

Research on Energy Efficiency and Carbon Emission Evaluation Methods of cogeneration Technology under the Background of Carbon Neutrality

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Abstract: This article delves into the energy efficiency evaluation methods and carbon emission evaluation methods of cogeneration technology. In terms of energy efficiency evaluation, the concept of energy efficiency and commonly used energy efficiency indicators of cogeneration systems were introduced, such as total energy efficiency, power efficiency, thermal energy efficiency, and fuel utilization efficiency. In terms of carbon emission evaluation, the concept of carbon emissions and commonly used carbon emission indicators for cogeneration systems were analyzed, such as carbon emissions per unit of power generation, carbon emissions per unit of thermal energy, and total carbon emissions. For these evaluation methods, different implementation steps and calculation formulas were introduced in detail, and their application scenarios and advantages and disadvantages were illustrated with examples. These evaluation methods help to evaluate the performance and environmental impact of cogeneration systems, providing scientific basis for relevant decision-making.

Keywords: Combined Heat and Power Generation, Energy Efficiency Evaluation, Carbon Emissions.

1. Introduction

With the rapid development of global industry and the improvement of urbanization level, the demand for electricity and thermal energy is also showing a significant growth trend. Industrial heat demand accounts for two-thirds of industrial energy demand and one-fifth of global energy consumption [1]. Cogeneration is an energy production method that utilizes primary energy sources such as natural gas and coal for power generation, and uses the waste heat generated during the power generation process for heating. In the context of carbon neutrality, cogeneration technology has become an important development direction for global energy technology. Compared with traditional single power and heating systems, cogeneration systems have many advantages. They can not only effectively utilize clean energy, but also form a complementary relationship between seasonal gas peaks and valleys and electricity load peaks and valleys, alleviating the problem of electricity shortage. The cogeneration system can simultaneously produce electricity and heat, and effectively utilize some waste heat, greatly improving energy utilization efficiency [2-4]. This article will discuss the energy efficiency and carbon emission evaluation methods of cogeneration technology.

2. Energy Efficiency Evaluation Methods for Cogeneration Technology

2.1. The overview of energy efficiency in cogeneration

2.1.1. The concept of energy efficiency in cogeneration

The energy efficiency of a cogeneration system refers to the ratio of the useful energy (electricity and heat) provided by the system to the energy consumed (usually fuel). High energy efficiency means that the system can generate more useful energy with less energy consumption, improve energy utilization efficiency, and also have better economic and

environmental friendliness.

2.1.2. Common energy efficiency indicators for cogeneration

(1) Total energy efficiency: Total energy efficiency is the ratio of the total output of electrical and thermal energy in a system to the fuel energy consumed. It evaluates the overall energy utilization efficiency of the system, indicating that the system converts fuel energy into useful energy with higher efficiency [5].

(2) Electricity efficiency: Electricity efficiency refers to the ratio of the electricity generated by a system to the fuel energy consumed. It reflects the energy utilization efficiency of the system in terms of electricity generation, and high electricity efficiency means that the system can generate more electricity with less fuel consumption.

(3) Thermal efficiency: Thermal efficiency refers to the ratio of the heat energy generated by a system to the fuel energy consumed. It reflects the energy utilization efficiency of the system in terms of thermal energy generation, and high thermal energy efficiency means that the system can generate more thermal energy with less fuel consumption.

(4) Fuel utilization efficiency: Fuel utilization efficiency refers to the ratio of the useful energy generated by the system to the fuel energy consumed. It comprehensively considers the output effect of electricity and heat energy, and is a comprehensive indicator for evaluating the energy utilization efficiency of the system. High fuel utilization efficiency indicates that the system is able to utilize fuel energy with higher efficiency [6].

2.2. Energy efficiency evaluation method for cogeneration systems

2.2.1. Heat sharing method

In the cogeneration industry, the heat allocation method is usually used to calculate the standard coal consumption for power generation. This method is based on the first law of thermodynamics, treating both electrical and thermal energy as heat and allocating them according to the proportion of heat

consumed in heating and power generation. By allocating the total coal consumption according to the proportion of heat consumption for power generation and heating, the standard

coal consumption for power generation can be calculated. The calculation formula is as follows [7]:

$$\text{Coal consumption for power generation} = \frac{\text{Total coal consumption}}{\text{Power generation} + \text{Heat supply}} \quad (1)$$

$$\text{Heating coal consumption} = \frac{\text{Total coal consumption} - \text{Coal consumption for power generation}}{\text{Heat supply}} \quad (2)$$

$$\text{Total thermal efficiency} = \frac{\text{Power generation} + \text{Heat supply}}{\text{Total coal consumption} \times \text{Calorific value of standard coal}} \quad (3)$$

The formula for dividing the unit coal consumption of different types of units by heat is summarized as follows [8]:

$$b_{f, r} = \frac{1000 \times B_{b, h}}{W_{f, h} + 1000 \times \frac{Q_{gr, h}}{R}} \quad (4)$$

In the formula: $b_{f, r}$ — The comprehensive power generation standard coal consumption (g standard coal/kWh) of each type of unit under the heat sharing method; $B_{b, h}$ — Boiler's hourly consumption of standard coal (tons of standard coal/h); $W_{f, h}$ — Hourly power generation of the unit (MWh); $Q_{gr, h}$ — Hourly heating capacity of the unit (GJ/h).

Among them, R is defined as the thermal equivalent of electricity (kJ/kWh), and the formula is as follows:

$$R = R_b \times R_e \quad (5)$$

In the formula: R_b — Calorific value of standard coal; R_e — Equivalent conversion coefficient of electricity to standard coal.

This method can comprehensively consider the energy consumption of heating and power generation, and provide a comprehensive evaluation of the energy efficiency of cogeneration systems. However, this heat allocation method

did not fully consider the quality difference between electricity and thermal energy. Although this method has certain applicability in the parameters of high temperature, high pressure (or ultra-high pressure) back pressure heating units, it is not very suitable for condensing cogeneration units. Whether it is the direct heating of the high-temperature and ultra-high pressure boiler matched with the back pressure unit, or the heating of the back pressure machine with air extraction, the heat consumption for heating has not changed, resulting in no significant change in the heating ratio. The specific calculation methods may vary depending on standards, regulations, or corporate practices, so in practical applications, appropriate calculation methods should be selected according to the situation, and the accuracy and reliability of the data should be ensured.

2.2.2. Referring to the Boiler Law

In cogeneration, according to the boiler method, the amount of coal consumed for heating is equivalent to the amount of coal consumed by a standard large coal-fired boiler. This method is used to convert the energy consumption required for heating into coal consumption corresponding to coal-fired boilers for measurement and comparison. At present, the heat generation efficiency of standard large coal-fired boilers is generally set at 0.9. According to the boiler method, the calculation formula is as follows [9]:

$$\text{Heating coal consumption} = \frac{34.12}{\text{Standard large-scale coal-fired boiler heat generation efficiency}} \quad (6)$$

$$\text{Coal consumption for power generation} = \frac{\text{Total coal consumption} - \text{Heat supply} \times \text{Heating coal consumption}}{\text{Power generation}} \quad (7)$$

2.2.3. Thermoelectric separation method

In the selection of design schemes for cogeneration units, the combination of centralized heating boilers and pure generator units is often compared and demonstrated with cogeneration. This method equates the heat generated by cogeneration units with the temperature and pressure reduction method of directly supplying heat from coal-fired boilers. By using this method, the standard coal required for the same amount of heat consumed by the central heating boiler can be subtracted from the total consumption of standard coal in cogeneration, thereby obtaining the standard coal consumed by the pure power generation unit [10]:

$$b_{f, d} = 1000 \times \frac{B_{b, h} - 1000 \times \frac{Q_{gr, h}}{R_b}}{W_{f, h}} \quad (8)$$

In the formula: $b_{f, d}$ — The comprehensive power generation standard coal consumption (g standard coal/kWh) of various types of units under the thermoelectric separation method; $B_{b, h}$ — Boiler's hourly consumption of standard coal (tons of standard coal/h); $Q_{gr, h}$ — Hourly heating capacity of the unit (GJ/h); R_b — Calorific value of standard coal; $W_{f, h}$ — Hourly power generation of the

unit (MWh); $Q_{gr, h}$ — Hourly heating capacity of the unit (GJ/h); $\eta_{gb, d}$ — Heating boiler rate (%). Generally, the efficiency of large coal-fired heating boilers is approximately 90%.

When evaluating the energy efficiency of the cogeneration method and the cogeneration unit, it was found that the unit coal consumption of the back pressure cogeneration unit was lower than that of the condensing cogeneration unit. This indicates that the cogeneration method is actually based on a reasonable foundation where the heating efficiency of coal-fired boilers reaches 90%, and electricity is generated by conventional condensing units. This coal-fired boiler only

provides temperature parameters of about 100°C low-grade heat.

2.2.4. Referring to the Power Plant Law

In cogeneration, according to the Power Plant Law, the amount of coal consumed in power generation is equivalent to the amount of coal consumed in coal-fired pure power plants. This method is used to convert the energy consumption required for power generation into coal consumption corresponding to coal-fired pure power plants for measurement and comparison. The calculation formula is as follows [11]:

$$\frac{\text{Heating coal consumption} = \text{Total coal consumption} - \text{Power generation} \times \text{National average heating coal consumption}}{\text{Heat supply}} \quad (9)$$

2.2.5. Equivalent electrical method

The equivalent electricity method is an evaluation method that comprehensively considers the amount of heating and the quality of electricity. It uniformly converts the energy carried by steam or hot water of different grades into equivalent electricity, assuming that the energy quality coefficient of electricity is 1. The energy mass coefficient determined by applying the second law of thermodynamics, i.e. the equivalent electrical conversion coefficient δ , The heat content can be expressed as equivalent electricity using a formula. This method balances the importance of heating and electricity, providing a comprehensive energy efficiency evaluation index [12]:

$$E_{r, e} = \delta_s \times \frac{Q}{R_b \times R_e} \quad (10)$$

In the formula: $E_{r, e}$ — The equivalent electricity quantity of steam or hot water converted according to the "equivalent electricity method" is defined as MW_e or MW_{he} ; R_b and R_e are the equivalent electrical quantity of steam or hot water converted into electricity; δ_s — The equivalent electrical conversion coefficient for converting hot water or steam of a certain grade parameter into electricity; Q — Energy carried by steam or hot water (GJ or GJ/h).

The coal-fired thermal power unit can supply saturated steam with a temperature of T_s to the outside world, which can release latent heat through isothermal heating and do work to reach a saturated water state, and then cool it to ambient temperature T_0 . Based on the definition of the work form of saturated steam in two stages, we can obtain the equivalent electrical conversion coefficient δ_s for converting saturated steam into electricity. This coefficient can quantify the efficiency of converting the energy contained in saturated steam into electricity and provide an indicator for measuring energy conversion efficiency.

$$\delta_s = \delta_1 + \delta_2 = \frac{r_s}{h_s - h_0} \left(1 - \frac{T_r}{T_s}\right) + \left(1 - \frac{r_s}{h_s - h_0}\right) \left(\frac{T_0}{T_r - T_0} \ln \frac{T_r}{T_0} - \frac{T_0}{T_s - T_0} \ln \frac{T_s}{T_0}\right) \quad (11)$$

In the formula: δ_s — The equivalent electrical conversion coefficient of converting saturated steam of a certain quality parameter into electricity; r_s — The latent heat of vaporization of saturated steam (kJ/kg); h_s — The

enthalpy value of saturated steam (kJ/kg); h_0 — The specific enthalpy of water at ambient temperature is selected as 83.9 kJ/kg; T_s — Temperature of saturated steam or saturated water (K); T_r — Boiler water replenishment temperature (K); T_0 — The final working environment temperature (K).

By converting saturated steam supplied by thermal power units into electricity, we can more scientifically analyze and evaluate the efficiency of energy processing and conversion systems. This method comprehensively considers the influence of parameters such as steam pressure, temperature, vaporization latent heat, enthalpy, and boiler feedwater enthalpy, and can also distinguish the quality differences between the two products (electricity and heat) produced by cogeneration units. This comprehensive consideration approach is more in line with the essence of energy processing and conversion in thermal power plants, which is to convert low-grade primary energy into high-quality secondary energy [13].

By converting the supplied saturated steam heat into equivalent electrical energy, we can comprehensively consider the differences in steam characteristics such as pressure, temperature, enthalpy, and latent heat. In this way, by using the equivalent electricity method to allocate the standard coal consumption of the boiler according to the ratio of thermal energy and electrical energy, the calculation formula for the standard coal consumption of unit power generation can be obtained, as shown below:

$$b_{f, e} = \frac{1000 \times B_{b, h}}{E_{r, e} + W_{f, h}} \quad (12)$$

In the formula: $b_{f, e}$ — Unit standard coal consumption for power generation under equivalent electricity method (gram standard coal kWh); $B_{b, h}$ — Boiler's hourly consumption of standard coal (tons of standard coal/h); $E_{r, e}$ — Equivalent electricity after steam conversion (MW or MWh/h); $W_{f, h}$ — Hourly power generation of the unit (MWh).

2.2.6. Exergy efficiency method

According to the second law of thermodynamics, the process of energy conversion is not completely efficient, but is limited by energy level differences. When different forms of energy are converted into other forms, there is energy loss. The concept of energy levels is described using the ratio of

exergy to enthalpy in thermodynamics [14]. In a cogeneration system, the chemical energy of electricity and fuel can be completely converted into thermal energy, with an exergy to enthalpy ratio of 1. However, when converting thermal energy

into mechanical energy and further into electrical energy, the conversion rate is limited by Carnot's law. The formula is as follows [15]:

$$\text{The ratio of exergy to enthalpy} = \frac{\text{Exergy}}{\text{Enthalpy}} \quad (13)$$

$$\frac{\text{Exergy efficiency} = \text{Total thermal efficiency} \times \frac{1 + \text{The exergy to enthalpy ratio of supplied heat energy} \times \text{Heat-to-electric ratio}}{1 + \text{The exergy to enthalpy ratio of electric energy} \times \text{Heat-to-electric ratio}} \times 100\% \quad (14)$$

3. Carbon Emission Evaluation Method for Cogeneration Technology

3.1. The overview of carbon emission evaluation for cogeneration

3.1.1. The concept of carbon emissions in cogeneration

The carbon emissions of cogeneration systems refer to the greenhouse gases released by the system during the combustion of fuel, generation of electricity, and heat, mainly carbon dioxide. The combustion of fuel is the main source of carbon emissions, and factors such as energy efficiency and fuel selection in cogeneration systems will directly affect carbon emissions. Reducing carbon emissions from cogeneration systems is one of the important means to reduce greenhouse gas emissions and address climate change.

3.1.2. Common carbon emission indicators for cogeneration

(1) Carbon emissions per unit of electricity generation: Carbon emissions per unit of electricity generation refer to the amount of carbon dioxide released by a system for every unit of electricity generated. It is a key indicator for evaluating the carbon emission effect in the power generation process of the system. A lower unit of carbon emissions from power generation indicates that the system generates electricity with lower carbon emissions.

(2) Unit thermal carbon emissions: Unit thermal carbon emissions refer to the amount of carbon dioxide released by a system for every unit of thermal energy generated. It reflects the carbon emission effect of the system during the heating process. A lower unit of thermal energy carbon emissions indicates that the system generates thermal energy with lower carbon emissions.

(3) Total carbon emissions: Total carbon emissions refer to the total amount of carbon dioxide released by the system during the entire energy conversion and utilization process. It comprehensively considers the output effects of electricity and heat, and is a comprehensive indicator for evaluating the carbon emissions of the system. Reducing total carbon emissions can reduce the negative impact of the system on climate change [16-17].

3.2. Carbon emission evaluation method for cogeneration systems

3.2.1. Benchmark method

The benchmark method is a commonly used carbon emission evaluation method that compares the carbon emissions of a cogeneration system with a certain benchmark system. The benchmark system is usually the same type of traditional energy system, such as independent power

generation and heating systems. The core idea of this method is to evaluate the carbon reduction effect of a cogeneration system by comparing the carbon emissions of two systems. When implementing, first determine the carbon emissions of the benchmark system, then measure or estimate the carbon emissions of the cogeneration system, and compare and analyze the two. The advantage of the benchmark method is that it is simple and intuitive, easy to understand and apply [18].

The application summary in article Research on Carbon Emission Benchmarks and Carbon Reduction Potential of the Central Heating Industry in Jilin Province under the Background of "Dual Carbon" is as follows [19]:

(1) Data collection and accounting: Based on environmental statistical data from 2011 to 2020, calculate the carbon emissions of the central heating industry over the years. This includes calculating the carbon emissions per unit area of cogeneration heating enterprises during this period.

(2) Benchmark selection: Based on urban characteristics and heating demand, select the "coal consumption emission scenario" and "cogeneration emission scenario" as carbon emission benchmarks. These scenario models consider the changing characteristics of carbon emissions in the central heating industry in Jilin Province.

(3) Carbon emission intensity analysis: Analyze the carbon emission intensity of the heating industry in various cities throughout the province, classify the levels based on the average carbon emissions of each city over the years, and establish a baseline for carbon emissions based on this.

(4) Research on Carbon Reduction Potential: Based on the selected baseline, analyze the carbon reduction potential of the industry. The research results indicate that the carbon emission reduction of the central heating industry in Jilin Province is 11.7837 million tons per year, with a carbon reduction potential of 37.5%.

(5) Conclusion: The research results indicate that the heating method of cogeneration is the dominant source of carbon reduction potential. At the same time, considering environmental protection and regional development characteristics, we cannot blindly reduce the coal consumption of cogeneration enterprises.

In summary, this method aims to achieve low-carbon transformation and sustainable development of the central heating industry through scientific evaluation and reasonable planning.

3.2.2. Process analysis method

Process analysis method is a detailed analysis method for various processes of cogeneration systems, including fuel combustion, energy conversion, and waste heat utilization. This method measures and calculates the carbon emissions of each process to obtain the total carbon emissions of the

system. The process analysis method can help identify the main sources of carbon emissions in the system, thereby guiding the development of emission reduction measures. When implementing, it is necessary to collect data from various processes, such as fuel consumption, combustion efficiency, and waste heat utilization rate, and then calculate the carbon emissions of each process and accumulate them to obtain the total carbon emissions of the system. The general steps for calculating carbon emissions using process analysis can be summarized as [20-21]:

(1) Data collection: Collect energy consumption data of thermal jump generation facilities, including fuel types (such as coal, natural gas, etc.) and consumption. Obtain power generation and heating data for cogeneration facilities.

(2) Determine carbon emission factors: For each fuel, determine its carbon emission factor. These factors can usually be found in IPCC guidelines or other official published data.

(3) Calculate the carbon content of the fuel: Calculate the amount of carbon dioxide produced during fuel combustion based on its beauty and calorific value. This usually involves the carbon oxidation rate of the fuel and the net calorific value of the fuel.

(4) Calculate carbon emissions: Calculate the total carbon dioxide emissions using the following formula:

$$C = E \times NCV_s \times CEC \times COF \times \frac{44}{12} \quad (15)$$

In the formula: C — The total carbon emissions generated by fuel combustion (unit: 10000 tons); E — Fuel consumption (unit: 10000 tons of standard coal); NCV_s — Net calorific value of fuel (unit: TJ/Gg); CEC — Carbon emission factor (unit: kg CO_2 /GJ); COF — The carbon oxidation rate of fuel, usually taken as 1; $44/12$ — Molecular weight ratio of carbon dioxide to carbon.

(5) Adjustment and verification: Adjust the calculation results to consider possible errors and uncertainties. Use on-site monitoring data or third-party validation data to select rows for verification, ensuring the accuracy of calculations.

3.2.3. Input-output analysis method

The input-output analysis method is based on material and energy flows to analyze the input and output of a cogeneration system. This method considers the energy input and output of the system, and calculates the carbon content to evaluate the carbon emissions of the system. The input-output analysis method comprehensively considers the energy conversion efficiency and energy utilization of the entire system. When implementing, first collect input data from the system, including fuel type, usage, and carbon content, and then measure or estimate the energy output and carbon emissions of the system. By comparing and analyzing inputs and outputs, the carbon emission performance of the system can be evaluated [22].

3.2.4. Life cycle assessment method

The life cycle assessment method considers the carbon emissions of cogeneration systems throughout their entire life cycle, from construction, operation to disposal. This method comprehensively considers the carbon emissions of various links such as raw material collection, equipment manufacturing, transportation, use, and treatment. By assessing carbon emissions throughout the entire lifecycle, a comprehensive understanding of the environmental impact of the system can be obtained. When implementing, it is

necessary to collect data from various links, such as material and energy consumption, transportation distance, and waste disposal methods, and then calculate the carbon emissions of each link, and accumulate them to obtain the total carbon emissions of the system [23]. The following is the application of the life cycle assessment method for cogeneration to calculate carbon emissions [24]:

(1) Definition of objectives and scope: Clearly define the purpose of the evaluation and the research question. Determine system boundaries, including upstream (raw material extraction and processing), midstream (cogeneration equipment manufacturing and installation), and downstream (operation and maintenance) stages.

(2) Data collection: Collect data on all activities related to cogeneration, including raw material production, equipment manufacturing, transportation, installation, operation, maintenance, retirement, and waste disposal.

(3) Life Cycle Inventory (LCI) analysis: Quantify energy consumption and emissions for each stage, including fossil fuel consumption, electricity consumption, water consumption, waste generation, etc. Determine the greenhouse gas emissions generated by each activity, including carbon dioxide, methane, nitrous oxide, etc.

(4) Life Cycle Impact Assessment (LCIA): Using LCIA methods to assess the environmental impact of greenhouse gas emissions, typically expressed as Global Warming Potential (GWP). Calculate the carbon emission impact of each activity, including direct emissions (such as those generated by combustion) and indirect emissions (such as emissions from electricity production processes).

(5) Explanation and improvement of results: Analyze the results, identify the main sources and influencing factors of carbon emissions. Compare the impact of different technological paths or management measures on carbon emissions. Propose improvement measures based on the results of the life cycle assessment to reduce carbon emissions in the cogeneration process.

The life cycle assessment method not only focuses on the direct carbon emissions of cogeneration, but also considers the environmental impacts of the entire system, including resource consumption, waste generation, and ecological impacts. This method helps to comprehensively understand the environmental footprint of cogeneration and provides scientific basis for emission reduction strategies.

4. Conclusions

Driven by the goal of carbon neutrality, cogeneration (CHP) technology will usher in new development opportunities. In the future, the CHP system will pay more attention to improving energy efficiency and reducing carbon emissions. By integrating advanced energy conversion technologies, intelligent control and energy management systems, as well as deep integration with renewable energy, it will achieve efficient energy utilization. Energy efficiency evaluation methods will tend to be more refined and comprehensive, focusing not only on the utilization efficiency of a single energy source, but also on the overall energy flow and carbon footprint of the system. The carbon emission assessment method will be combined with the life cycle assessment method to comprehensively evaluate the full life cycle carbon emissions of the CHP system, providing scientific basis for formulating emission reduction strategies. With the advancement of data collection and analysis technology, evaluation methods will become more accurate and real-time,

providing strong support for policy formulation and enterprise operation.

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