Waste Heat Recovery and Utilization of Cement Rotary Kiln Based on Biomass Energy

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A rotary kiln is a central piece of equipment for the calcination of clinker in the production of cement. Biomass energy has been applied to rotary kilns, and solar energy has been introduced to assist the energy supply. Coupled optimization results for biomass energy and solar energy applications are compared to the single fossil energy used in the base period. A field survey and statistical analysis and integration of cement clinker production sites in China's Central Plains Economic Zone revealed a negative linear correlation between the consumption of raw coal in the cement production process and the environmental temperature and humidity parameters of the production lines. The energy consumption is large and the energy utilization of the system is low, with goodness of fit of R=0.962. Coupled solar and biomass energy use in the audit period and single energy use in the base period comparison revealed a 19.5% reduction in electricity consumption, a 25.4% reduction in coal consumption and a 4.39% increase in heavy oil consumption. From 2017 to 2020, the average annual consumption cost of electricity and raw coal decreased, while the average annual consumption cost of heavy fuel oil slowly increased. After verification during the audit period, compared with the base period, the total production cost of the case enterprise can be reduced approximately 5.17%, in which the energy cost decreased 0.9%.

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Keywords: Cement production enterprises; Biomass energy; Energy audit; Energy consumption analysis; Energy saving potential

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INTRODUCTION

The wide application of biomass energy has brought huge economic benefits while reducing pollution (Xu 2023). The energy resource conservation, rational utilization of resources, and improvement of energy efficiency of cement production enterprises, the application of new energy to rotary kilns to alleviate the pressure of fossil energy, the replacement of fossil energy with new energy, and the improvement of biomass energy utilization have attracted the attention of the whole society. In view of the high energy consumption of the cement industry, the waste heat has not been efficiently recycled, and the potential space of energy-saving resources needs to be further explored and integrated. Therefore, how to ensure the stable production of the cement industry, quality of product process while saving energy, and reduce overall energy consumption must be researched. The application of biomass energy in a rotary kiln, coupled with solar energy-assisted energy supply to reduce energy consumption, and to optimize and upgrade the traditional rotary kiln system to improve the overall efficiency of the waste heat step efficient recovery system, has increasingly become the core issue of research by experts and scholars at home and abroad. Li *et al.* (2016) conducted a detailed audit analysis based on the data of energy consumption and energy consumption in the production process of cement enterprises. On this basis they put forward targeted constructive suggestions and continuous improvement strategies. Jia (2017) discussed the stability of the production process in view of the current situation of comprehensive energy consumption in the cement production industry, and the construction of an energy management platform was of great significance to the mining of the energy saving potential of the cement industry. Through systematic analysis and diagnosis of energy consumption in cement production industry, Chen *et al.* (2018) proposed energy saving approaches and energy efficiency improvement technologies to effectively solve energy problems in the production process of enterprises. Ma (2012) took the rotary kiln of the new dry cement production line as the research object, analyzed the waste heat recovery and utilization technology on the surface of the rotary kiln cylinder, proposed the strategy of reasonable recovery and utilization of the waste heat on the surface of the cylinder, and optimized the design of the waste heat recovery device.

For the accurate measurement of dust particle sampling in boiler flue gas flow, Jia (2004) proposed a test scheme of unorganized pipes comprising a pipeline (all permutations were used) and selecting the measurement position of sampling points and a representative number. Zhu (2001)’s study was on flue gas waste heat, waste heat from clinker, kiln body heat loss using, and processing recycling waste heat in the rotary kiln cement production line links, which are a variety of ways that waste heat is utilized. The rotary kiln shell waste heat recovery that was proposed for the development of low energy consumption, high efficiency, and low carbonization direction of cement enterprises has important realistic and far-reaching significance. Engin and Ari (2005) conducted an energy audit, and energy-saving detection and analysis on the rotary kiln system of cement production line. They found that approximately 40% of the total input energy of the system was lost through waste gas and heat dissipation on the surface of the rotary kiln cylinder. Farag (2012) took heat consumption of cement clinker calcination in dry cement kiln as the research object, elaborated the distribution theory and practical parameters affecting the balance between energy and exergy in the production process, and then analyzed and evaluated the energy and exergy efficiency of dry cement kiln based on actual operation data.

To realize an effective and efficient energy management plan, Kabir *et al.* (2010) conducted a thermal audit analysis on a high temperature treatment device from a cement plant. Wang (2019b) designed a waste heat recovery device on the surface of the cylinder to improve the efficiency of radiant heat recovery on the cylinder surface of cement rotary kiln, and discussed its structural strength, stability, and thermo-structural coupling with ANSYS software. Gu *et al.* (2009a) designed and developed a set of hot water systems for waste heat recovery in cement plants for production to realize cascading and efficient recovery and utilization of waste heat during the cement production process. Wang (2019) proposed a practical and reliable energy-saving optimization scheme based on the comprehensive energy efficiency of cement production system and energy saving in production links, which can make cement production enterprises achieve efficient and comprehensive utilization of energy to a large extent and ensure orderly and stable operation of the production process. Chu (2017) proposed an online monitoring system for thermal efficiency of cement rotary kiln based on thermodynamic mechanism and in combination with the energy consumption distribution and production status of the calcination process in the rotary kiln of cement production line, which helps cement enterprises to rationally use and save energy and maximize the comprehensive utilization of energy. Madlool *et al.* (2012) discussed exergic analysis, exergic balance, and exergic efficiency of the cement production process. The research results showed that exergic efficiency of cement production process equipment ranged from 18% to 49%, and the potential space of energy saving resources needed to be further explored and integrated. Sui *et al.* (2014) made a detailed study on exergic efficiency of cement clinker production process system, and compared and analyzed the efficiency and energy utilization rate of each link in the cement production process according to the energy audit and energy saving potential mining status of cement production enterprises. Caputo *et al.* (2011) analyzed the energy consumption based on the waste heat resource recovery of cement rotary kiln, and proposed that the surface heat dissipation of rotary kiln cylinder occupies a large proportion of the main energy consumption of the system. Thus, the enterprise has a large potential of energy saving and efficiency improvement. Cui (2020) analyzed the energy consumption of cement production process system and discussed the energy expenditure, energy metering equipment configuration, energy application, and management of each link in the production process, which helped to put forward more suitable measures for energy application and energy management of enterprises. Li (2019) investigated the current situation of unorganized dust emission control in the cement industry, went into the energy utilization status and management level of the cement industry, and suggested corresponding treatment measures that can effectively reduce pollutant emissions and promote energy efficiency improvement of enterprises to a large extent.

Currently at home and abroad, most scholars of the production process of cement enterprises recognize that the process could benefit from an in-depth study on the current situation, energy consumption, and application of biomass energy. Alternatively, analysis can be based on the existing cement rotary kiln waste heat resource recovery system to optimize the design. The research content is both regional and contemporary, but there are questions of how to focus on improving the overall efficiency of waste heat cascade efficient recycling system. There have been relatively few studies on energy consumption measurement analysis and energy saving of cement production enterprises. Especially there has been a lack of studies that discuss recycling and utilization of rotary kiln waste heat and total output value, improving system energy use quality by comprehensive biomass energy, coupling and reasonable combination of energy consumption sources, and collaborative interconnection of production technology innovation with high energy efficiency and low carbonization. Based on the relationship between energy consumption and the environment under high-quality development of cement production enterprises, biomass energy and solar energy can be organically combined to rationally optimize the coupled system in conjunction with system optimization techniques. The structure and energy supply pattern of the biomass rotary kiln are properly optimized and adjusted to achieve the resource utilization of biomass energy through the changes in energy consumption before and after the application of biomass energy. This study proposes to improve the overall efficiency of the waste heat stepwise efficient recovery and utilization system and investigate the coupling properties of the waste heat recovery and utilization of the rotating kiln with the total output value of the enterprise and the energy consuming carriers. Exploring the correlation degree of “technology, cost, and market,” in addition to reducing the environmental pollution caused by animal manure, can effectively alleviate the agricultural non-point source pollution of each link in the cement production process, and realize the coordinated interconnection of comprehensive utilization of biomass energy in the production area and stable operation of peak regulation.

The effective utilization of waste heat can improve the overall efficiency of kiln body and also reduce the environmental pollution caused by the emission of waste heat.

EXPERIMENTAL

Theoretical Analysis of Enterprise Energy Consumption

SPSS curve comparison

Using SPSS (IBM Corp., IBM SPSS statistics v.26, Chicago, IL, USA) software, the changes of various indexes before and after the application of biomass energy can be summarized and compared in a targeted manner. The difference between the base period and the audit period can be clearly seen by comparing the SPSS curves. SPSS curve comparison is a data statistics software that integrates a variety of data management and analysis methods. Its basic functions mainly include data management, statistics, analysis, and output. The statistical analysis procedure for SPSS data includes descriptive statistics, mean comparison, general linear model, correlation analysis, regression analysis, log-linear model, and multiple responses. In this paper, a linear regression model is used to analyze the relationship between output, cost, and revenue of cement production enterprises: the annual revenue, annual cost, and annual net income of the enterprises in the audit period are selected as the model data.

After applying biomass energy during the audit period curve regression analysis

In recent years, according to relevant literature, domestic and foreign experts and scholars have conducted in-depth research on the energy audit and energy saving potential mining of cement production enterprises, but there are limitations in the research area and method, lack of accuracy in energy data analysis, and no reliable energy saving optimization scheme has been proposed. In this paper, aiming at the coupling characteristics of energy consumption and environment and the integration of system optimization technology under the high quality development of cement production enterprises, it is proposed to apply biomass energy to rotary kiln and strive to improve the overall efficiency of the efficient step recovery and utilization system of waste heat. Coupling properties of waste heat recovery efficiency, total output value, and energy consumption sources of the rotating kiln were investigated after the application of biomass energy technology and the optimization and tuning of the system. The correlation degree of “technology, cost, and market” in the collaborative regulation of technological innovation, high energy efficiency, and low carbonization were also explored. Theoretical data were input, analyzed, and compared horizontally and vertically by means of charts, with the aim of optimizing the energy-saving scheme of the system and achieving energy saving and emission reduction in the enterprise.

The regression analysis of the linear and quadratic curve regression estimation models between production quantity and annual income, production cost, annual cumulative net revenue and production cost during the audit period are shown in Figs. 1, 2, 3, and 4, respectively.

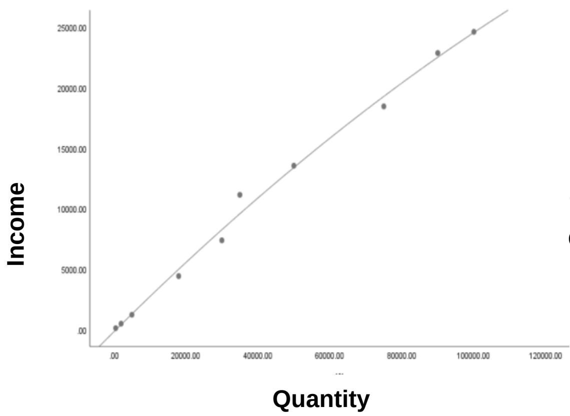


Fig. 1. Regression analysis of production quantity and annual revenue curve in audit period

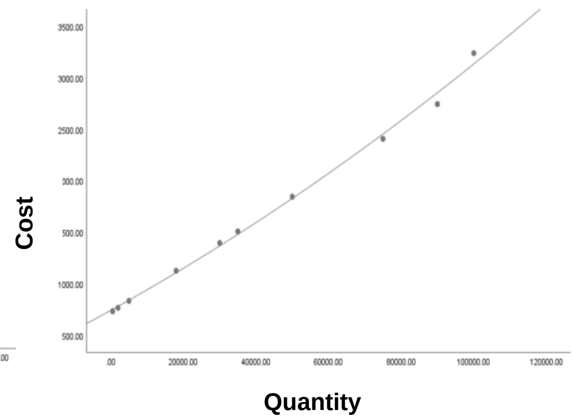


Fig. 2. Regression analysis of production quantity and cost curve in audit period

A quadratic curve fit was performed based on the scatter distribution of the test data. As shown in Fig. 1, the annual revenue of the independent variable, production volume, has an impact on the annual revenue of the variable, which increases with the aluminate cement output of the enterprise. Annual revenue growth was highest when aluminate production was between 50,000 and 90,000 tonnes. Annual revenue growth is slow when production is less than 50,000 tonnes, and enters a phase of diminishing marginal utility when production exceeds 90,000 tonnes, meaning that the marginal revenue of the business gradually decreases.

Figure 2 shows that the amount of production of the independent variable has an impact on the annual production cost of the variable. The minimum marginal cost is achieved when aluminate production is between 60,000 and 90,000 tonnes. When production exceeds 90,000 tonnes, the marginal utility exhibits an increasing phase, meaning that the marginal cost of the business gradually increases.

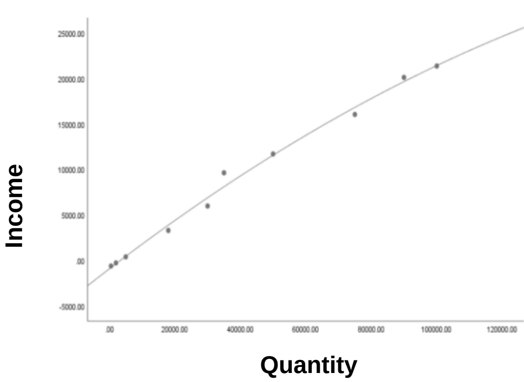


Fig. 3. Regression of enterprise production quantity and annual cumulative net income during the audit period

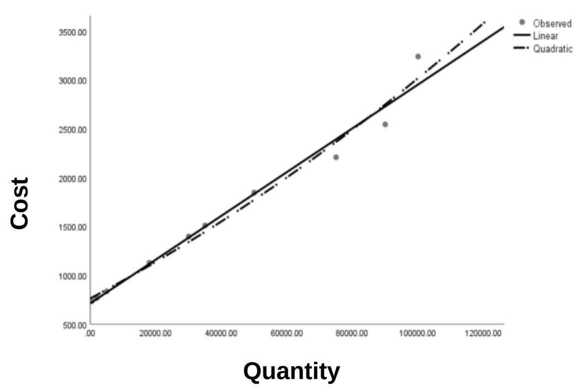


Fig. 4. Quadratic regression between production quantity and production cost during audit period

A quadratic curve fit was performed based on the scatter distribution of the test data. As shown in Fig. 3, the annual cumulative net income of the variable corresponds to the amount of production of the independent variable, and the two are roughly proportional.

Due to fixed production costs, the Company's annual cumulative net income is negative when aluminate cement production is less than or equal to 2,000 tonnes. Annual cumulative net income increases most rapidly when aluminate cement production is between 50,000 and 90,000 tonnes, with maximum marginal net income achieved at a certain point between 50,000 and 90,000 tonnes. When production is above 90,000 tonnes, the marginal utility decreases, meaning that the annual cumulative net income gradually tends to stabilize or even show a downward trend. Figure 4 shows that the amount of production of the independent variable has an effect on the annual production cost of the variable. The minimum marginal cost is achieved when aluminate production is between 60,000 and 90,000 tonnes. When production exceeds 90,000 tonnes, the marginal utility enters an increase phase, meaning that the marginal cost of the business will gradually increase.

The results show that after the application of biomass energy in rotary kiln and the improvement of its technology, as well as the production cost and land rent, the enterprise can achieve the maximum economic scale when the production quantity of aluminate cement ranges from 50,000 to 90,000 tons, and may enter the decreasing stage for economies of scale after exceeding 100,000 tons.

Case Analysis of Enterprise Energy Consumption

The rotary kiln is one of the central pieces of equipment for the calcination of clinker in the cement production of cement. The energy consumption of the calcination process accounts for approximately 80% of the total energy consumption. The average temperature of the zone from kiln head to kiln tail is as follows: The burning of section I was approximately 300 to approximately 350 ℃, the decomposition and exothermic reaction zone II is approximately 280 to approximately 300 ℃, and the drying and pre-heating zone III was approximately 240 ℃. The kiln body consists primarily of cylinders, feeding, supports, transmission, sealing, and other equipment components. According to the field research on the types of energy used by enterprises (cement clinker production base in China Central Plains Economic Zone), they mainly include electricity, raw coal, and heavy oil, the energy consumption and type changes before and after the application of biomass energy in rotary kilns are analyzed. According to the weighted calculation of energy discount coefficients (equivalent discount coefficients of power, heavy oil, and raw coal were 1.229 tce/ 10,000 kWh, 1.4286 tce/t, and 0.7143 tce/t, respectively), annual and quarterly statistical analysis of energy consumption was carried out. The advantages and disadvantages of biomass energy applications are summarized, and targeted improvements are made to the biomass rotary kiln system.

Through the coupling of technology, cost, and market, the amount of energy used can be reset and analyzed by means of multi-energy regulation, thus enabling technological innovation, high energy efficiency and low carbon regulation.

Comparison of energy consumption before (2017) and after (2020) application of biomass energy

1) For other energy consumption after biomass energy application in the audit period (2020), SPSS was used to conduct data analysis on the composition of comprehensive energy consumption and the proportion of main energy in the enterprise: the equivalent of comprehensive energy consumption was 22919.85 tce, and the equivalent value of standard coal was 27465.14 tce. Among them, electricity consumption was 23.91 million kWh, raw coal consumption was 22101.62 t, and heavy oil consumption was 2878.40 t. According to statistical calculation, raw coal consumption is large, the upper

and the second half of the year accounted for respectively, 57.5% and 68.9%, and heavy oil consumption was small. It was 15.27% in the first half and 18.3% in the second half.

During the audit period (2020), when biomass energy was applied to rotary kilns, the amount of energy saved varied from quarter to quarter. The SPSS was used to conduct a detailed investigation and analysis of on the quarterly energy consumption of the enterprises. Energy consumption in the second and third quarters was slightly higher than that in the first and fourth quarters, but the overall fluctuation was relatively stable. Among them, quarters I, II, III, and IV: Power consumption was 4.582 million kWh, 882 million kWh, 4.982 million kWh, and 4.682 million kWh, respectively. Coal consumption was 5514.91 t, 5529.90 t, 5529.91 t, and 5524.90 t, respectively. The heavy oil consumption was 709.1 t, 709.1 t, 729.1 t, and 709.1 t, respectively. The statistical comparative analysis of quarterly energy consumption after the application of biomass energy (2020) is shown in Figs. 5 and 6.

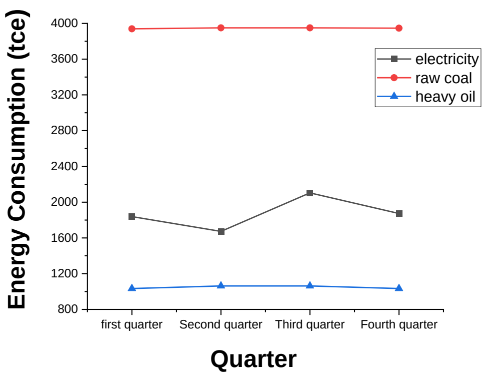


Fig. 5. Quarterly performance source consumption (discounted as standard coal)

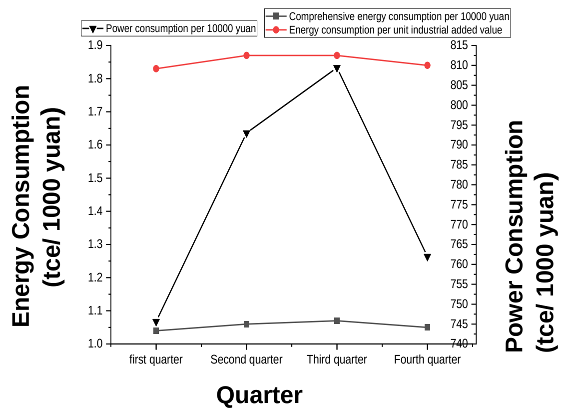


Fig. 6. Quarterly energy consumption per ten thousand yuan of output value of enterprises during the audit period

According to Figs. 5 and 6, according to the annual field tracking survey data in the audit period (2020), the proportion of annual energy consumption (quarterly energy consumption ratio was about 24.5%, 25.3%, 25.5%, and 24.7%, respectively) was slightly higher than that of quarterly energy consumption. For an annual comprehensive energy consumption of 10,000-yuan output value (in the audit period and the base period, it was calculated as 1.12 tce/10,000-yuan and 1.40 tce/10,000-yuan according to the equal value of standard coal), the quarterly energy consumption was about 25.98%, 25.02%, 25.02%, and 24.98%, respectively.

2) In the base period (2017), biomass energy was not applied to rotary kilns, and all kinds of energy consumption in this period were greater than that in the audit period (2020). To make the comparison clearer, SPSS was used to perform data analysis on the composition of the integrated energy consumption and the proportion of primary energy in the enterprise. A statistical comparison analysis of the annual energy consumption between the audit period and the base period is presented in Fig. 7.

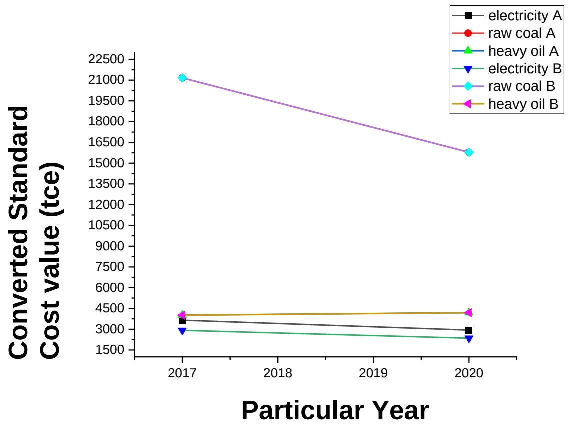


Fig. 7. Comparison of energy consumption between audit period and base period

According to Fig. 7, the equivalent energy consumption of standard coal is 28,800 tce and equivalent value of standard coal is 34,500 tce. Of these, electricity consumption was 29.7 million kilowatt-hours, raw coal consumption was 29,600 t, and heavy fuel oil consumption was 27,500 t. The raw coal consumption is large based on the statistical calculation of the equivalent and equivalent reduction scales were 73.4% and 61.4%, respectively. Heavy fuel consumption was small, with 13.9% and 11.6% in the upper and lower half of the year, respectively.

Based on the principle of mass balance and material balance, according to GB/T2589-2008, the energy audit guidelines and the general rules for the calculation of comprehensive energy consumption were followed, according to the field tracking survey of the energy consumption data of aluminate cement produced by the cement clinker production base in the Central Plains Economic Region of China. Within the audit period (2020), it has changed the way of energy application, replacing traditional energy with biomass energy, and its energy consumption calculation has also changed. At the same time, the comprehensive energy consumption and power consumption per unit product of the field investigation enterprise were calculated according to Eq. 1 and Eq. 2 respectively,

$$E_0 = \frac{E_{sum}}{G} \tag{1}$$

$$P_{co} = \frac{P_{sum}}{G} \tag{2}$$

where E_0 is the comprehensive energy consumption per unit product (kg ce/t); E_{sum} is comprehensive energy consumption (kg ce); P_{co} is power consumption per unit product (kWh/t); P_{sum} is the total power consumed by the product (kWh); and G is the total amount of production (t).

According to the calculation, during the audit period (2020), the comprehensive energy consumption per unit product of the field investigation enterprise was calculated as equivalent of standard coal. That is, the energy consumption of aluminate cement and α -alumina was 184 kg ce/t and 446 kg ce/t, respectively, and the comprehensive power consumption of unit product was 215 and 236 kWh/t. In the base period (2017), the comprehensive energy consumption per unit product of the field survey enterprise was calculated according to the equivalent standard coal: the energy consumption of aluminate cement and α -alumina were 255 kg and 418 kg ce/t, respectively, and the comprehensive power consumption of unit product was 279 and 282 kWh/t. It can be seen that after the application of biomass energy, the energy consumption of aluminate cement is reduced 71 kg ce/t, the energy consumption of α-alumina is increased 28.4 kg ce/t, and the saving of comprehensive electric energy is approximately 109.5 kWh/t per year. The comparison of annual energy consumption between the audit period (2020) and the base period (2017) is shown in Fig. 8.

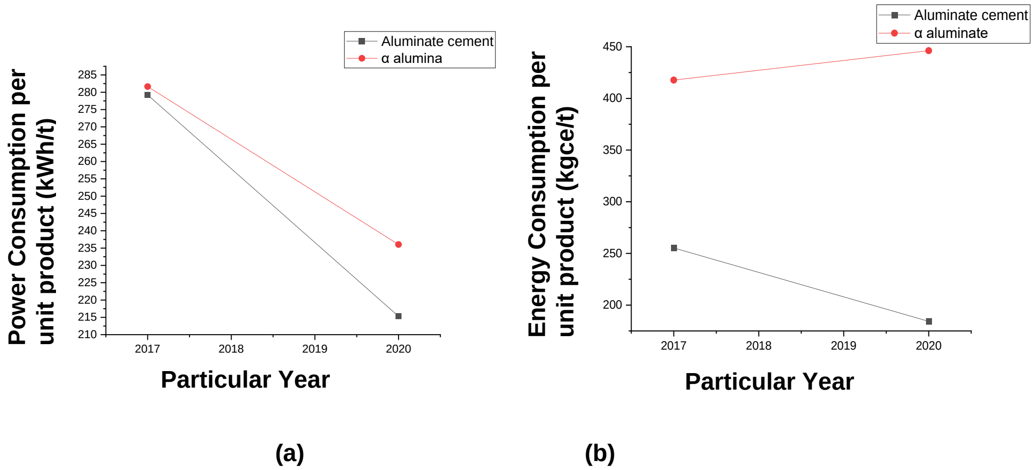


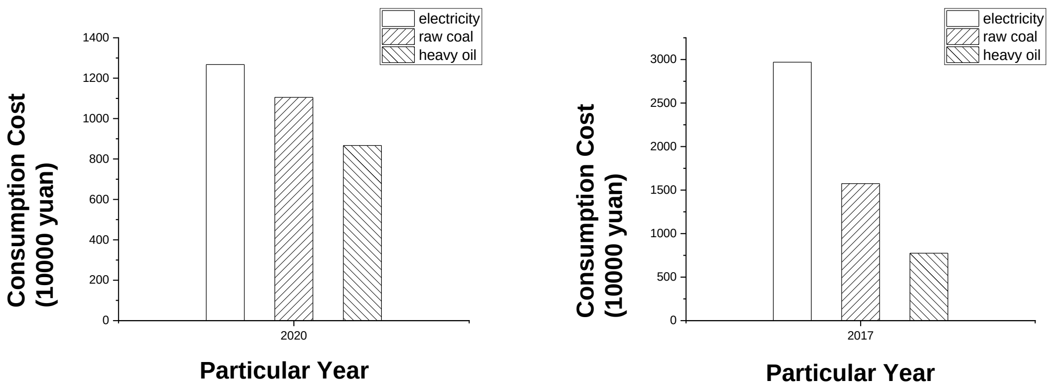
Fig. 8. Annual comprehensive energy consumption and power consumption change of unit product during audit period and base period: (**a**) Comprehensive energy consumption per unit product (**b**) Power consumption per unit product

As shown in Fig. 8, during the base period (2017) and audit period (2020), the comprehensive energy consumption per unit product of "α -alumina" shows a slow growth trend, with an increase of about 6.8%, while the comprehensive power consumption per unit product decreases to about 16.2%. The comprehensive energy consumption per unit product of “aluminate cement” decreased each year, about 27.8%, and its comprehensive power consumption per unit product decreased 22.9%, which was similar to that of “α –alumina,” but the decrease was more obvious than that of “α –alumina.” It showed that the rotary kiln with biomass energy can save energy while reducing the comprehensive energy consumption of Portland cement products, but the energy consumption of α-alumina products will increase slightly.

Annual comprehensive energy consumption comparison

Comprehensive energy consumption in audit period (2020) and base period (2017) was mainly reflected in energy consumption, such as electricity, raw coal, and heavy oil, and its energy consumption (equivalent folding scale), is shown in Fig. 9.

According to Fig. 9, the energy consumption comparison between audit period (2020) and base period (2017) was analyzed and integrated by SPSS based on environmental factors (environmental temperature and humidity), physical and chemical properties (effects) of raw materials used in production, and the instability of outsourcing unit price annually in the energy guarantee area of the enterprise. When the biomass energy is applied to the rotary kilns, electricity consumption can be reduced by 19.5%, the raw coal consumption by 25.4%, and the heavy oil consumption by 4.4%. The average annual consumption cost of heavy fuel oil shows a slowly increasing trend.



(a) **(b)**

Fig. 9. Comparison of energy consumption expenses between the audit period and the base period: (**a**) Energy consumption during the audit period (2020); (**b**) Base period (2017) energy consumption

Regression analysis of energy consumption during application of biomass energy

A linear regression model was used to validate and analyze the relationship between energy consumption and temperature change in cement production enterprises during the audit period, and thus explore the linear relationship between energy consumption and temperature in production systems during the audit period. The regression equation is given as follows:

$$E = \beta_0 + \beta_1 T \tag{3}$$

where E is the monthly energy consumption (t) and (10,000 kWh) of the production line; T is the average temperature of the external environment (°C); β_0 and β_1 are the coefficient of regression variables. Where, the linear relationship between energy consumption and air temperature in the affiliated production system of the enterprise during the audit period can be established as follows:

$$E = \gamma_0 + \gamma_1 T \tag{4}$$

where E is the monthly energy consumption of the affiliated production system of the enterprise (10,000 kWh); T is the average temperature of the external environment (°C); and γ_0 and γ_1 are the coefficient of regression variables. The power consumption-air temperature scatter plots and the primary and secondary linear fits are shown in Figs. 10 and 11, respectively. Raw coal consumption-air temperature scatter distribution and linear regression relationship of primary fitting are shown in Figs. 12 and 13, respectively.

Linear regression analysis of power consumption and air temperature.

The scatter distribution of the data is plotted according to Fig. 10, and the primary fitting and secondary fitting were carried out, as shown in Fig. 11. In the clinker production process, the power consumption does not show a linear trend with the change of air temperature. Further, the linear regression model Eqs. 3 and 4 were substituted for significance test and significance value $P > 0.05$. Therefore, the regression model was not statistically significant. That is, there is no significant direct linear relationship between the power consumption of aluminate cement clinker in the production process and the external temperature environment.

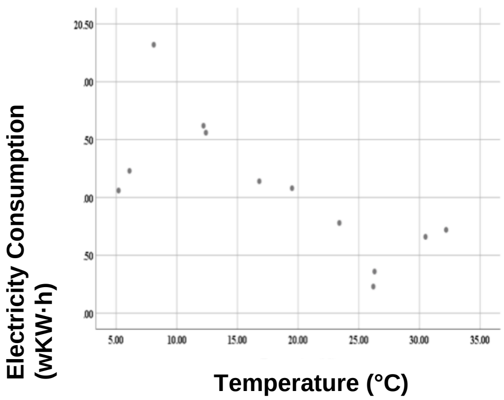


Fig. 10. Power consumption-air temperature scatter distribution

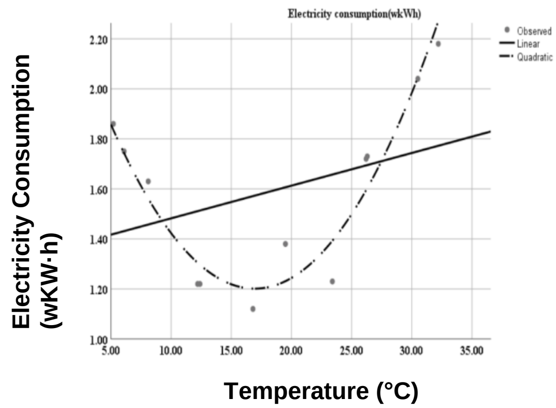


Fig. 11. Primary and secondary fitting diagram

Linear regression analysis of raw coal consumption and air temperature

Based on the scatter plot of the data in Fig. 12, it can be seen that the consumption of raw coal is linearly dependent on the air temperature. A linear regression model with air temperature as an independent variable and raw coal consumption as a dependent variable was developed and fitted. The fit plot is shown in Fig. 13.

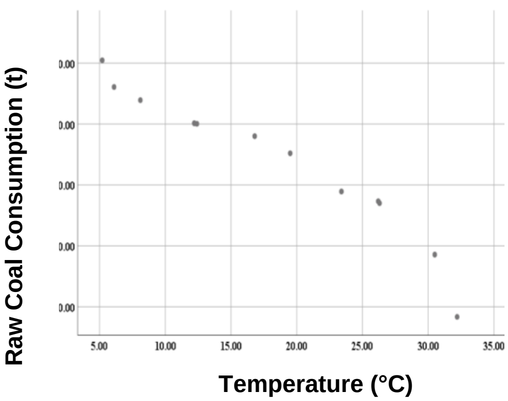


Fig. 12. Scatter distribution of raw coal consumption-air temperature

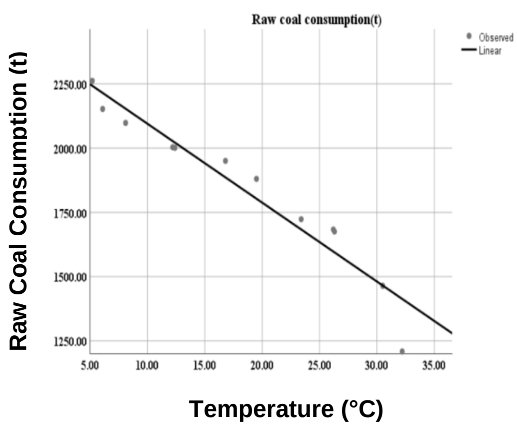


Fig. 13. Fitting linear regression relationship once

According to Figs. 12 and 13, the authors substituted linear regression model Eqs. 3 and 4 to conduct a significance test for regression, where the significance value was $P < 0.05$, indicating that the model has practical statistical significance. There was a negative linear correlation between the consumption of raw coal and the external ambient temperature during the production process of aluminate cement clinker, and the goodness of fit R value of 0.962 indicates that the consumption of raw coal was highly linear and correlated with the change of ambient temperature change. Through regression analysis and research, the results show that the thermal energy system of the enterprise was greatly affected by the external environment, which essentially reflects the low energy utilization efficiency of the production system of the enterprise, especially the need to improve the energy utilization efficiency of the calcination process stage. Under ideal assumptions, the smaller the regression coefficient in the linear regression relation between energy consumption and temperature, the smaller the fluctuation of energy consumption with the change of the temperature of the external environment, that is, the higher efficiency of energy utilization of the energy consuming system. Therefore, it is necessary to further optimize the biomass energy application scheme and explore the thermal energy potential of the system to improve the working efficiency and energy utilization rate of biomass energy and achieve a more reasonable allocation of biomass energy.

Enterprise Energy Saving Optimization Scheme

Existing problems

Through investigation and analysis of the comprehensive energy consumption and production cost of the cement case enterprise, the following enterprises are found: 1) the pulverized coal in the high temperate zone of the rotary kiln was not fully burned, and the pulverized coal in the combustion process moves too fast to the end of the kiln, and the heat transfer rate was slow; 2) The existing production equipment of the case enterprise has high energy consumption, and the overall efficiency and resource allocation of the stepped efficient recovery and utilization system of surplus waste heat (waste heat of kiln cylinder, high-temperature gas heat exchange in the third chamber of grate cooler, *etc.*) are unreasonable; 3) The outsourcing unit price of the enterprise energy guarantee area was unstable each year, and the enterprise energy use does not adopt time-sharing module and coordinated interconnection scheme with adaptive regulation.

Energy saving optimization scheme of biomass energy

A high-temperature gas heat exchange and waste heat recovery system was added to the third chamber of the barrel heat exchange grate cooler, on top of the existing rotating kiln buckets at Case Enterprises. According to literature (Fan *et al.* 2020), considering the temperature difference of different parts of the rotary kiln barrel (average temperature area was about 350 to 240 °C) and the waste heat of the flue gas in the third chamber of grate cooler by classification and utilization (average temperature area was about 250 to 200 °C), the cylinder heat exchanger was designed in sections and regions. At the same time, according to the different degrees of waste heat recovery and classification utilization of the flue gas in the third chamber of grate cooler, high and low temperature heat exchangers are set separately, which was conducive to efficient recovery of waste heat, aiming to reduce the overall system heat dissipation energy consumption and improve the economic benefits of the case enterprise.

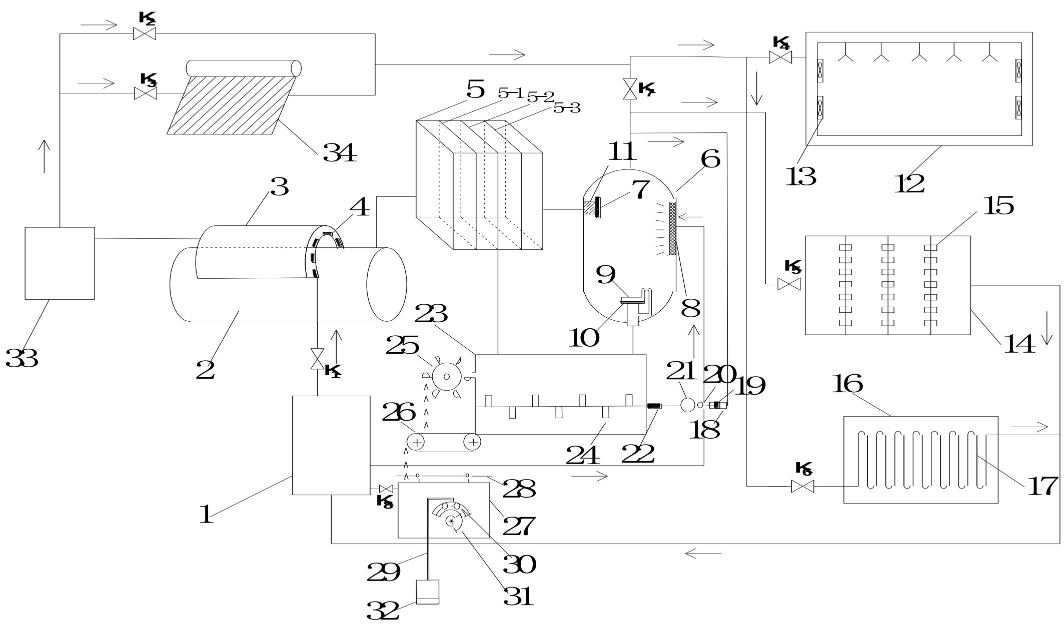
Improvement of biomass energy application and waste heat utilization in rotary kiln

Based on energy consumption analysis and energy saving measures in energy audit, this study proposes an optimization scheme for the production system of waste heat recovery and comprehensive utilization of a compound rotary kiln by setting a vortex ring atomizing pump with groove in the waste heat recovery and utilization system, as shown in Fig. 14.

1) Vortex ring atomizing pump with groove (material was elastic diaphragm, with expansion and deflection) was set. The water flowing into the atomizing pump from the cold water storage tank passes through the grooved entrance to the outlet on the other side. Small deviations in the position of the vortex ring atomization pump are affected, and the inner wall of the tube has an ejection effect on the water flow, which is perturbed by the boundary layer. The incoming flow can pass through the groove, changing the minor direction of the water flow, forming a vortex ring and entraining and rising. It flows out in

different directions from the outlet of each groove in different directions, and is sent to the nozzle of the atomization pump. The generating fog is heat changed with the high-temperature flue gas in the flue gas purifier. The impurities contained in the flue gas are mixed with the water vapour during the heat exchange process, and the impurities are sunk to the bottom of the flue gas purifier. Another part of the high-temperature steam is emitted from the upper end of the purifier.

2) The biogas produced by the biogas digester is processed and piped to the kiln body for primary energy supply and heating. Solar panels enable waste heat recovery in rotating kiln systems by absorbing external sunlight. Biogas from the digester can also provide the corresponding energy for waste heat recovery in rainy weather or when sunlight is scarce. At the same time, solar energy can also be used to supply energy and heat the kiln to avoid a lack of biomass energy causing the overall system to fail.



1. Cold water storage tank; 2. Rotary kiln body; 3. Heat shield; 4. Oblate hot water exchange pipe; 5. Filters- 5-1, 5-2, and 5-3: First, second, and third filter; 6. Flue gas purifier; 7. Sealing pad; 8. Atomizing pump; 9. Drainer; 10. Rubber diaphragm; 11. Exhaust pipe; 12. Shower room; 13. Fan; 14. Heater; 15. The fin; 16. Biogas digester; 17. Hot coil; 18. Vacuum tube; 19. The sliding block; 20. Linkage gear A; 21. Linkage gear B; 23. Waste disposal box; 24. Agitate bar; 25. Collecting hopper; 26. Conveyor belt; 27. Multi-functional area room; 28. Orbit; 29. Coupling; 30. Roller drive rod; 31. CAM; 32. Detector; 33. Hot water storage tank; 34. Solar heat collector plate; K_1, K_2, K_3, K_4, K_5, K_6, K_7, K_8, K_9, and K_{10} are the valves

Fig. 14. Production system of composite rotary kiln waste heat recovery and comprehensive utilization

3) Kiln body waste heat recovery mode: I. When the weather was sunny and the light was sufficient, the valve K_3 was opened (K_2 is closed), and the water in the hot water storage tank was secondary heated by the solar heat collector plate. Water from the hot water storage tank was heated to the shower room and biogas digester according to the end demand. II. When it was rainy and illumination was insufficient, valves K_2 and K_7 were open (K_3 can end coupling, timely switch open and closed), The water in the hot water storage tank is re-heated by the high-temperature steam transported from the flue gas

purifier, and heats the shower room and biogas digester according to the end demand. The heat-exchanged water flows back into a cold water storage tank for recycling. At the same time, the biogas produced in the biogas pond also powers the kiln, reducing the consumption of electricity and other fossil fuels

4) Working process: the biomass waste generated in the filter and flue gas purifier in the system is transferred and distributed to the waste disposal box, moved to the multi-function area room through the collecting hopper and conveyor belt, mixed with other fertilizers in proportion, and decomposed for the use of crop fields. At the same time, the high-temperature flue gas in the filter of the system is discharged through the exhaust pipe into the gas purifier, and the secondary filtration is achieved with an atomization pump. Stirred biomass fertilizer from the system flows into the aggregate hopper through the waste bin upper port into the aggregate hopper and is transported to the field for fertilizer replenishment.

Change of waste heat recovery efficiency and comprehensive energy consumption after the system transformation

Based on cement production enterprise under the high quality development and coupling characteristics of energy consumption and environmental system optimization technology integration, according to the central plains economic zone of cement clinker production base in China, rotary kiln cylinder heat transfer case enterprise, grate cooler, more than 3 rooms gas heat transfer in high temperature hot cascade recycling waste and the enterprise output, the coupling of energy consumption carrier and biomass energy was considered to be well integrated and a reasonable combination. This can help to improve the overall efficiency and rationality of resource allocation in an efficient residual heat and utilization system of residual heat.

A three-level energy management network system should be constructed with metering data management mode (mainly including energy procurement, energy transportation, and storage, energy consumption quota management, energy metering, energy statistical analysis, and energy-saving technical transformation, *etc.*).

The induced draft fans at the kiln head and kiln tail, as well as the motors, such as cement mill, raw material mill and coal mill, biomass occurrence and reaction device, and biogas digester, shall be equipped with frequency converters, and the operation status of powder mill, raw material mill, and coal mill shall be timely adjusted to avoid excessive operation of powder mill (material mill, coal mill, *etc.*). At the same time, to prevent the clinker dust from entering the coal mill, the hot air needs to pass through the cyclone dust collector. The vortex ring air dispenser is set at the inlet of the micro air duct near the middle and lower sides of the cone of the separator, which can effectively improve the separation efficiency. After effective dust removal and purification treatment, the dust emission (concentration of 15 to 25 mg/m^3) was reduced, which helps to save electricity and environmental protection and reduce the energy consumption of cement products per unit of the case enterprise.

Result analysis

According to the verification after the audit period (2020), compared with the base period (2017), the total production cost of the case enterprise can be reduced by about 5.17%, among which the energy cost was reduced 0.9%. The comparison of energy consumption index, production cost, and energy cost before and after the technological transformation is shown in Figs. 15 and 16, respectively.

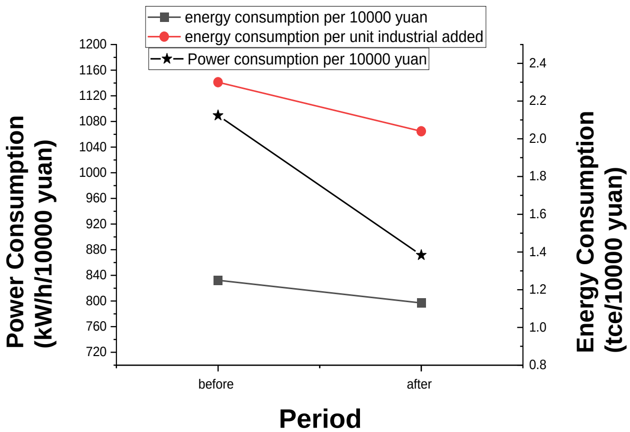


Fig. 15. Comparison of energy consumption indexes before and after technological transformation

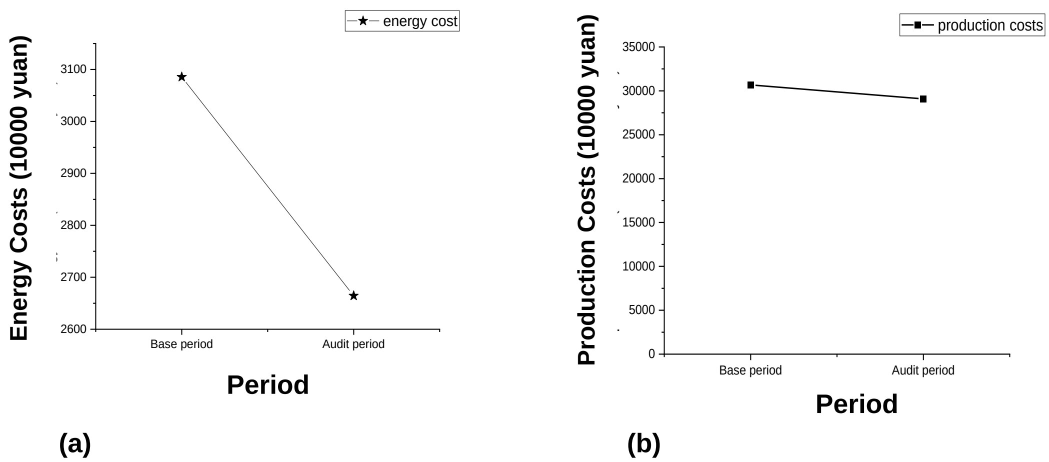


Fig. 16. Production cost and energy cost of enterprises after technological transformation: (a) Industry production costs; (b) Energy costs

According to Figs. 15 and 16, by applying the biomass energy to the rotary kiln and optimizing its related technologies, the use of outsourced electricity in enterprise life and work was greatly reduced. It can be seen from the above data that the energy consumption and energy consumption per ten thousand yuan of output value of the enterprise show a downward trend, which greatly reduces the total production cost and energy cost of the enterprise, saves a large part of production investment for the enterprise, and improves the economic benefits of the enterprise. After optimizing energy conservation, the main energy consumption of enterprises was significantly reduced, and the energy unit price was more reasonable. According to market research, the unit price of electricity was 0.53 yuan/kWh and the unit price of raw coal was 455 yuan/t. The price of heavy oil is stable at 3011 yuan/t in the audit period and 2811 yuan/t in the base period. According to the above data, the comprehensive energy consumption and production cost of enterprises show a downward trend after energy saving potential mining and energy saving optimization, which saves a large part of production investment and improves enterprise benefits. It can be seen that the optimization scheme has a significant effect and has the possibility of gaining popularity. According to the data obtained from the field investigation and calculation, the enterprise cost in the base period after the implementation of the optimization plan was 306,717,600 yuan, of which the energy cost accounts for 10.06%. After 4 years of implementation and audit, the cost of the optimized scheme will be reduced to 298.8755 million yuan, of which energy cost accounts for 9.16%. To sum up, the overall cost of the enterprise was reduced 5.17%, among which the energy cost was reduced 0.9%. The results show that after the audit period (2020), the energy consumption of enterprises was reduced, and at the same time, the application of biomass energy in rotary kiln can adjust and optimize the energy structure of enterprises.

CONCLUSIONS

1. Base period compared with the audit period: Electricity consumption decreased 19.5%, raw coal consumption decreased 25.4%, and heavy oil consumption increased 4.4%. From 2017 to 2020, the consumption of electricity and raw coal decreased year by year, while the consumption of heavy oil increased year by year, but the increase was slow.
2. The research results show that after the audit period (2020), through the application of biomass energy and the technical transformation and energy-saving optimization of the previous system, about 20% energy saving can be achieved compared with the base period (2017), and the total production cost of the case enterprise will be reduced by about 5.2%, among which the energy cost will be reduced 0.9%.

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