International Journal of Heat and Technology
Vol. 42, No. 4, August, 2024, pp. 1240-1250
Journal homepage: http://iieta.org/journals/ijht

Thermodynamic Analysis of the Relationship Between Energy Conversion Efficiency in Industrial Enterprises and Economic Growth

Jinfeng Miao

Department of Economic Management, Hebei Vocational University of Technology and Engineering, Xingtai 054000, China

Corresponding Author Email: miaojinfeng@xpc.edu.cn

https://doi.org/10.18280/ijht.420414

Received: 1 March 2024
Revised: 18 June 2024
Accepted: 2 July 2024
Available online: 31 August 2024

Keywords:
thermodynamic analysis, energy conversion efficiency, economic growth, industrial enterprises, energy economics

ABSTRACT

With the rapid development of the global economy, industrial enterprises have become increasingly dependent on energy to drive economic growth. However, the relationship between efficient energy utilization and economic growth remains insufficiently explored. Existing research primarily focuses on either economic or engineering perspectives, often overlooking the thermodynamic nature of energy conversion processes. This limitation leads to an incomplete understanding of the relationship between energy efficiency and economic growth. This paper constructs a model of energy conversion efficiency in industrial enterprises through thermodynamic analysis and further explores the relationship between energy conversion efficiency and economic growth. The findings reveal that analyzing energy efficiency from a thermodynamic perspective provides a more scientific and comprehensive insight into the actual energy utilization in enterprises, offering theoretical support for achieving the dual goals of economic growth and efficient energy use. This study not only offers new perspectives for research in energy economics but also serves as a valuable reference for policymakers and corporate managers in strategic decision-making.

1. INTRODUCTION

In the increasingly complex global economic context, energy, as a critical foundation for the development of industrial enterprises, directly influences production costs, competitiveness, and environmental burdens of enterprises [1-3]. With the rapid growth of the economy, energy demand continues to rise, and how to improve energy conversion efficiency while achieving economic growth has become a pressing issue for governments and enterprises alike [4-7]. Therefore, in-depth research on the energy conversion efficiency of industrial enterprises from a thermodynamic perspective, exploring its relationship with economic growth, not only holds academic value but also provides important references for the formulation of economic policies and the planning of corporate strategies.

The study of the relationship between energy conversion efficiency and economic growth in industrial enterprises is of great significance. First, improving energy efficiency can not only reduce the operating costs of enterprises but also reduce resource waste and environmental pollution, providing a solid foundation for sustainable development [8, 9]. Second, analyzing the energy conversion process from a thermodynamic perspective allows for a more scientific and comprehensive understanding of energy utilization efficiency in the production process, providing a theoretical basis for improving the overall efficiency of industrial production [10-14]. Furthermore, researching the relationship between energy efficiency and economic growth helps to clarify the energy dependency of economic development and its potential environmental impact, thereby providing policy support for achieving green economic growth.

However, existing research methods have some shortcomings and deficiencies when exploring the relationship between energy conversion efficiency in industrial enterprises and economic growth. Most studies analyze from either an economic or a single engineering perspective, neglecting the thermodynamic nature of the energy conversion process, leading to a lack of systematicity and accuracy in the research results [15, 16]. In addition, existing studies often fail to fully consider the heterogeneity among enterprises and the differences among various industries when constructing models, limiting the generalizability of the research conclusions [17-21]. Therefore, it is necessary to develop more precise and multidimensional analytical methods to address these shortcomings in the research.

This paper will construct a model of energy conversion efficiency for industrial enterprises from the perspective of thermodynamic analysis and further explore the relationship between energy conversion efficiency and economic growth. Specifically, the paper will include two main aspects: first, based on thermodynamic principles, a model suitable for energy conversion efficiency in industrial enterprises will be constructed to reveal the conversion mechanism of energy in the production process and its efficiency level; second, based on the constructed model, the impact of energy efficiency on economic growth in different enterprises will be analyzed, providing decision-making references for policymakers and corporate managers. This study not only expands the research field of energy economics but also provides new perspectives for improving the energy utilization efficiency of industrial enterprises and achieving sustainable economic growth.

2. THERMODYNAMIC ANALYSIS-BASED ENERGY CONVERSION EFFICIENCY MODEL FOR INDUSTRIAL ENTERPRISES

In this study, the energy conversion efficiency model for industrial enterprises is based on thermodynamic analysis. The core of this model lies in comprehensively assessing the efficiency of energy conversion processes within enterprises, particularly focusing on the relationship between energy input and actual effective output. Specifically, the model first considers the forms of energy input, including fossil fuels, electrical energy, etc., and then conducts a detailed analysis of energy conversion and utilization in the production process through the First and Second Laws of Thermodynamics. The model introduces the concept of boiler thermal efficiency, drawing on the calculation formulas from GB and ASME standards. By measuring the thermal efficiency of boilers under different operating conditions, a more accurate overall energy efficiency indicator for the enterprise is obtained. Additionally, the model is not limited to the evaluation of boiler equipment's thermal efficiency but also comprehensively considers the energy conversion efficiency of various thermal equipment and production processes within the enterprise. The model views the entire enterprise as a thermodynamic system, tracking the entire process of energy from entering the enterprise to the final output, evaluating the efficiency of key aspects such as energy loss, waste heat recovery, and energy reuse. Through these analyses, the model can reveal which aspects of daily operations are inefficient or wasteful in energy use and propose possible directions for improvement. Figure 1 presents the structure of the thermodynamic analysis-based energy conversion efficiency model for industrial enterprises.

In the energy conversion process of industrial enterprises, especially within complex production systems, some key parameters cannot be measured online or have insufficient measurement accuracy due to technical conditions or cost constraints, which poses challenges for real-time calculation of energy conversion efficiency. To overcome these difficulties and achieve dynamic monitoring of energy conversion efficiency, this study adopts a simplified reverse balance method based on thermodynamic analysis to calculate the energy conversion efficiency of industrial enterprises. The core idea of this method is to indirectly calculate energy losses and then deduce the overall energy conversion efficiency of the system.

In the constructed energy conversion efficiency model for industrial enterprises, the accurate calculation of input heat is key to evaluating overall energy efficiency. Based on thermodynamic theory, this study analyzes the input heat in detail from two main aspects: the physical sensible heat of the fuel and the heat brought into the air by heating air using extraction steam from the turbine to construct a scientific and reasonable energy conversion efficiency model. Suppose the lower heating value of the fuel is represented by $W^b{}_F$, the physical sensible heat of the fuel by W_{ea}, and the heat brought into the air by heating air using extraction steam from the turbine by W_{qm}. Then the expression for input heat in the model is:

$$W_e = W_F^b + W_{ea} + W_{qm} \tag{1}$$

Physical sensible heat refers to the heat that the fuel possesses before entering the combustion process, that is, the heat absorbed by the fuel when it is heated to the combustion temperature from its initial state. In industrial enterprises, common fuels such as coal, natural gas, and oil need to undergo a series of processes such as heating and drying before being burned in boilers. During this process, the physical sensible heat of the fuel can directly affect combustion efficiency and the final energy output. Suppose the fuel temperature is represented by s_e, and the specific heat of the fuel by z_e, then the calculation formula for the physical sensible heat of the fuel is:

$$W_{ea} = z_e s_e \tag{2}$$

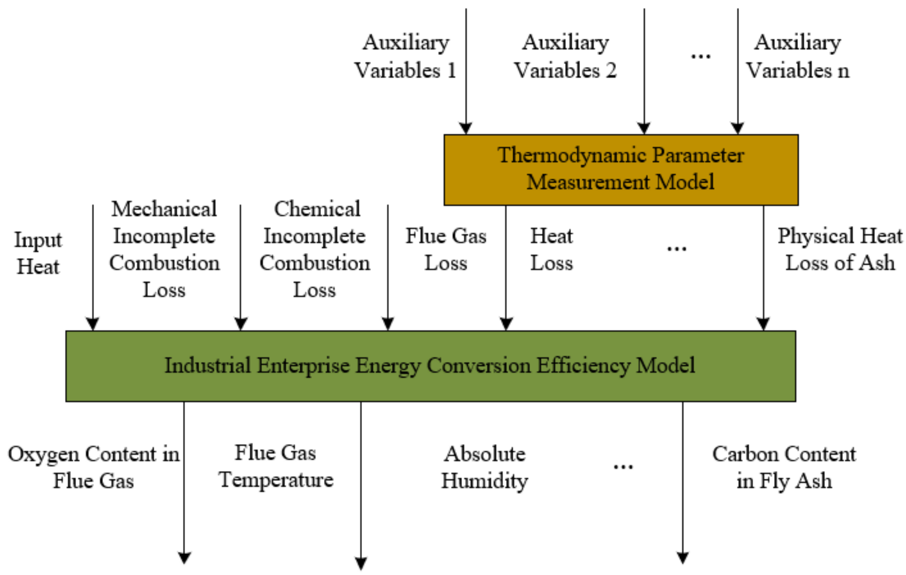


Figure 1. Thermodynamic analysis-based energy conversion efficiency model structure for industrial enterprises

Suppose the specific heat of solid fuel on a dry basis is represented by z^h_e, and the mass percentage of moisture on a received basis by Q^b. Then the calculation formula for the specific heat of solid fuel is:

$$z_e = \left[z_e^h \left(100 - Q^b \right) + 4.1868 Q^b \right] / 100 \tag{3}$$

In the industrial production process, especially in enterprises that use steam turbines as a power source, extraction steam is usually used to heat air or other media to improve the overall thermal utilization rate of the system. For example, the air heating process in an air heater is realized by the extraction steam of the turbine, and this part of the heat is calculated based on parameters such as the temperature, pressure, and flow rate of the extraction steam. Although this heat does not directly come from fuel combustion, it is still an important source of energy input in the thermodynamic system. Including this part of the heat in the input heat calculation can more comprehensively reflect the energy conversion process and efficiency of the enterprise. Suppose the air volume entering the air heater is represented by N_{TD}, the fuel quantity by Y, the specific heat of air at constant pressure at the air heater outlet temperature by z'_{oj}, the specific heat of air at constant pressure at the air heater inlet temperature by z_{oj}, the air heater outlet temperature by s'_j, and the air heater inlet temperature by s_j. Then the calculation formula for the heat brought into the air by heating air using extraction steam from the turbine is:

$$W_{qm} = \frac{N_{td}}{3600Y} \left(z'_{oj} s'_j - z_{oj} s_j \right) \tag{4}$$

Mechanical incomplete combustion loss refers to the energy loss caused by the incomplete conversion of chemical energy into thermal energy during the combustion process. This loss is often one of the main reasons for the decline in energy efficiency in industrial enterprises' energy conversion processes, particularly in boilers and other combustion equipment. From a thermodynamic analysis perspective, mechanical incomplete combustion loss mainly includes the energy loss from solid particles and incompletely burned gases generated during incomplete combustion. These solid particles and incompletely burned gases still contain chemical energy that has not been fully utilized. If this portion of energy is not effectively released and utilized during the combustion process, it will directly reduce the overall efficiency of the system. In practice, the magnitude of this loss is influenced by factors such as the type of fuel, combustion conditions, equipment design, and operational parameters. To accurately assess mechanical incomplete combustion loss, the thermodynamic analysis model calculates the actual mechanical incomplete combustion loss by measuring the chemical composition of residual fuel in flue gas and ash after combustion, combined with the lower heating value of the fuel and combustion efficiency. Suppose the mass percentage of ash content on an as-received basis is represented by X^b, the mass percentage of carbon in fly ash is represented by Z_{dg}, the mass percentage of carbon in bottom ash is represented by Z_{mc}, the proportion of ash in fly ash to the total ash content in coal is represented by β_{dg}, and the proportion of ash in bottom ash to the total ash content in coal is represented by β_{mc}. Then the calculation formula is as follows:

$$w_4 = 328.66 X^b \left\{ \begin{matrix} \left[\beta_{dg} Z_{dg} / \left(100 - Z_{dg} \right) \right] \\ + \left[\beta_{dg} Z_{dg} / \left(100 - Z_{dg} \right) \right] \end{matrix} \right\} \Big/ W_e \times 100 \tag{5}$$

In the energy conversion process of industrial enterprises, Chemical incomplete combustion loss refers to the energy loss where the chemical energy in the fuel is not fully converted into thermal energy during the combustion process, and thus remains in the emissions in an unburned form. For industrial enterprises, this loss not only signifies wasted energy but may also lead to environmental pollution issues. From a thermodynamic analysis perspective, chemical incomplete combustion loss is primarily manifested as carbon monoxide, hydrocarbons, and other incompletely burned compounds in the exhaust gases. These compounds are not fully oxidized during combustion, resulting in the incomplete release of the chemical energy of the fuel. The model calculates the specific value of chemical incomplete combustion loss by analyzing the composition of exhaust gases, combined with the chemical composition of the fuel and the thermodynamic characteristics of combustion. In the constructed energy conversion efficiency model for industrial enterprises, chemical incomplete combustion loss is regarded as a key variable in thermodynamic analysis. By measuring the composition of exhaust gases after combustion, the model can accurately assess the energy loss caused by incomplete combustion and incorporate it into the overall energy conversion efficiency calculation. Reducing chemical incomplete combustion loss can not only improve the energy utilization efficiency of enterprises but also reduce the harmful components in emissions, thereby alleviating environmental burdens. Suppose the actual dry flue gas volume is represented by N_{hb}, and the percentage of carbon monoxide in the dry flue gas volume is represented by ZP, then the calculation formula is as follows:

$$w_3 = 126.36 N_{hb} ZP \left(100 - w_4 \right) / W_e \times 100 \tag{6}$$

Suppose the dry flue gas volume generated by the complete combustion of a unit of fuel is represented by N^0_{hb}, the dry air volume required for the complete combustion of a unit of fuel is represented by N^0, the excess air coefficient at the flue gas exit is represented by β, and the oxygen content in the flue gas at the flue gas exit is represented by P_2, with the mass content of carbon, sulfur, hydrogen, oxygen, and nitrogen on an as-received basis in the fuel represented by Z^b, G^b, T^b, P^b, and V^b, respectively. Then the calculation formulas are as follows:

$$N_{hb} = N_{hb}^0 + \left(\beta - 1 \right) N^0 \tag{7}$$

$$N_{hb}^0 = \left(1.886 Z^b + 0.7 T^b + 0.8 V^b \right) / 100 + 0.79 N^0 \tag{8}$$

$$N^0 = 0.0889 Z^b + 0.265 G^b + 0.0333 \left(T^b - P^b \right) \tag{9}$$

$$\beta = 21 / \left(21 - P_2 \right) \tag{10}$$

In the energy conversion process of industrial enterprises, Flue Gas Loss mainly refers to the energy loss caused by the heat that is not effectively utilized by the system after fuel combustion and is discharged with the flue gas, resulting in energy loss. Suppose the enthalpy of the flue gas is represented by U_{ob}, and the enthalpy of the air at the air blower inlet is represented by U_{mj}. Then the calculation formula is as follows:

$$w_2 = \left[\left(U_{ob} - U_{mj}\right)\left(1 - \frac{w_4}{100}\right)\right] \Big/ W_e \times 100 \tag{11}$$

Based on thermodynamic analysis, the energy conversion efficiency model for industrial enterprises in this paper will assess flue gas loss in detail by analyzing two key factors: the enthalpy of the flue gas and the enthalpy of the air at the air blower inlet. Among them, flue gas enthalpy refers to the heat carried by the flue gas before discharge after fuel combustion. This portion of heat is not effectively recovered or utilized during the combustion process and is directly discharged into the atmosphere with the flue gas, resulting in energy waste. In thermodynamic analysis, flue gas enthalpy is usually calculated based on the temperature, pressure, composition, and flow rate of the flue gas. High-temperature flue gas indicates that a large amount of thermal energy is being discharged, directly leading to a reduction in system efficiency. Therefore, reducing flue gas temperature or recovering heat from the flue gas through a heat recovery system is an important means to improve energy conversion efficiency. Suppose the average specific heat at constant pressure for dry flue gas, water vapor, carbon dioxide, oxygen, and nitrogen is represented by z_{hb}, z_{H2O}, z_{CO2}, z_{O2}, and z_{N2}, respectively, the percentage content of triatomic gases in the flue gas is represented by EP_2, the percentage content of oxygen in the flue gas is represented by P_2, the percentage content of nitrogen in the flue gas is represented by V_2, the characteristic coefficient of the fuel is represented by α, the mass percentage of moisture on an as-received basis in the fuel is represented by Q^b, the absolute humidity of the air is represented by f_j, the flue gas temperature is represented by s_{ob}, the actual volume of water vapor in the flue gas is represented by N_{H2O}, the enthalpy of fly ash is represented by U_{dg}, and the enthalpy of 1 kg of ash is represented by $(z\phi)_g$. Then the calculation formulas are as follows:

$$U_{ob} = \left(N_{ob} z_{gy} + N_{H_2O} z_{H_2O}\right) s_{ob} + U_{dg} \tag{12}$$

$$z_{hb} = \left(z_{CO_2} EP_2 + z_{N_2} V_2 + z_{O_2} P_2\right) \big/ 100 \tag{13}$$

$$N_{H_2O} = 0.01244 Q^b + 0.111 G^b + f_j \beta N_0 \tag{14}$$

$$EP_2 = \frac{21 - P_2}{1 + \alpha} \tag{15}$$

$$\alpha = 2.35 \frac{G^b - 0.125 P^b + 0.038 V^b}{Z^b + 0.375 T^b} \tag{16}$$

$$V_2 = 100 - EP_2 - P_2 \tag{17}$$

$$U_{dg} = X^b \beta_{dg} \left(z\varphi\right)_g \big/ 100 \tag{18}$$

The enthalpy of air at the air blower inlet refers to the heat content of the air before entering the combustion system. This portion of the air will be heated during the combustion process and eventually discharged with the flue gas. If the enthalpy value of the air at the air blower inlet is high, it means that the air already possesses a high level of energy before entering the combustion system. After combustion, this portion of energy will further increase the enthalpy value of the flue gas, thereby increasing flue gas loss. Suppose the specific heat of air is represented by z_j and the temperature of the air at the air blower inlet is represented by s_j. Then the calculation formula is as follows:

$$U_{mj} = N^0 z_j s_j \tag{19}$$

In the model constructed in this paper, heat loss refers to the heat dissipated to the external environment due to the equipment, pipelines, and other system components during energy conversion and transmission. This type of energy loss occupies an important position in thermodynamic analysis and directly affects the energy conversion efficiency of enterprises. The industrial enterprise energy conversion efficiency model based on thermodynamic analysis in this paper provides a scientific basis for improving energy utilization efficiency through accurate analysis of heat loss. From a thermodynamic perspective, heat loss mainly occurs in equipment such as boilers, pipelines, and heat exchangers in industrial enterprises. During operation, the surface temperature of these devices is usually higher than the surrounding environmental temperature, leading to heat dissipation to the environment through conduction, convection, and radiation. This portion of the dissipated heat cannot be recovered or utilized, thereby reducing the overall efficiency of the system. In the industrial enterprise energy conversion efficiency model, heat loss is usually estimated by calculating the surface temperature of each piece of equipment and pipeline, the heat conduction coefficient, the surrounding environmental temperature, and the surface area of the equipment. Suppose the rated evaporation capacity is represented by F_{ED}, the actual evaporation capacity by F, and the heat loss corresponding to the rated evaporation capacity by $w_{5.ED}$. Then the calculation formula is as follows:

$$w_5 = w_{5.ED} F_{ED} / F \times 100 \tag{20}$$

where,

$$w_{5.ED} = 5.82 \left(F_{ED}\right)^{-0.38} \tag{21}$$

Heat loss not only leads to a decrease in energy utilization efficiency but may also have negative impacts on the production environment. For example, high-temperature heat loss may increase the air conditioning load in the workshop, thereby increasing additional energy consumption. Therefore, methods to reduce heat loss are particularly important in the energy management of industrial enterprises. Specific measures include effective insulation treatment of equipment and pipelines, improving equipment design to reduce surface temperature, and further enhancing energy utilization efficiency by recovering dissipated heat.

Physical heat loss of ash refers to the energy loss caused by ash generated during the combustion process, where the heat contained in the ash is directly dissipated along with the ash discharge due to its high-temperature state not being fully cooled or recovered. This type of energy loss directly impacts the overall energy utilization efficiency of enterprises and is a key aspect of the industrial enterprise energy conversion efficiency model that needs to be analyzed. From a thermodynamic analysis perspective, physical heat loss of ash is mainly determined by the temperature, mass, and discharge method of the ash. After the fuel is burned, the ash produced is often in a high-temperature state. If this ash is discharged directly without being processed by a heat recovery device, a large amount of heat will be lost. For example, the slag produced after boiler combustion is usually at a high temperature when discharged. If no appropriate heat recovery measures are taken, the thermal energy contained in the ash will be directly dissipated into the environment, resulting in energy waste. In the constructed industrial enterprise energy conversion efficiency model, physical heat loss of ash is quantified by analyzing the temperature, flow rate, and heat capacity of the ash discharge. The specific calculation formula is as follows:

$$w_6 = X^b \beta_{mc} \left(z\varphi\right)_g / W_e \tag{22}$$

Figure 2 shows the thermodynamic calculation flowchart for process heat transfer and incomplete combustion loss.

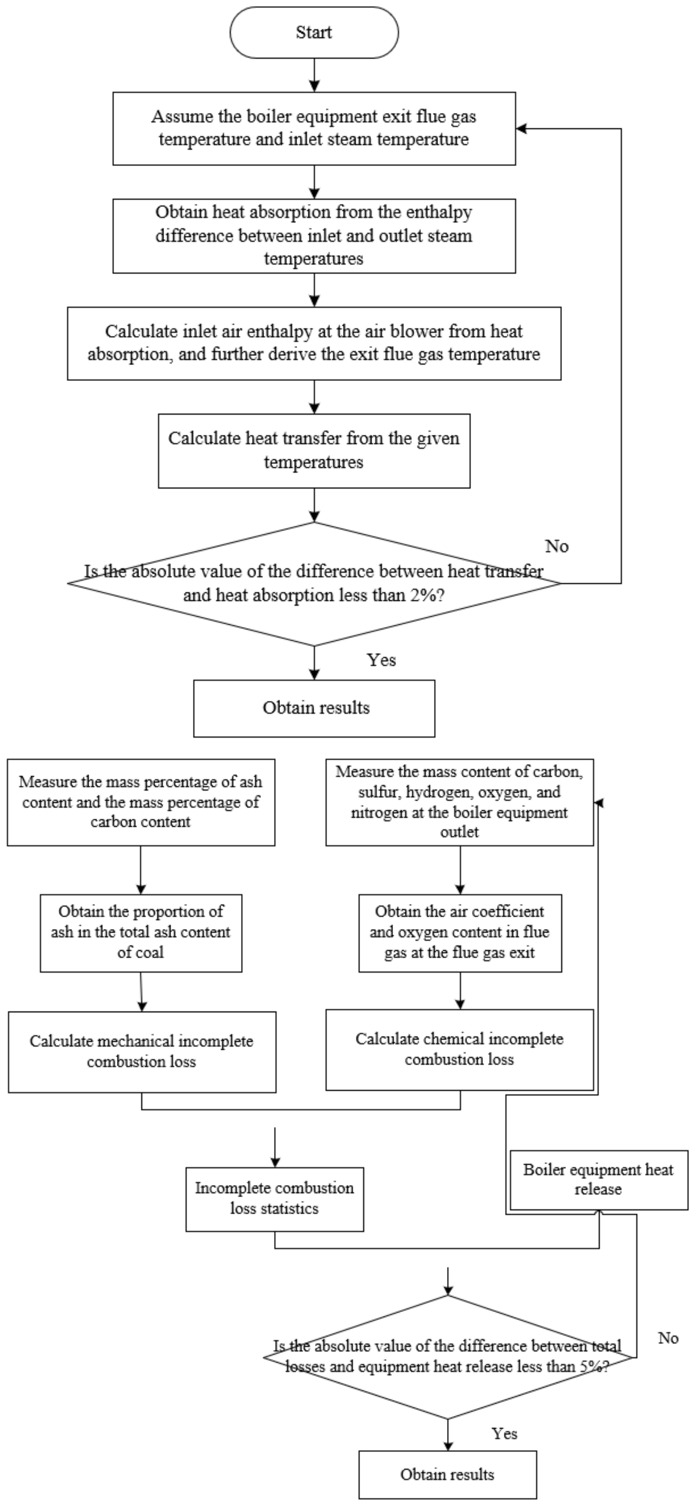


Figure 2. Thermodynamic calculation flowchart for process heat transfer and incomplete combustion loss

3. THERMODYNAMIC ANALYSIS OF THE RELATIONSHIP BETWEEN ENERGY CONVERSION EFFICIENCY IN INDUSTRIAL ENTERPRISES AND ECONOMIC GROWTH

When studying the relationship between energy conversion efficiency in industrial enterprises and economic growth, the thermodynamic analysis-based model provides a scientific and comprehensive perspective. This paper presents different scenarios, offering a deeper understanding of how energy conversion efficiency affects the economic performance of enterprises and overall economic growth. Figure 3 shows the energy conversion system flowchart for industrial enterprises.

Scenario 1: The impact of energy efficiency improvement in high energy-consumption industries on economic growth

In high energy-consumption industries, such as steel, chemical, and cement production, energy conversion efficiency directly impacts production costs and profitability. In this scenario, the thermodynamic analysis model quantifies the potential for improving energy utilization efficiency by assessing losses at different stages of conversion, such as flue gas enthalpy during fuel combustion, heat loss during equipment operation, and physical heat loss of ash. As enterprises implement technological improvements, such as optimizing the combustion process, introducing waste heat recovery devices, and enhancing equipment insulation, increased energy conversion efficiency will directly reduce energy costs and increase profitability. The increase in profits not only contributes to expanding reinvestment and production capacity but also enhances overall economic benefits, promoting economic growth. Therefore, the thermodynamic analysis model helps enterprises identify key points for efficiency improvement and provides reliable technical support for achieving economic growth. Figure 4 illustrates the losses at different stages of conversion.

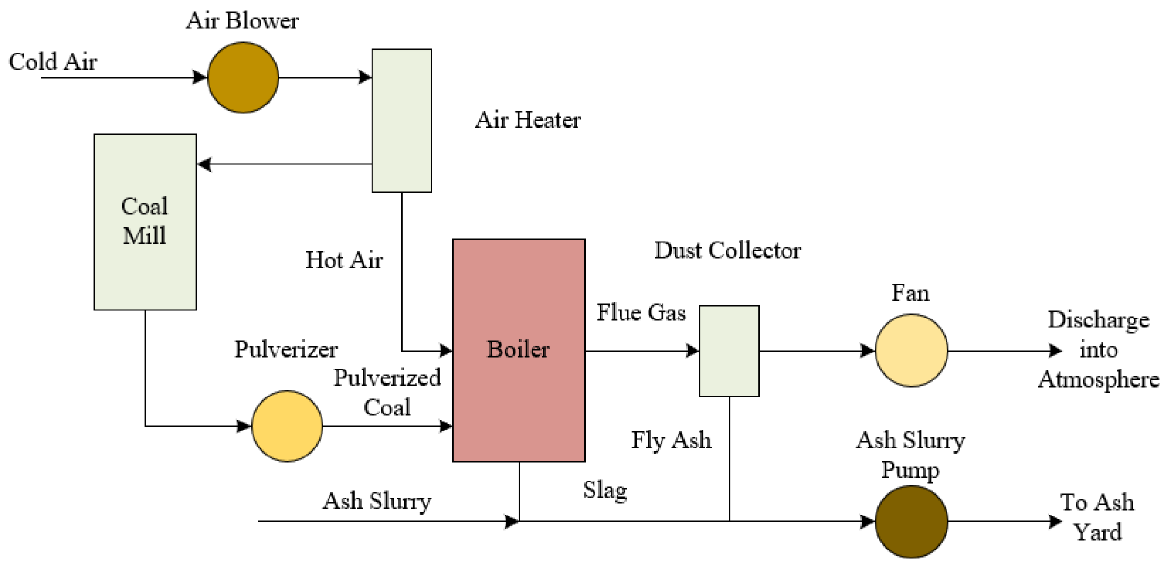


Figure 3. Energy conversion system flowchart for industrial enterprises

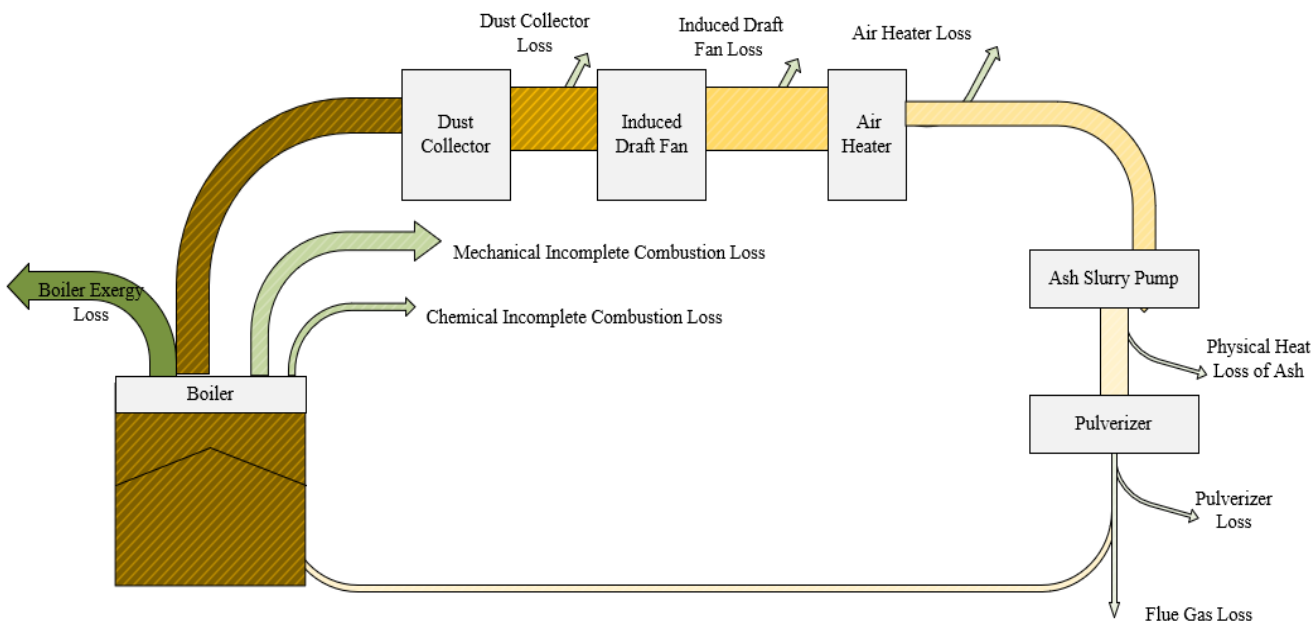


Figure 4. Schematic diagram of losses at different stages of conversion

Scenario 2: The impact of energy conversion efficiency on environmental protection and sustainable economic development

In the current context of global concern for environmental protection and sustainable development, the relationship between energy conversion efficiency in industrial enterprises and economic growth has become more complex. In this scenario, the thermodynamic analysis model not only focuses on efficient energy utilization but also involves the assessment of environmental impacts. By reducing flue gas enthalpy and physical heat loss of ash, enterprises can decrease emissions of greenhouse gases and other harmful substances, thereby reducing environmental pollution. This environmental benefit not only helps enterprises remain compliant with increasingly stringent environmental regulations but also allows them to obtain carbon credits by reducing carbon emissions, creating new points of economic growth. As enterprises improve energy conversion efficiency, they also reduce environmental management costs, achieving a win-win situation between economic and environmental benefits, which is of great significance for realizing sustainable economic growth.

Scenario 3: The adaptability of enterprises to energy price fluctuations and economic stability

In a market environment where energy prices fluctuate frequently, the level of energy conversion efficiency determines an enterprise's ability to cope with energy price fluctuations. In this scenario, the thermodynamic analysis model helps enterprises improve energy utilization by finely managing heat losses at various stages of energy conversion, such as optimizing flue gas enthalpy and reducing heat loss. Increased energy conversion efficiency enables enterprises to maintain stable production costs in the face of rising energy prices, thereby reducing economic uncertainty caused by cost fluctuations. At the same time, the improvement in energy efficiency allows enterprises to maintain high production efficiency even during periods of low energy prices, helping them maintain a competitive advantage in the market. By improving energy conversion efficiency, enterprises can not only maintain stable operations during energy price fluctuations but also ensure the stable growth of the overall economy.

Scenario 4: Technological innovation-driven improvement in energy conversion efficiency and economic transformation

With technological advancements, particularly innovations in thermodynamic-related technologies, enterprises have significantly improved their energy conversion efficiency. In this scenario, the thermodynamic analysis model introduces advanced combustion control technologies, waste heat recovery technologies, and the application of new materials, enabling enterprises to reduce energy consumption while improving production efficiency. The improvement in energy conversion efficiency brought about by technological innovation not only reduces production costs but also drives technological upgrades and economic transformation within the industry. As more enterprises adopt these new technologies, the overall energy utilization efficiency of the industry improves, further promoting economic growth and optimizing industrial structure. This technology innovation based on thermodynamic analysis not only enhances the market competitiveness of enterprises but also provides a new driving force for the high-quality development of the economy.

4. EXPERIMENTAL RESULTS AND ANALYSIS

As can be seen from the data in Table 1, there are significant differences in energy conversion efficiency, heat loss, flue gas loss, irreversible combustion loss, irreversible heat transfer loss, and exergy efficiency among different equipment. The highest thermal efficiencies are found in Equipment 13 and 14, reaching 92.26% and 92.36%, respectively, while their heat losses are relatively low, at 5.58 and 5.68, respectively. In contrast, Equipment 1 has the lowest thermal efficiency at 85.36%, with a relatively high heat loss of 10.25. In addition, Equipment 4 and 5 have lower flue gas loss and irreversible combustion loss, at 1.58 and 1.56, and 23.64 and 22.35, respectively, showing good combustion and heat transfer performance. It is worth noting that Equipment 13 and 14 not only perform well in thermal efficiency but also have higher exergy efficiency, at 32.63% and 33.42%, respectively, indicating that these pieces of equipment have higher effective energy utilization rates in the energy conversion process. From the perspective of sustainable economic growth, improving the energy conversion efficiency of industrial enterprises has significant economic and environmental benefits. The high thermal efficiency and exergy efficiency of Equipment 13 and 14 indicate that optimizing the combustion process, reducing heat loss, and minimizing irreversible losses can significantly enhance energy utilization efficiency, thereby reducing production costs and resource consumption. This optimization not only helps enterprises improve economic benefits but also reduces greenhouse gas emissions, aligning with the requirements for sustainable development. Furthermore, the performance differences among equipment suggest that enterprises can further improve overall energy conversion efficiency through technological improvements and equipment upgrades.

As shown by the data in Figure 5, different types of boilers exhibit significant differences in thermal efficiency and exergy efficiency. The thermal efficiency of coal/biomass boilers ranges from 74% to 79%, with boilers less than 4t/h having the lowest thermal efficiency at 74%, while boilers greater than 10t/h have the highest thermal efficiency, reaching 79%. In contrast, the thermal efficiency of coal/gas boilers is significantly higher, with boilers under 4t/h having a thermal efficiency of 88%, and boilers above 4t/h reaching 90%. In terms of exergy efficiency, coal/biomass boilers have relatively low exergy efficiency, ranging from 16% to 24%; among them, boilers greater than 10t/h perform the best, with an exergy efficiency of 24%. Coal/gas boilers have higher exergy efficiency, with boilers below 4t/h and above 4t/h reaching 26% and 28%, respectively. From the perspective of sustainable economic growth, improving energy conversion efficiency, especially exergy efficiency, is key to achieving energy conservation, emission reduction, and economic efficiency improvement. The data show that coal/gas boilers are significantly superior to coal/biomass boilers in terms of thermal efficiency and exergy efficiency, especially for coal/gas boilers above 4t/h, where thermal efficiency and exergy efficiency reach 90% and 28%, respectively, indicating that this type of boiler can more effectively convert energy and reduce losses in the energy utilization process. Efficient energy conversion not only helps reduce the operating costs of enterprises but also reduces greenhouse gas emissions, contributing to green economic growth and environmental protection goals.

Table 1. Test data of energy conversion equipment in industrial enterprises

Equipment Number	Heat Loss	Thermal Efficiency	Flue Gas Loss	Irreversible Combustion Loss	Irreversible Heat Transfer Loss	Exergy Efficiency
1	10.25	85.36	2.69	26.32	38.26	27.26
2	9.56	86.24	2.56	26.23	38.24	28.44
3	7.42	88.23	2.23	28.69	34.26	30.22
4	4.58	90.23	1.58	23.64	40.36	31.23
5	4.36	91.25	1.56	22.35	40.12	32.56
6	6.21	89.36	1.89	25.62	38.69	30.24
7	6.23	89.54	1.75	25.48	38.26	30.12
8	5.36	91.23	2.23	22.36	40.45	31.26
9	7.21	89.36	1.89	26.58	38.36	29.68
10	6.25	91.25	1.85	24.26	39.58	30.22
11	5.62	91.23	1.96	23.36	37.59	33.69
12	6.35	91.25	1.85	23.41	38.12	31.25
13	5.58	92.26	1.87	23.58	38.26	32.63
14	5.68	92.36	1.96	23.69	38.44	33.42
15	5.14	91.36	2.15	24.23	39.26	31.26
16	6.36	90.36	2.12	24.25	38.69	31.25

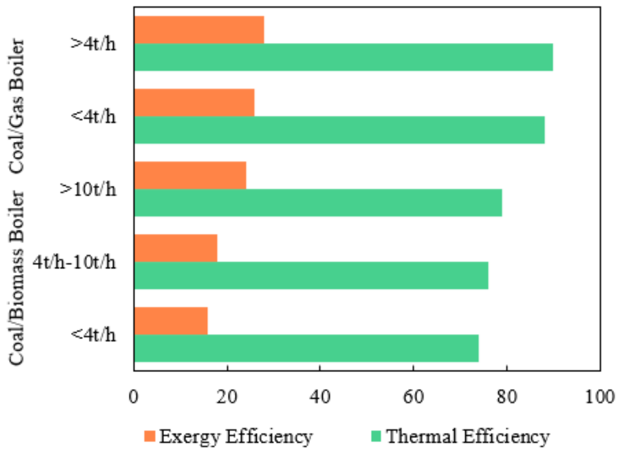
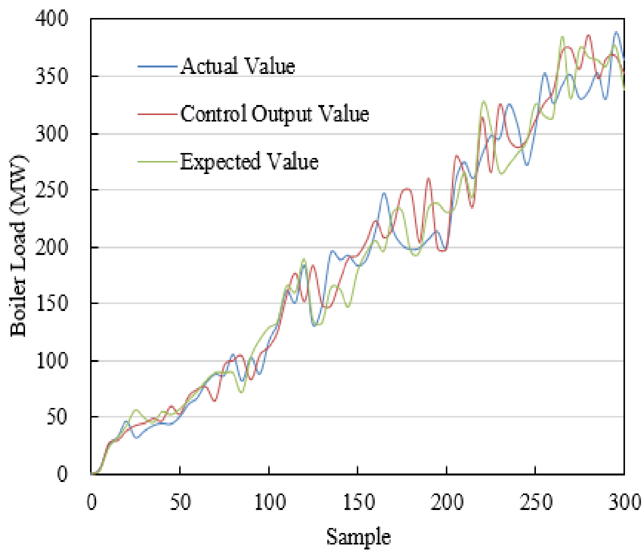


Figure 5. Comparison of thermal efficiency and exergy efficiency in energy conversion for industrial enterprises

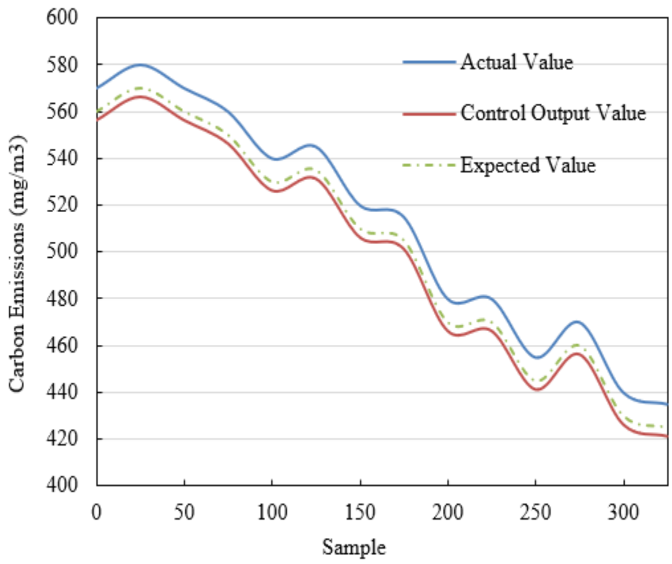
From the data on load control processes and carbon emissions provided in Figure 6, it can be seen that there is a certain deviation between actual values, control output values, and expected values. In the load control process, the overall trend of actual values is relatively close to control output values, but there are still significant differences at some sample points. For example, at sample points 195 and 192, the actual values are significantly higher than the control output values (195 VS. 170 and 192 VS. 190), indicating a lag or insufficiency in the control system's response under high load conditions. Additionally, the differences between expected values and actual values and control output values are also large at some sample points, particularly when the load reaches around 100 and 150, where actual values fluctuate significantly, and control effectiveness is unstable. For carbon emissions data, the overall trend of actual values, control output values, and expected values is downward, but there is a noticeable deviation between actual values and control output values at sample points 250 and 300, with values of 540 VS. 526 and 520 VS. 506, respectively, showing a deviation in the control system's management of emissions. From the perspective of sustainable economic growth, industrial enterprises must improve the precision of load control and the effectiveness of emission management in the energy conversion process. The data indicate that although the control system can generally follow changes in expected values well, there is a significant deviation between actual load and control output under high load conditions, indicating that the existing control system may lack the response speed or adjustment capability needed during drastic load changes, potentially leading to reduced energy utilization efficiency and unnecessary energy waste. Additionally, the deviation between actual values and control output values for carbon emissions suggests that there is room for improvement in emission control, particularly under high load or long-duration operating conditions, where more precise control of emissions is needed to meet higher environmental standards. These results suggest that optimizing load control and emission management systems not only helps improve energy conversion efficiency but also reduces environmental pollution, promoting the sustainable development of industrial enterprises.

From the energy conversion efficiency and energy recovery efficiency data provided in Figure 7, it can be seen that energy conversion efficiency shows a relatively stable state after implementing energy recovery strategies. Conversion efficiency data generally remains between 88% and 92%, with most samples fluctuating around 90%, indicating that enterprises have a high level of efficiency in the energy conversion process. However, energy recovery efficiency values are relatively low, mainly concentrated between 86.5% and 88.5%, and in multiple sample points, energy recovery efficiency is lower than conversion efficiency. Particularly around sample 200, energy recovery efficiency drops below 86.8%, while conversion efficiency remains above 89%, indicating that there may be some losses or instability factors in the energy recovery process. From the perspective of sustainable economic growth, improving energy recovery efficiency is key to enhancing overall energy utilization efficiency. Although the enterprise's energy conversion efficiency is relatively high, remaining stable at around 90%, the relatively low and fluctuating energy recovery efficiency suggests that some energy is not effectively recovered and reused in the energy conversion process, possibly leading to resource waste and increased production costs. To achieve more efficient resource utilization and economic benefits, enterprises should further optimize energy recovery strategies to reduce losses in the energy recovery process.

From the data provided in Figure 8, it can be seen that the optimized inlet air volume and inlet air velocity show significant improvement at most sample points. For inlet air volume, the optimized variable is closer to the expected value in most cases, with smaller fluctuations. For example, at sample point 20, the optimized inlet air volume is 359, while the unoptimized air volume is 335, indicating that the optimized control system can better adjust the inlet air volume. Similarly, the inlet air velocity data also shows that the optimized variable is more stable in most cases, with the optimized inlet air velocity reaching 85 at sample point 20, while the unoptimized air velocity is 73, indicating that the precision of the optimized system in air velocity control has been improved. From the perspective of sustainable economic growth, optimizing the control of inlet air volume and air velocity in industrial enterprises is a key step in improving energy conversion efficiency. The data show that the system optimized with economic cost variables performs more stably and precisely in controlling inlet air volume and air velocity, which not only helps improve energy utilization efficiency but also effectively reduces energy waste and operating costs. Especially the smaller fluctuations in the optimized inlet air velocity and air volume data indicate that the system is more responsive and better able to adapt to changes in the production process, reducing unnecessary energy loss. Therefore, optimizing energy control parameters in industrial enterprises not only helps improve production efficiency but also supports sustainable economic development. It is recommended that policymakers and enterprise managers increase the promotion and application of similar optimization technologies to help industrial enterprises make greater progress in energy conservation, emission reduction, and economic benefit improvement.



(1) Load



(2) Carbon emissions

Figure 6. Load and carbon emissions in the energy conversion control process of industrial enterprises

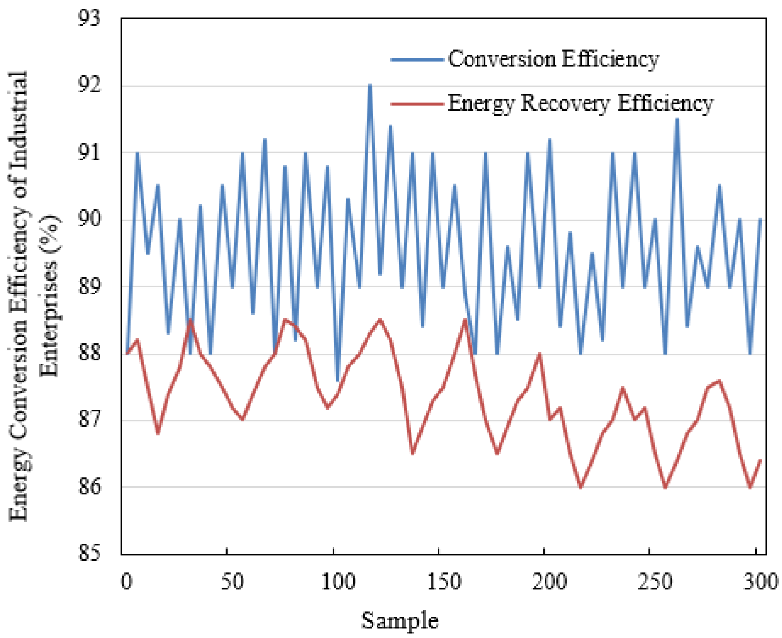
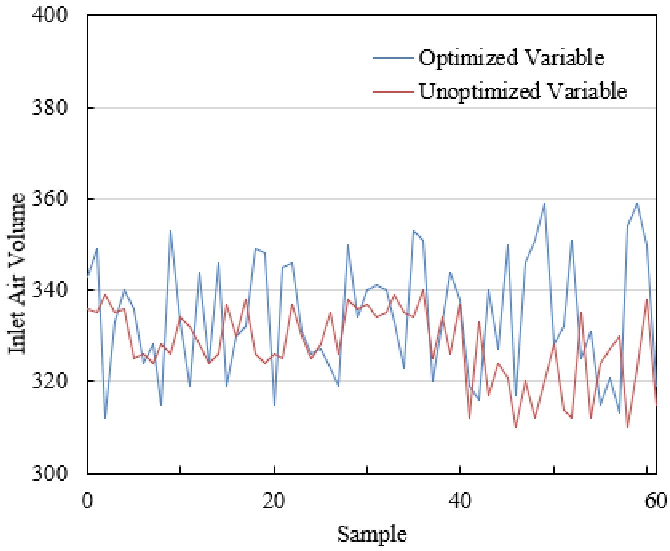
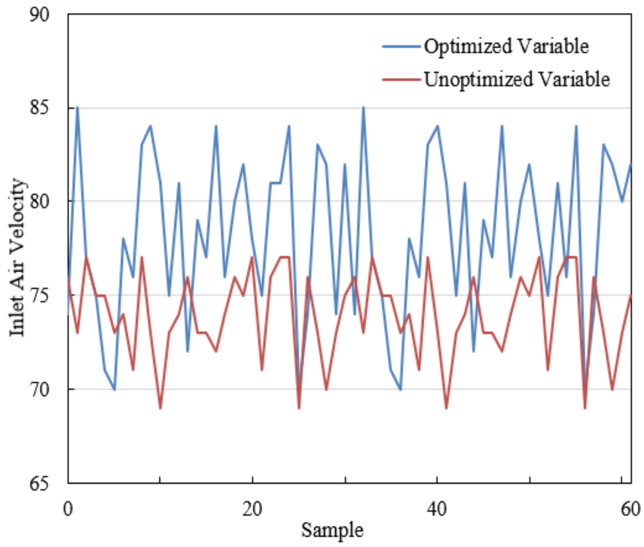


Figure 7. Energy conversion efficiency control results for industrial enterprises implementing energy recovery strategies



(1) Inlet Air Volume



(2) Inlet Air Velocity

Figure 8. Changes in energy conversion efficiency control parameters in industrial enterprises optimized with economic cost variables

5. CONCLUSION

This paper constructs an energy conversion efficiency model for industrial enterprises based on thermodynamic principles, comprehensively revealing the conversion mechanism of energy in the industrial production process and its efficiency levels. The research results show that energy conversion efficiency of industrial enterprise equipment fluctuates significantly under different load conditions, and the management of carbon emissions needs to be improved. Through the implementation of energy recovery strategies, enterprises have improved their energy conversion efficiency, but there are still some losses in the energy recovery process. Further experimental data also indicate that energy conversion efficiency and control parameters in industrial enterprises have been significantly improved based on optimized economic cost variables, particularly in the control of inlet air volume and air velocity, where the optimized system shows higher stability and precision. This research provides substantial guidance for industrial enterprises in balancing energy management and economic growth, particularly in how to improve energy utilization efficiency and reduce environmental burdens through technological optimization, which has important application value.

Although this study provides empirical evidence for improving energy conversion efficiency in industrial enterprises, there are still some limitations. For example, the experimental data mainly come from specific industrial enterprise scenarios, and the generalizability of the research results to other industries needs further validation. In addition, the long-term effects of energy recovery strategies and the collaborative optimization mechanisms between different equipment also need to be explored in future research. Future research can further expand the applicability of this model, exploring the impact of cross-industry energy conversion efficiency on economic growth, particularly how to promote sustainable development through energy technology innovation in the context of globalization. Additionally, further optimization of energy recovery and cost control strategies in enterprises can be pursued to achieve higher energy conversion efficiency and lower environmental impact, providing more specific decision-making support for policymakers and enterprise managers.

REFERENCES

[1] Topchiy, D. (2020). Energy audit of buildings commissioned upon completion of industrial facility conversion projects. In IOP Conference Series: Materials Science and Engineering, 960(4): 042074. https://doi.org/10.1088/1757-899X/960/4/042074

[2] Abi Chahla, G., Zoughaib, A. (2019). Agent-based conceptual framework for energy and material synergy patterns in a territory with non-cooperative governance. Computers & Chemical Engineering, 131: 106596. https://doi.org/10.1016/j.compchemeng.2019.106596

[3] Mu, C., Ding, T., Zeng, Z., Liu, P., He, Y., Chen, T. (2020). Optimal operation model of integrated energy system for industrial plants considering cascade utilisation of heat energy. IET Renewable Power Generation, 14(3): 352-363. https://doi.org/10.1049/iet-rpg.2019.0651

[4] Tagle-Salazar, P.D., Nigam, K.D., Rivera-Solorio, C.I. (2020). Parabolic trough solar collectors: A general overview of technology, industrial applications, energy market, modeling, and standards. Green Processing and Synthesis, 9(1): 595-649. https://doi.org/10.1515/gps-2020-0059

[5] Carmona-Martínez, A.A., Rueda, A., Jarauta-Córdoba, C.A. (2024). Deep decarbonization of the energy intensive manufacturing industry through the bioconversion of its carbon emissions to fuels. Fuel, 371: 131922. https://doi.org/10.1016/j.fuel.2024.131922

[6] Petrichenko, L., Kozadajevs, J., Petrichenko, R., Ozgonenel, O., Boreiko, D., Dolgicers, A. (2021). Assessment of PV integration in the industrial and residential sector under energy market conditions. Latvian Journal of Physics and Technical Sciences, 58(3): 82-97. https://doi.org/10.2478/lpts-2021-0018

[7] Abd Elkodous, M., Hamad, H.A., Abdel Maksoud, M.I., et al. (2022). Cutting-edge development in waste-recycled nanomaterials for energy storage and conversion applications. Nanotechnology Reviews, 11(1): 2215-2294. https://doi.org/10.1515/ntrev-2022-0129
[8] Abi Chahla, G., Zoughaib, A. (2019). Agent-based conceptual framework for energy and material synergy patterns in a territory with non-cooperative governance. Computers & Chemical Engineering, 131: 106596. https://doi.org/10.1016/j.compchemeng.2019.106596
[9] Kristia, K., Rabbi, M.F. (2023). Exploring the synergy of renewable energy in the circular economy framework: A bibliometric study. Sustainability, 15(17): 13165. https://doi.org/10.3390/su151713165
[10] Felix, C.B., Ubando, A.T., Chen, W.H., Goodarzi, V., Ashokkumar, V. (2022). COVID-19 and industrial waste mitigation via thermochemical technologies towards a circular economy: A state-of-the-art review. Journal of Hazardous Materials, 423: 127215. https://doi.org/10.1016/j.jhazmat.2021.127215
[11] Saravanan, A., Karishma, S., Kumar, P.S., Rangasamy, G. (2023). A review on regeneration of biowaste into bio-products and bioenergy: Life cycle assessment and circular economy. Fuel, 338: 127221. https://doi.org/10.1016/j.fuel.2022.127221
[12] Abdullah, M.A., Nazir, M.S., Hussein, H.A., Shah, S.M. U., Azra, N., Iftikhar, R., Iqbal, M.S., Qamar, Z., Ahmad, Z., Afzaal, M., Om, A.D., Shaharah, M.I., Bak, A.E., Hung, Y.T. (2024). New perspectives on biomass conversion and circular economy based on Integrated Algal-Oil Palm Biorefinery framework for sustainable energy and bioproducts co-generation. Industrial Crops and Products, 213: 118452. https://doi.org/10.1016/j.indcrop.2024.118452
[13] Guevara, Z., Henriques, S., Sousa, T. (2021). Driving factors of differences in primary energy intensities of 14 European countries. Energy Policy, 149: 112090. https://doi.org/10.1016/j.enpol.2020.112090
[14] Chai, Y.H., Mohamed, M., Lam, M.K. (2023). A review on potential of biohydrogen generation through waste decomposition technologies. Biomass Conversion and Biorefinery, 13(10): 8549-8574. https://doi.org/10.1007/s13399-021-01333-z
[15] Elroi, H., Zbigniew, G., Agnieszka, W.C., Piotr, S. (2023). Enhancing waste resource efficiency: Circular economy for sustainability and energy conversion. Frontiers in Environmental Science, 11: 1303792. https://doi.org/10.3389/fenvs.2023.1303792
[16] Wang, X., Zhang, Y., Ma, K. (2024). The influence of regional industrial structure on the suitability of biomass energy development: A case study of 30 counties and cities in a cold region of China. Sustainable Cities and Society, 11: 105555. https://doi.org/10.1016/j.scs.2024.105555
[17] Kristia, K., Rabbi, M.F. (2023). Exploring the synergy of renewable energy in the circular economy framework: A bibliometric study. Sustainability, 15(17): 13165. https://doi.org/10.3390/su151713165
[18] Awasthi, S.K., Sarsaiya, S., Kumar, V., Chaturvedi, P., Sindhu, R., Binod, P., Zhang, Z., Pandey, A., Awasthi, M.K. (2022). Processing of municipal solid waste resources for a circular economy in China: An overview. Fuel, 317: 123478. https://doi.org/10.1016/j.fuel.2022.123478
[19] Song, G.M. (2019). Thoughts on carrying out enterprise energy audit under the background of new and old kinetic energy conversion. In IOP Conference Series: Earth and Environmental Science, 267(2): 022011. https://doi.org/10.1088/1755-1315/267/2/022011
[20] Frantál, B., Nováková, E. (2019). On the spatial differentiation of energy transitions: Exploring determinants of uneven wind energy developments in the Czech Republic. Moravian Geographical Reports, 27(2): 79-91. https://doi.org/10.2478/mgr-2019-0007
[21] Shah, S.Z.A., Ahmad, M. (2019). Entrepreneurial orientation and performance of small and medium-sized enterprises: Mediating effects of differentiation strategy. Competitiveness Review: An International Business Journal, 29(5): 551-572. https://doi.org/10.1108/CR-06-2018-0038