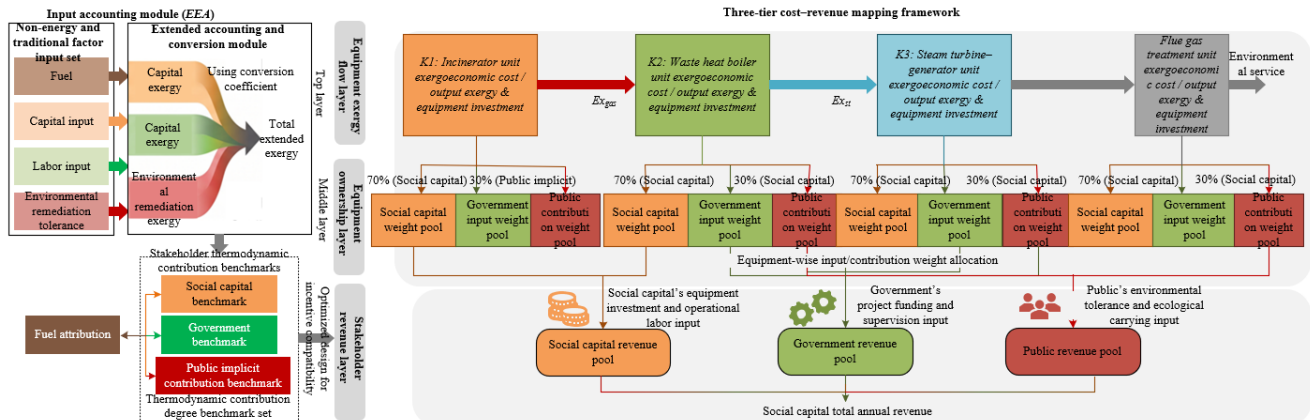


Figure 2. Framework of multi-stakeholder extended exergy accounting (EEA) and the three-tier cost–revenue mapping

Based on the equipment-level exergoeconomic cost accounting results and combined with the financing and investment structural features of PPP projects, a differentiated revenue allocation system adapted to multi-stakeholder scenarios is constructed. The study defines revenue allocation weights according to each stakeholder's equipment investment share, sets equipment-specific revenue distribution coefficients to realize matching of rights and liabilities, and clarifies the allocation ratio between social capital and government according to predetermined investment proportions. Environmental benefit claims of the public are separately quantified through the subsequent EEA system. Through coupled calculation of distribution coefficients and annual equipment exergoeconomic output, the stakeholder-specific sub-revenue corresponding to a single equipment can be solved:

$$R_{j,k} = \alpha_{j,k} \times (c_{ex,k} \times \dot{Ex}_{out,k} \times \tau) \quad (11)$$

where, $R_{j,k}$ is the annual revenue obtained by stakeholder from equipment k , $\alpha_{j,k}$ is the revenue distribution coefficient of stakeholder in equipment k , and τ is the annual effective operating hours of the unit. Summing the revenues of all equipment for a single stakeholder gives the stakeholder's total annual revenue:

$$R_j = \sum_{k=1}^4 R_{j,k} \quad (12)$$

where, R_j is the annual total distributable revenue of stakeholder j . This model deeply binds equipment exergy loss level, economic cost characteristics, and stakeholder investment-risk rights/liabilities, establishing a quantitative linkage mechanism between thermodynamic efficiency optimization and multi-stakeholder revenue increment, consistent with the core operational principle of risk-return equivalence in PPP projects.

3.2 Extended exergy accounting

The traditional exergoeconomic accounting system only focuses on quantitative analysis of system energy flows and fixed-asset capital input, and cannot cover the diversified non-energy input values in the operation process of WtE PPP projects, making it difficult to adapt to the right-liability accounting scenarios under multi-stakeholder collaborative operation. Based on the EEA method, this paper incorporates implicit elements neglected by traditional thermodynamic evaluation—such as capital input, human management, environmental carrying capacity, and ecological restoration—into a unified measurement system, realizing same-dimension thermodynamic quantification of tangible energy input and intangible socio-economic input, and constructing a full-domain exergy input accounting framework adapted to multi-stakeholder projects. The study decomposes total project exergy input into five core elements, with a unified accounting paradigm as follows:

$$Ex_{total} = Ex_{fuel} + Ex_{capital} + Ex_{labor} + Ex_{env} + Ex_{other} \quad (13)$$

where, Ex_{total} is the annual total extended exergy input of the project, Ex_{fuel} is the fuel exergy input of municipal solid waste raw material, $Ex_{capital}$ is the capital exergy input of project fixed assets, Ex_{labor} is the labor exergy input in operation and

supervision links, Ex_{env} is the environmental remediation exergy input for pollutant treatment, and Ex_{other} is the exergy input of auxiliary links such as land and transportation. This paper retains only four core dominant elements for quantitative calculation, ignoring auxiliary exergy items with extremely low proportions, thereby simplifying model computation logic while ensuring accounting integrity.

Based on the constructed EEA framework, layered refined quantitative calculations are carried out for each core input element. Fuel exergy parameters follow the waste thermodynamic analysis results presented earlier, and the annual total fuel exergy input is obtained by conversion according to the annual waste treatment scale of the project. Capital exergy is converted via a macroeconomic conversion coefficient into the thermodynamic equivalent of fixed-asset investment, calculated as follows:

$$Ex_{capital} = I_{total} \times \varepsilon_{capital} \quad (14)$$

where, I_{total} is the total construction investment of the project, and $\varepsilon_{capital}$ is the capital exergy conversion coefficient adapted to domestic economic conditions. The converted total capital exergy is evenly apportioned over the full project life cycle to obtain the annual capital exergy input scale. Labor exergy is cumulatively calculated based on staffing configuration, working hours, and baseline labor exergy parameters:

$$Ex_{labor} = \sum_m N_m \times H_m \times \varepsilon_{labor,m} \quad (15)$$

where, N_m is the number of personnel in various operation and supervision posts, H_m is the annual standard working time, and $\varepsilon_{labor,m}$ is the unit working-hour exergy equivalent for different posts. Environmental remediation exergy is quantified based on the exergy difference of flue gas across the inlet and outlet of the flue gas treatment system, accurately characterizing the thermodynamic resources consumed by the environmental protection system to offset pollution and maintain environmental steady state. All accounting parameters conform to the actual operating characteristics of commercial waste incineration PPP projects.

To establish an objective thermodynamic benchmark for multi-stakeholder revenue allocation, this paper introduces the extended exergy contribution degree indicator to quantify the differentiated input weights of the three parties—government, social capital, and the public. The core calculation expression is:

$$\gamma_j = \frac{Ex_{contributed,j}}{Ex_{total}} \quad (16)$$

where, γ_j is the extended exergy contribution degree of the j -th type of participating stakeholder, and $Ex_{contributed,j}$ is the total effective annual exergy input contributed by the corresponding stakeholder. Combined with the financing/investment structure, operation-maintenance right-liability division, and environmental risk bearing boundaries of the PPP project, this paper hierarchically decomposes the exergy contribution sources of each stakeholder, respectively quantifying equipment investment and operation labor input by social capital, project funding and supervision input by government, and environmental tolerance and ecological carrying input by the public, to obtain standardized contribution coefficients for the three parties. Project fuel exergy belongs to the inherent resource endowment of

municipal solid waste valorization and serves as a common basic condition for project operation, and therefore does not fall under the contribution category of any single stakeholder. This accounting logic clarifies the input value differences among multiple stakeholders, realizes precise matching between stakeholder rights/liabilities and thermodynamic contribution, and provides a rigorous quantitative basis for the subsequent construction of a fair revenue allocation mechanism.

4. COUPLED MODEL OF THERMODYNAMIC EFFICIENCY AND REVENUE ALLOCATION

To quantify the intrinsic correlation between the thermodynamic performance of WtE systems and project economic benefits, and to realize quantitative characterization of the economic value of thermodynamic optimization outcomes, this paper constructs an exergoeconomic efficiency coefficient indicator to break through the quantitative barrier between thermodynamic output and market-oriented revenue.

Taking system effective exergy output and annual distributable total revenue as core variables, this indicator precisely depicts the economic value level corresponding to unit thermodynamic output. The specific expression is as follows:

$$EEC = \frac{R_{total}}{\dot{E}x_{out,sys} \times \tau} \quad (17)$$

where, EEC is the exergoeconomic efficiency coefficient, R_{total} is the annual comprehensive distributable revenue of the project, $\dot{E}x_{out,sys}$ is the net exergy output power under steady-state system operation, and τ is the annual rated operating hours of the unit. Quantitative calculation is completed based on the baseline case parameters of the studied project. Combining the net electrical exergy output of the unit with annual comprehensive revenues from electricity sales and waste treatment, the exergoeconomic efficiency coefficient under the baseline condition is solved, providing a unified quantitative benchmark for subsequent coupling analysis of efficiency optimization and revenue variation.

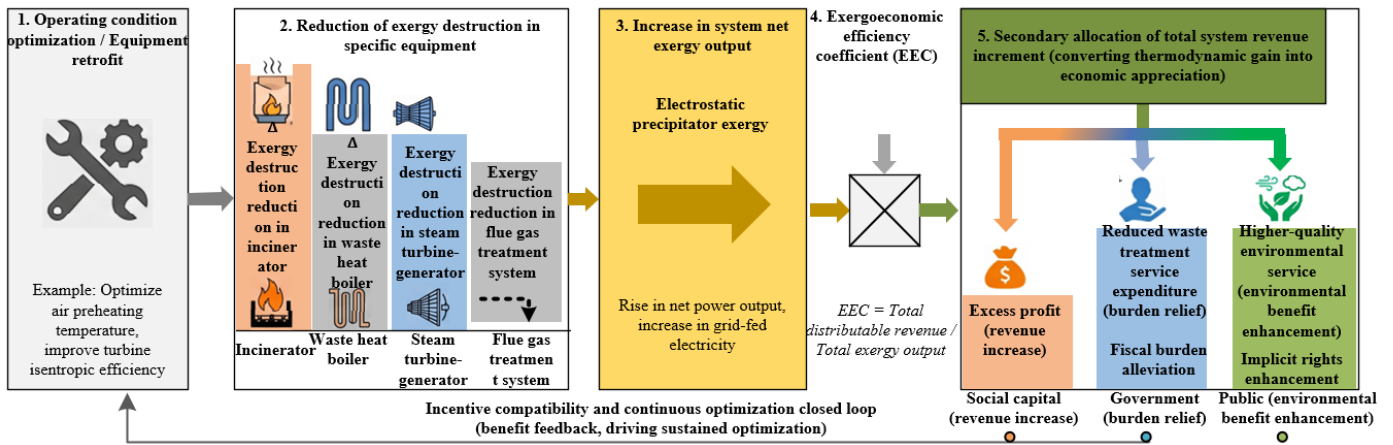


Figure 3. Dynamic transmission diagram of coupled thermodynamics efficiency improvement and incremental revenue allocation

Based on the established exergoeconomic efficiency benchmark, this paper establishes a dynamic mapping relationship between system thermodynamic efficiency optimization and project revenue increment, quantifying the economic benefit growth law brought by efficiency improvement. Figure 3 shows the dynamic transmission diagram of thermodynamics efficiency improvement and incremental revenue allocation coupling. Under the operating condition where waste treatment scale and fuel properties remain stable, the increase in system exergy efficiency directly corresponds to an incremental change in effective exergy output. The exergy output increment is calculated as:

$$\Delta \dot{E}x_{out} = \dot{E}x_{fuel} \times (\eta_{ex,sys}^{(1)} - \eta_{ex,sys}^{(0)}) \quad (18)$$

where, $\Delta \dot{E}x_{out}$ is the net exergy output increment of the system, $\dot{E}x_{fuel}$ is the annual total exergy input of waste fuel, $\eta_{ex,sys}^{(0)}$ and $\eta_{ex,sys}^{(1)}$ are the overall system exergy efficiencies before and after optimization, respectively. Considering the variation characteristics of the exergoeconomic efficiency coefficient, a total revenue increment model incorporating both direct output gain and unit exergy value variation is constructed:

$$\Delta R_{total} = EEC \times \Delta \dot{E}x_{out} \times \tau + \dot{E}x_{out,sys}^{(0)} \times \Delta EEC \times \tau \quad (19)$$

where, the first term characterizes the direct revenue increment brought by increased total exergy output, and the second term characterizes the indirect revenue increment triggered by unit exergoeconomic value variation. In market-oriented operation scenarios, the economic value per unit exergy output remains relatively stable, and fluctuations in the exergoeconomic efficiency coefficient can be ignored. Accordingly, reasonable simplification is made to obtain the revenue increment calculation form under a constant coefficient:

$$\Delta R_{total} = EEC \times \Delta \dot{E}x_{out} \times \tau \quad (20)$$

To accurately trace the equipment-level source of system revenue increments and avoid overall performance evaluation masking the differentiated contributions of unit equipment, this paper establishes an equipment-level decomposition mechanism for incremental revenue, precisely matching total system revenue increment to each core sub-equipment. Taking equipment exergy destruction reduction as the contribution judgment basis, the single equipment exergy destruction optimization amount is calculated as:

$$\Delta \dot{E}x_{dest,k} = \dot{E}x_{dest,k}^{(0)} - \dot{E}x_{dest,k}^{(1)} \quad (21)$$

where, $\Delta \dot{E}x_{dest,k}$ is the exergy destruction reduction amount of equipment k , $\dot{E}x_{dest,k}^{(0)}$ and $\dot{E}x_{dest,k}^{(1)}$ are the steady-state exergy destruction rates of equipment k before and after optimization, respectively. By the ratio of single equipment exergy destruction reduction to total system exergy destruction reduction, the revenue contribution weight of each equipment is defined:

$$\theta_k = \frac{\Delta \dot{E}x_{dest,k}}{\sum_{k=1}^4 \Delta \dot{E}x_{dest,k}} \quad (22)$$

where, θ_k is the incremental revenue contribution coefficient of equipment k . Combining total revenue increment and equipment contribution weight, the special revenue increment created by single equipment thermodynamic optimization can be solved:

$$\Delta R_k = \theta_k \times \Delta R_{total} \quad (23)$$

This decomposition strictly follows the objective law of thermodynamic loss improvement, realizing one-to-one correspondence between economic revenue increment and equipment energy efficiency optimization effect.

Relying on the equipment-level incremental revenue decomposition result and combining the previously constructed multi-stakeholder exergoeconomic allocation system, secondary allocation of incremental revenue between public and private entities is completed, forming a complete transmission chain from equipment optimization to stakeholder revenue. Based on each stakeholder's investment rights/liabilities and distribution weight in different equipment, the stakeholder incremental revenue corresponding to a single equipment is calculated as:

$$\Delta R_{j,k} = \alpha_{j,k} \times \Delta R_k \quad (24)$$

where, $\Delta R_{j,k}$ is the incremental revenue obtained by stakeholder from energy efficiency optimization of equipment k , and $\alpha_{j,k}$ is the revenue distribution coefficient of stakeholder for equipment k . Summing the incremental revenues of all equipment owned by a single stakeholder gives the stakeholder's annual total incremental revenue:

$$\Delta R_j = \sum_{k=1}^4 \Delta R_{j,k} \quad (25)$$

This allocation logic consistently adheres to the operation principle of equal rights and liabilities in PPP projects, precisely converting the technical value of equipment energy efficiency optimization into economic revenue increment of different stakeholders, realizing deep coupling between technical optimization and interest distribution.

To guarantee the rigor of the whole coupled model and the conservation of allocation results, closed-loop verification of the model is completed at the mathematical level to validate the completeness of the entire chain from thermodynamic optimization to revenue allocation. The model conservation check formula is as follows:

$$\sum_{j=1}^3 \Delta R_j = \sum_{j=1}^3 \sum_{k=1}^4 \alpha_{j,k} \Delta R_k = \sum_{k=1}^4 \Delta R_k \quad (26)$$

$$\Delta R_k \sum_{j=1}^3 \alpha_{j,k} = \sum_{k=1}^4 \Delta R_k = \Delta R_{total}$$

Formula verification results show that the total incremental revenue after multi-stakeholder allocation is completely equivalent to the total revenue increment created by system energy efficiency optimization, with no redundant or missing revenue. This conservation property confirms that the transmission chain of equipment exergy destruction optimization, system revenue appreciation, and multi-stakeholder revenue redistribution is fully closed-loop, and the constructed thermodynamic-economic coupling model possesses strict self-consistency, providing reliable theoretical support for designing fair and reasonable dynamic revenue allocation mechanisms in PPP projects.

5. MULTI-OBJECTIVE OPTIMIZATION AND SENSITIVITY ANALYSIS

5.1 Optimization problem definition

This paper constructs a dual-objective optimization framework balancing thermodynamic performance improvement and revenue distribution fairness, breaking through the single limitation of traditional waste incineration system optimization that only focuses on equipment operating parameters. Engineering operation variables and PPP institutional variables are synchronously introduced to form a multi-dimensional decision space. The study selects five categories of core continuous operating parameters, determining parameter boundaries according to unit safety thresholds and commercial engineering operation ranges, covering excess air coefficient, main steam temperature, main steam pressure, feedwater temperature, and exhaust gas temperature, fully covering key thermodynamic regulation nodes of incineration, heat exchange, and power generation processes. Meanwhile, multi-stakeholder equipment revenue distribution coefficients are incorporated into the decision variable system. Combined with contract constraint rules of PPP projects, the adjustable range of parameters is limited. On the premise of guaranteeing project contract stability, the fluctuation amplitude of distribution coefficients is controlled to no more than 10%, realizing refined optimization of the revenue allocation mechanism, and opening a coupled optimization channel linking thermal condition regulation and institutional parameter optimization.

The optimization system sets dual core objectives, corresponding respectively to the research demands of optimal system energy efficiency and optimal revenue distribution fairness, establishing an evaluation paradigm for the co-optimality of technical performance and economic allocation. The first objective takes maximization of overall system exergy efficiency as the admission criterion. The objective function expression is:

$$f_1 = \max \eta_{ex,sys} \quad (27)$$

where, $\eta_{ex,sys}$ is the comprehensive exergy efficiency of the waste incineration power generation system. The second objective centers on optimal revenue distribution fairness. The Gini coefficient is adopted to quantify the equilibrium degree of multi-stakeholder revenue distribution. The calculation expression is:

$$G = 1 - \sum_{j=1}^8 \left(\frac{R_j}{R_{total}} \right)^2 \quad (28)$$

where, G is the Gini coefficient, R_j is the annual distributable revenue of a single stakeholder, and R_{total} is the total project revenue. The Gini coefficient value range stably adapts to the three-party allocation scenario, with lower numerical values indicating a more balanced revenue distribution pattern. To compensate for the defect that a single Gini coefficient lacks a thermodynamic benchmark, a distribution deviation index is additionally introduced to quantify the matching difference between the actual distribution ratio and stakeholder extended exergy contribution:

$$D = \sum_{j=1}^8 \left| \frac{R_j}{R_{total}} - \gamma_j \right| \quad (29)$$

where, D is the distribution deviation index and γ_j is the extended exergy contribution degree of each stakeholder. This indicator can precisely judge the consistency between revenue allocation results and stakeholders' actual thermodynamic input contributions. Relying on the NSGA-II algorithm to complete multi-objective problem solving, the unified optimization objective expression is:

$$\min \left[-\eta_{ex,sys}, G \right] \quad (30)$$

The solution process strictly constrains system mass, energy, and exergy balance relations, while limiting constraint conditions such as upper/lower boundaries of equipment operating parameters, non-negative stakeholder revenue, and normalization of distribution coefficients, ensuring that optimization results conform to engineering reality and project contract rules.

5.2 Experimental design

This section conducts a comprehensive verification and analysis of the established models through six groups of experiments. Experiment 1 calculates the exergy flow, exergy destruction rate, and exergy efficiency of each subsystem under baseline design parameters to establish a reference benchmark for thermodynamic performance, where the excess air coefficient λ is taken as 1.4, main steam temperature T_{st} is 400 °C, main steam pressure P_{st} is 4.0 MPa, feedwater temperature T_{fw} is 140 °C, and exhaust gas temperature T_{eg} is 180 °C. Experiment 2 performs multi-stakeholder exergoeconomic cost allocation under the baseline condition according to the investment proportion stipulated in the PPP contract; social capital and government bear 70% and 30% of

fixed-asset investment respectively, calculating the unit exergoeconomic cost of each equipment and the revenue share of each stakeholder. Experiment 3 calculates the extended exergy contribution degree of each stakeholder (γ_j) and compares it with the actual revenue allocation ratio, quantifying the fairness deviation degree of the current allocation mechanism through the distribution deviation index D . Experiment 4 takes excess air coefficient λ , main steam temperature T_{st} , main steam pressure P_{st} , feedwater temperature T_{fw} , and exhaust gas temperature T_{eg} as decision variables to carry out single-parameter sensitivity analysis, revealing the influence law of each parameter on system exergy efficiency and unit exergoeconomic cost, and quantifies the incremental revenue created by parameter optimization and its allocation ratio among equipment based on the coupling model in Section 4. Experiment 5 uses the NSGA-II algorithm to solve the multi-objective optimization problem aiming at maximizing system exergy efficiency and minimizing the revenue allocation Gini coefficient; population size is set to 100, iterations are 500 generations, crossover probability is 0.8, mutation probability is 0.1, and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is adopted to select the optimal compromise solution after obtaining the Pareto front. Experiment 6 examines the impact of three categories of uncertainty factors—fluctuation of waste lower heating value, variation of feed-in tariff, and adjustment of waste treatment subsidy—on the optimal compromise solution, providing robustness references for the design of revenue allocation clauses in PPP contracts.

Figure 4 and Table 1 report the exergy balance and exergy efficiency of each subsystem under the baseline condition. The overall system exergy efficiency is 31.7%, which is at an upper-middle level within the reported range of 17%–40% for WtE systems in the literature. The incinerator has the largest exergy destruction, reaching 14,850 kW, accounting for 39.6% of total exergy destruction, mainly originating from the chemical irreversibility of the combustion reaction. The waste heat boiler ranks second, with exergy destruction of 11,200 kW, accounting for 29.9%, mainly originating from the heat transfer temperature difference between flue gas and working fluid. The steam turbine generator set has exergy destruction of 8,900 kW, accounting for 23.8%, mainly originating from the irreversibility of steam expansion. The sum of the three accounts for 93.3% of total exergy destruction, indicating the main potential for thermodynamic efficiency improvement.

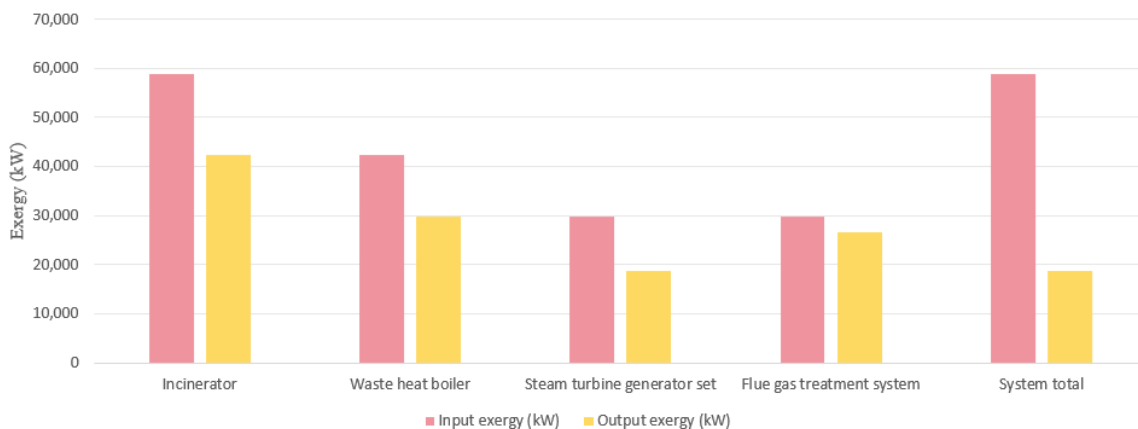


Figure 4. Input exergy and output exergy of each subsystem under the baseline condition

Table 1. Exergy balance and exergy efficiency of each subsystem under the baseline condition

Subsystem	Exergy Destruction (kW)	Exergy Loss (kW)	Exergy Efficiency (%)
Incinerator	14,850	1,600	72
Waste Heat Boiler	11,200	1,300	70.5
Steam Turbine Generator Set	8,900	2,300	62.4
Flue Gas Treatment	2,500	800	88.9
System Total	37,450	6,000	31.7

**Note: The input exergy of flue gas treatment is the flue gas exergy at the waste heat boiler outlet, 29,800 kW, numerically identical to the waste heat boiler output exergy, indicating flue gas entering the flue gas treatment system from the waste heat boiler.*

Table 2 presents the unit exergoeconomic cost of each equipment and the stakeholder revenue allocation results. The steam turbine generator set has the highest unit exergoeconomic cost, 2.43×10^{-4} ¥/kJ, mainly because of its high equipment investment density and relatively high exergy destruction. The flue gas treatment system is the lowest, at 1.49×10^{-4} ¥/kJ, because this subsystem mainly undertakes environmental protection rather than energy conversion functions. According to the 70:30 investment ratio, the total revenue obtained by social capital from the four equipment items is 76.30 million ¥/year, and that of government is 32.70 million ¥/year. Although the incinerator does not have the highest unit exergy cost, due to its largest exergy output, it

contributes 46.3% of the total revenue of social capital, meaning the thermodynamic performance of the incinerator has the most significant impact on social capital's revenue, providing social capital with a direct economic incentive to optimize incinerator operation. The traditional SPECO method aggregates all revenue into a single system operator account, totalling 116.7 million ¥/year, failing to reveal the revenue structure and incentive relations among stakeholders; whereas the multi-stakeholder model in this paper clearly shows the revenue distribution of each stakeholder at each equipment level, providing refined quantitative support for designing revenue allocation clauses in PPP contracts.

Table 2. Unit exergoeconomic cost of equipment and stakeholder revenue allocation

Equipment	Annualized Investment (10^6 ¥/y)	Annual O&M (10^6 ¥/y)	Exergy Output (10^9 kJ/y)	Unit Exergy Cost (10^{-4} ¥/kJ)	Social Capital Revenue (10^6 ¥/y)	Govt. Revenue (10^6 ¥/y)
Incinerator	21	8.5	1,218	2.42	35.3	15.1
Waste Heat Boiler	12.2	6.2	858	2.14	19.8	8.5
Steam Turbine Set	8.2	4.8	536	2.43	12.5	5.4
Flue Gas Treatment	6.4	5	763	1.49	8.7	3.7
Total	47.8	24.5	—	—	76.3	32.7

Table 3. Comparison of extended exergy contribution degree and revenue allocation ratio of stakeholders

Stakeholder	Extended Exergy Input (10^{12} kJ)	Contribution Degree γ_i	Actual Revenue Ratio R_i/R_{total}	Deviation
Social Capital	3.24	0.549	0.654	0.105
Government	1.05	0.178	0.28	0.102
Public	0.02	0.0034	0.066	0.063
Total	4.31	0.73	1	0.27

Table 3 compares the extended exergy contribution degree of each stakeholder with the actual revenue allocation ratio. The distribution deviation index $D = 0.270$, indicating that the current revenue allocation mechanism significantly deviates from each stakeholder's thermodynamic contribution. The actual revenue proportion of social capital (65.4%) exceeds its extended exergy contribution degree (54.9%), with a deviation of 10.5%, showing that social capital obtains a revenue share exceeding its thermodynamic contribution under the existing allocation mechanism. The government's actual revenue proportion (28.0%) exceeds its contribution degree (17.8%), deviation 10.2%. The public's actual revenue proportion (6.6%) is far higher than its contribution degree (0.34%), deviation 6.3%. Although the public makes very small direct thermodynamic contributions, it bears environmental risks whose negative contribution is not fully accounted for in the traditional thermodynamic framework; the EEA method quantifies this as a positive contribution, revealing the rational basis for public revenue allocation. This finding indicates that the current allocation mechanism overly favors capital while

inadequately compensating the public's environmental rights.

Table 4 examines the influence of five key operating parameters on system exergy efficiency and unit exergoeconomic cost. Exhaust gas temperature has the most significant influence on system exergy efficiency, with a variation range of 3.3%; for every 10 °C decrease in exhaust gas temperature, exergy efficiency increases by about 0.55%, because exhaust gas exergy loss is the largest single exergy loss item in the waste heat boiler. Main steam temperature ranks second, variation range 3.3%; for every 10 °C increase in temperature, exergy efficiency rises by about 0.44%. Excess air coefficient has a relatively smaller influence but has an optimum value $\lambda = 1.35$; too low causes incomplete combustion, too high increases exhaust heat loss. The best values of all parameters lie near the upper limit of their respective ranges, indicating that raising steam parameters and lowering exhaust temperature are effective ways to improve system thermodynamic efficiency. Based on the coupling model in Section 4, when λ is optimized from 1.4 to 1.35, reduced excess air lowers exhaust gas flow, decreases waste

heat boiler exergy destruction by about 420 kW and incinerator exergy destruction by about 180 kW, increases total exergy output by 600 kW, and yields an annual incremental revenue of 3.76×10^6 ¥. Among this, the waste heat boiler contributes 70% and the incinerator 30%.

Following the 70:30 investment ratio, social capital gains an incremental revenue of 2.64 million ¥/year and government gains 1.13 million ¥/year, verifying the completeness of the transmission chain from thermodynamic improvement to economic appreciation and then to revenue redistribution.

Table 4. Influence of key operating parameters on system exergy efficiency and exergoeconomic efficiency coefficient

Parameter	Value Range	$\eta_{ex,sys}$ Variation Range (%)	Exergoeconomic Efficiency Coefficient (EEC) Variation Range (10^{-4} ¥/kJ)	Optimum Value
Excess Air Coefficient	1.2–1.8	29.5–32.8	2.03–2.25	1.35
Main Steam Temperature	380–440 °C	30.2–33.5	2.08–2.30	435 °C
Main Steam Pressure	3.5–5.0 MPa	30.8–33.1	2.12–2.27	4.6 MPa
Feedwater Temperature	130–180 °C	31.0–32.2	2.13–2.21	165 °C
Exhaust Gas Temperature	140–200 °C	30.5–33.8	2.10–2.32	145 °C

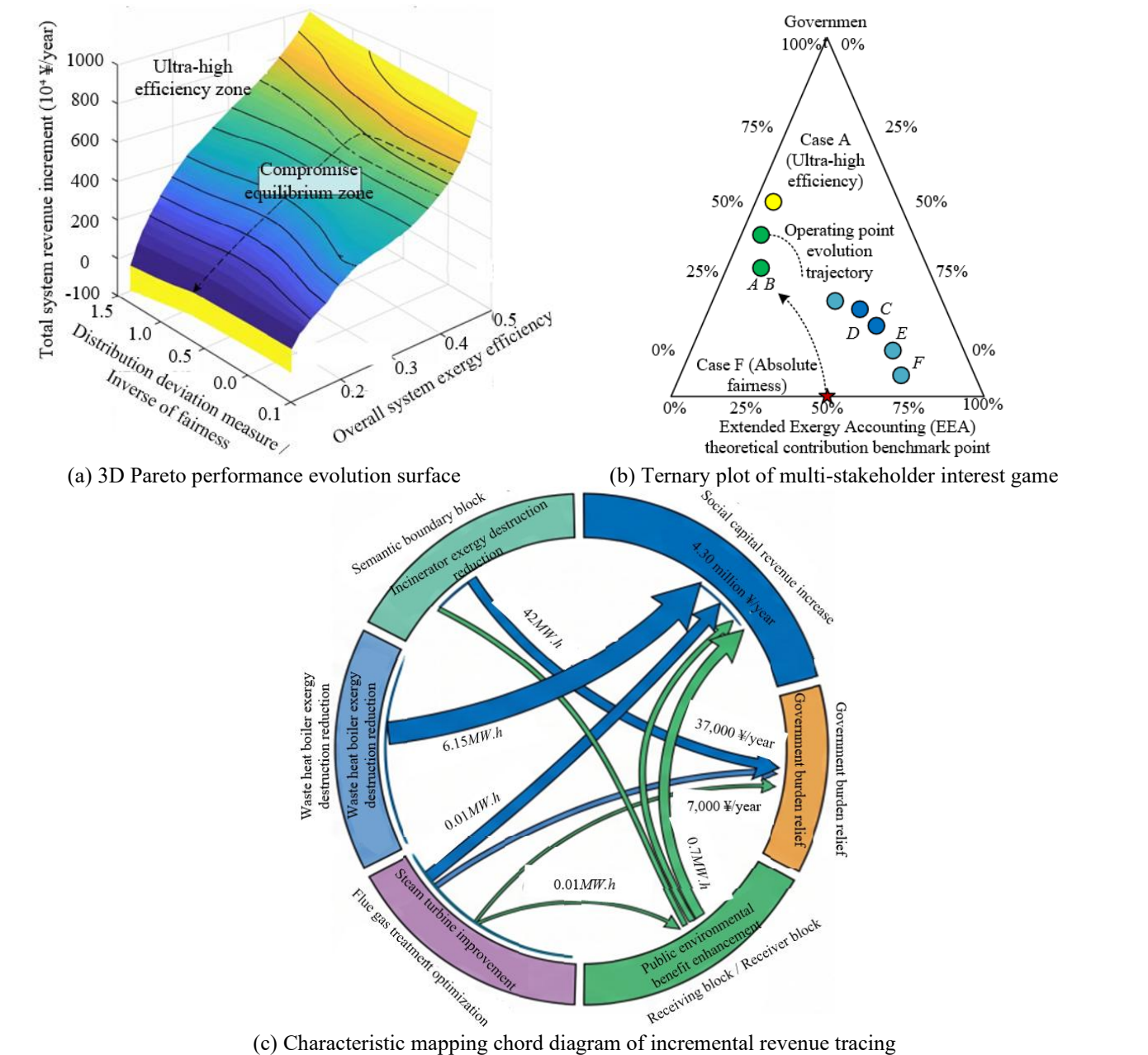


Figure 5. Synergistic evolution and stakeholder game diagrams of efficiency–fairness–revenue based on multi-objective optimization

To reveal the deep coupling game mechanism between thermodynamic parameter optimization and multi-stakeholder economic interest distribution in WtE PPP projects, this paper carries out multi-objective comprehensive optimization evaluation based on total exergy efficiency and distribution fairness deviation, with specific results shown in Figure 5. The 3D Pareto performance evolution surface shows that total project revenue increment increases markedly with rising total exergy efficiency, but upon entering the ultra-high efficiency zone, the distribution deviation degree climbs sharply to around 1.5, indicating that solely pursuing thermodynamic limits breaks the interest equilibrium under the original design framework. The ternary plot of multi-stakeholder interest games visually depicts this evolutionary trajectory: as the operating state continuously shifts from equilibrium-seeking Condition *F* toward ultra-high-efficiency Condition *A*, the actual allocation node of incremental revenue seriously deviates from the theoretical contribution benchmark determined by the EEA system, and the revenue share of social capital shows a significant polarization and expansion trend.

The characteristic mapping structure of incremental revenue tracing further quantifies the underlying value flow. The exergy destruction reductions of the incinerator and waste heat boiler, reaching scales of 42 MW·h and 6.15 MW·h respectively, are mainly converted through the mapping network into an annual excess profit increment of 4.30 million ¥ for social capital and a small amount of government burden relief quota, while thermodynamic optimization of the flue gas treatment link precisely empowers the public with targeted environmental performance enhancement. The above multi-dimensional performance evolution and characteristic mapping results fully prove that the technical retrofit dividends at the system physical equipment layer are not spontaneously transmitted equally according to the initial resource input weights of participating stakeholders.

Constructing a revenue dynamic adjustment and incentive-compatible mechanism based on exergoeconomic attributes is therefore the key pathway to ensure that waste incineration power generation projects not only achieve leaps in thermodynamic performance but also effectively balance public service attributes and multi-interest distribution fairness.

Table 5 gives the performance comparison of three typical solutions on the Pareto front. The High-Efficiency–Low-Fairness solution reaches an exergy efficiency of 34.2%, a 2.5% increase over the baseline, but the Gini coefficient is as high as 0.482 and the distribution deviation index $D=0.312$. This is because pursuing extreme efficiency pushes operating parameters to extremes, greatly increasing investment in high-temperature/high-pressure equipment, so revenue flows more to social capital bearing additional investment risk. The Low-Efficiency–High-Fairness solution reduces the Gini coefficient to 0.365 ($D = 0.168$), but exergy efficiency is only 31.5%, slightly below baseline, because operating parameters tend to be mild, equipment investment differences shrink, and revenue distribution approaches each stakeholder's input proportion. The Optimal Compromise Solution has exergy efficiency of 33.1%, Gini coefficient 0.418, $D = 0.235$; compared with the baseline condition, exergy efficiency rises by 1.4%, Gini coefficient drops by 0.036, and drops by 0.035, achieving dual improvement in thermodynamic efficiency and distribution fairness. Corresponding operating parameters are $\lambda = 1.32$, $T_{st} = 425$ °C, $P_{st} = 4.6$, $T_{eg} = 155$ °C. From slope analysis of the Pareto front, in the efficiency interval 31.5%–33.1%, every 1% efficiency rise increases the Gini coefficient by about 0.036; in the 33.1%–34.2% interval, every 1% efficiency rise increases the Gini coefficient by about 0.058, indicating that the marginal fairness sacrifice for efficiency improvement shows an increasing trend.

Table 5. Performance comparison of typical solutions on the Pareto front

Solution Type	$\eta_{ex,sys}$ (%)	G	D	λ	T_{st} (°C)	P_{st} (MPa)	T_{eg} (°C)
High-Eff–Low-Fair	34.2	0.482	0.312	1.25	440	5	145
Optimal Compromise	33.1	0.418	0.235	1.32	425	4.6	155
Low-Eff–High-Fair	31.5	0.365	0.168	1.45	395	4	175
Baseline Condition	31.7	0.454	0.27	1.4	400	4	180

Table 6. Influence of uncertainty factors on the optimal compromise solution

Scenario	$\eta_{ex,sys}$ (%)	G	R_{total} (10 ⁶ ¥/y)	Social Capital Revenue (10 ⁶ ¥/y)	Government Revenue (10 ⁶ ¥/y)	Public Revenue (10 ⁶ ¥/y)
Baseline ($LHV=7500$)	33.1	0.418	116.7	76.3	32.7	7.7
$LHV=5000$	30.8	0.435	98.5	63.2	28.5	6.8
$LHV=10000$	35.6	0.402	138.2	91.8	38.4	8
$P_{elec}+20\%$	33.1	0.425	136.1	89.5	38	8.6
$P_{elec}-20\%$	33.1	0.41	97.3	63.1	27.4	6.8
$P_{tip}+30\%$	33.1	0.408	122.7	80.3	34.4	8
$P_{tip}-30\%$	33.1	0.428	110.7	72.3	31	7.4

Note: LHV: Lower Heating Value

Table 6 examines the impact of three categories of uncertainty factors on the optimal compromise solution. Waste lower heating value has the most significant influence on system thermodynamic efficiency. When the lower heating value drops from 7500 to 5000 kJ/kg, exergy efficiency falls by 2.3% and the Gini coefficient rises by 0.017; when lower heating value rises from 7500 to 10000 kJ/kg, exergy efficiency rises by 2.5% and the Gini coefficient falls by 0.016,

because waste calorific value directly affects incinerator combustion temperature and steam generation of the waste heat boiler, being the decisive factor of system thermodynamic performance. Feed-in tariff variation exerts asymmetric influence on revenue allocation fairness. When electricity price rises by 20%, the Gini coefficient rises by 0.007; when falling by 20%, the Gini coefficient drops by 0.008, because electricity sales income is the main revenue source distributed

by power generation volume, and price rises make social capital's revenue growth larger than government's. Changes in waste treatment subsidy show the opposite direction of influence on the Gini coefficient: subsidy rise lowers Gini by 0.010, subsidy drop raises it by 0.010, because waste treatment fees are fixed revenue distributed by treatment volume and play a more prominent role in safeguarding government and public revenue.

Table 7 gives the decision variable values of the optimal compromise solution under each scenario, revealing response laws of decision variables to uncertainties. When waste calorific value is low, the system needs more extreme operating parameters to compensate for insufficient calorific value: excess air coefficient drops to 1.28, steam parameters rise to upper limits, exhaust gas temperature falls to the lower limit 150 °C; when waste calorific value is high, operating parameters tend to be mild. Electricity price changes mainly affect revenue distribution coefficients and thus indirectly affect decision variable selection: social capital has stronger motivation to raise efficiency when prices rise, and vice versa when prices fall. Subsidy changes exert relatively smaller influence because waste treatment fees are fixed revenue and provide weaker incentive for operating parameter optimization. The above sensitivity analysis results provide robustness references for designing revenue allocation clauses in PPP project contracts. Dynamic adjustment mechanisms responding to waste calorific value fluctuation and feed-in tariff policy changes should be set in contracts, so that revenue allocation ratios can adaptively adjust along with external condition variations.

Table 7. Decision variable values of the optimal compromise solution under each scenario

Scenario	λ	T_{st} (°C)	P_{st} (MPa)	T_{eg} (°C)	T_{fw} (°C)
Baseline	1.32	425	4.6	155	155
LHV=5000	1.28	440	5.0	150	160
LHV=10000	1.35	415	4.2	160	150
$P_{elec} + 20\%$	1.34	420	4.4	158	153
$P_{elec} - 20\%$	1.30	430	4.8	152	158
$P_{tip} + 30\%$	1.33	423	4.5	156	154

Note: LHV: Lower Heating Value

6. CONCLUSIONS

This study relies on exergy analysis theory and exergoeconomic methods to systematically carry out thermodynamic performance evaluation and multi-stakeholder revenue allocation mechanism research for WtE PPP projects, clarifying the system energy loss law, thermo-economic coupling mechanism, and public-private stakeholder revenue matching mechanism. Full-condition exergy analysis results show that the incinerator combustion irreversibility, waste heat boiler heat transfer temperature difference effect, and steam turbine unit steam expansion loss are the core sources of system exergy loss; the three constitute the main technical bottlenecks restricting unit thermodynamic efficiency improvement, while the flue gas treatment system has relatively limited influence on overall energy loss. The multi-stakeholder exergoeconomic allocation system constructed in this paper breaks through the limitation of the traditional SPECO method—which is only applicable to a single operating entity—and can realize refined splitting of

equipment-level cost, exergy destruction, and revenue, precisely distinguishing the revenue composition and investment incentive differences between social capital and government, effectively adapting to the right-liability accounting characteristics of multi-stakeholder PPP projects. The coupling model of thermodynamic efficiency and revenue increment fully reveals the quantitative transmission relationship among equipment exergy destruction optimization, system energy efficiency improvement, project economic appreciation, and multi-stakeholder revenue redistribution, establishing a quantitative correspondence paradigm between thermodynamic performance improvement and market-oriented revenue appreciation. Multi-objective optimization results confirm that system thermodynamic efficiency and revenue allocation fairness exhibit typical Pareto trade-off characteristics: extreme-efficiency conditions aggravate distribution imbalance, while extreme-fairness conditions sacrifice system energy utilization efficiency. The screened optimal compromise operating point achieves synergistic optimization of thermal performance and distribution fairness, while the fairness sacrifice cost corresponding to energy efficiency improvement continuously increases as system performance approaches the technical upper limit. Combined with the extended exergy contribution degree benchmark, it is found that the current revenue allocation mode based on fixed investment proportion suffers from significant right-liability mismatch: the revenue share of capital entities exceeds their thermodynamic contribution, and the public's environmental carrying contribution is not effectively reflected. Based on the dimension of true thermodynamic contribution, this study clarifies the optimization logic of dynamic revenue allocation for PPP waste incineration projects, providing reliable theoretical support and engineering quantitative basis for refined regulation of project operating parameters, PPP revenue contract design, and multi-stakeholder equity-balanced governance.

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