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# Clean Power Dispatching of Coal-Fired Power Generation in China Based on the Production Cleanliness Evaluation Method

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**Abstract:** China's achievements in climate change and clean energy have been recognized by the international community. Although China has achieved successes in the field of clean energy, especially clean power dispatch, power dispatch is still one-sided and incomplete when considering environmental aspects. This paper presents a comprehensive production cleanliness evaluation model to assign a comprehensive environmental value as a reference for clean power dispatch. The model considers all the pollutants currently regulated in China's coal-fired power plants, carbon emissions, and sustainability as three basic environmental constraints. Then, emergy analysis is used to unify the input/output materials with different units of measurement, and the emergy-based environmental value added (EEVA) value is constructed. As an integrated environmental value, the EEVA can provide an environmental reference for clean power dispatch. Finally, we selected a representative coal-fired power plant in China as a case study. By applying the above model, the dispatching sequence for four generating units was arranged from the perspective of cleanliness.

**Keywords:** coal-fired power generation; comprehensive production cleanliness evaluation model; emergy analysis; environmental constraints; sustainability

## 1. Introduction

Given the urgent need to address climate change and achieve the goals set out by the Paris Agreement, the United Nations Climate Action Summit was held in New York in 2019. China's emissions reduction actions were highly praised by the countries participating in the conference. At the Paris Climate Conference in 2015, the Chinese government promised that by 2030, China's CO<sub>2</sub> emission per unit of gross domestic product (GDP) will be 60–65% lower than that of 2005, non-fossil energy will account for about 20% of primary energy consumption, and forest stocks will increase by about 4.5 billion m<sup>3</sup> from 2005. As of 2018, China's CO<sub>2</sub> emission per unit of GDP had dropped by 46.85% compared with 2005, which basically reversed the rapid growth of greenhouse gas emissions [1]. The forest coverage rate is 22.96%, and the forest stock volume is increased by 4.5 billion m<sup>3</sup> compared with 2005 [1]. By the end of 2018, China's renewable energy power installed capacity exceeded 700 million kW, of which hydropower, wind power, and photovoltaic installed capacity accounted for 350, 180, and 170 kW, respectively; nuclear power installed capacity reached 44.64 million kW [2]. Overall, China's non-fossil energy power installed capacity accounted for 40% of total installed energy capacity, and non-fossil energy consumption accounted for nearly 30%. The exceeding of the goals indicates that China has been an active participant in the global response to climate change. Addressing climate change is both an intrinsic need for China's sustainable development and a responsibility for building an increasingly dense human community. This contribution has laid a foundation for the

implementation of the 13th Five-Year Plan for controlling greenhouse gas emissions and meeting the intended nationally determined contribution (INDC) objectives on climate change by 2030.

Although China has made remarkable achievements in tackling climate change, the total amount of CO<sub>2</sub> produced by the burning of fossil energy deserves attention. According to the data provided by the 13th Five-Year Plan for Power Development (2016–2020) [3], the coal-fired power industry emitted 3.476 billion tons of CO<sub>2</sub> into the air in 2016, and the total national carbon emissions in that year was 10.151 billion tons. The CO<sub>2</sub> generated by the coal-fired power industry accounts for more than 34.24% of the total CO<sub>2</sub> emissions in the country. Due to current economic and technical constraints, non-fossil energy power generation in China still cannot completely replace coal-fired power generation. By the end of 2018, the installed capacity of coal-fired power was 1.14 billion kW, accounting for 60.00% of the national installed capacity [2]. In addition to adopting clean coal technology and terminal treatment technology to control the cleanliness of coal-fired power generation, another method to effectively reduce carbon emissions is the cleaning of coal-fired dispatch units.

Traditional power dispatching mainly relies on economic cost as the basis for decision-making, which is also called economic dispatch [4]. Given the need for environmental protection and sustainable development, environmental aspects must be considered in power dispatch, especially the pollutants that are mainly regulated by the environmental protection department. King et al. proposed a multi-objective dispatching model to minimize both the cost function and the emission functions simultaneously, and selected SO<sub>2</sub> and NO<sub>x</sub> as the main environmental constraints [5]. Sáenz et al. proposed a two-stage economic and environmental load dispatching framework to reliably meet the demand at the lowest possible cost and to minimize emissions and other environmentally adverse effects [6]. Kerl et al. integrated fluctuating pollutant information into an electricity dispatching plan to encourage power plant including environmental impacts into cost-base decisions [7]. Liang et al. emphasized the importance of grid energy saving and environmental protection dispatching by constructing an energy saving and environmental protection dispatching (ESEP) model [8]. Goudarzi et al. proposed a combined environmental economic dispatch model, the model took NO<sub>x</sub> emission as the environmental consideration [9]. Zhang et al. proposed prioritizing the generator sets according to the energy consumption level, and then dispatching fossil energy generator sets according to the pollutant discharge level [10]. Li et al. analyzed real-time power system dispatch together with thermal power generators and wind power by taking the advanced adiabatic compressed air energy storage (AA-CAES) as an important scheduling resource [11]. Frigura-Iliasa et al. applied a modified tabu search algorithm to environmental and economic scheduling problems to optimize generator units' allocation and reduce total fuel cost [12]. Zhang and Wang proposed a hierarchical and distributed coordinated multi-source optimal dispatch scheme for a power system with a high proportion of renewable energy to improve the power grid operation economy and the ability to accommodate renewable energy [13].

However, only some pollutants (mainly NO<sub>x</sub> and SO<sub>2</sub>), regulated by the environmental protection department, are restricted in the power dispatch model, whereas electricity production can emit many other pollutants. In addition to pollutants that already have stated emission limits, other substances indirectly impact on the environment but have no clear emission limits, such as CO<sub>2</sub>. According to the Global Energy and CO<sub>2</sub> Status Report published by the international energy agency (IEA) in 2019, CO<sub>2</sub> emissions from electricity production account for nearly two-thirds of total CO<sub>2</sub> emissions [14]. If CO<sub>2</sub> is not controlled, coal-fired power generation will significantly impact the ecological environment. Although no separate carbon emission limitation requirement exists in the power dispatch field in China, several reports provide methods on carbon emission standards of power plants and other production systems. Karmaker et al. calculated and analyzed greenhouse gas emissions from the existing fossil fuel power plants in Bangladesh using Hybrid Optimization of Multiple Energy Resources (HOMER) software [15]. Chang et al. mapped the overall carbon budget of a metropolitan area following a statistical analysis of the numerical data and urban space information, and adopted the Taichung metropolitan area as the research target to assess carbon

emissions with respect to buildings, traffic, and carbon sinks [16]. Töbelmann and Wendler examined the effects of environmental innovation on CO<sub>2</sub> e emissions in the EU-27 countries between 1992 and 2014, and evaluated environmental innovation contribution to reductions in CO<sub>2</sub> emissions [17]. Hwang-Hee et al. calculated CO<sub>2</sub> emissions in materials and transportation stages, and evaluated CO<sub>2</sub> emissions from porous concrete at different production stages [18]. Brand et al. evaluated the effects of providing new infrastructure for walking and cycling on CO<sub>2</sub> emissions compared with motorized travel using a questionnaire survey [19]. Balbaa et al. examined how the optimum ports' commitment operation can be used to reduce CO<sub>2</sub> emissions that are released from the electrical power generation that meets the needs of the seaports [20]. Cheng et al. proposed a novel analytical model for carbon emission flow (CEF) in multiple energy systems (MES) to quantify the carbon emissions associated with the energy delivery and conversion process [21]. Yu et al. recalculated the carbon emissions from land use in the U.S. reported by national statistics using food and agriculture organization statistics (FAOSTAT)-based global land use harmonization (LUH2) data and a new high-resolution multisource harmonized national land use and land cover change (LULCC) database (YLmap) [22]. Wang et al. established the improved gray wolf optimizer and support vector machine (IGWO-SVM) model to quantitatively analyze and predict carbon emissions with different degrees of coordination [23].

The common feature of the above studies is constraining the decision behavior of power dispatch from the perspective of negative output (air pollutants). Power dispatch is a complex decision, so all inputs and outputs need to be considered together. Therefore, a comprehensive analysis method that covers all inputs and outputs of the system is needed. The comprehensive analysis methods in the environmental aspects mainly include life cycle assessment (LCA), analytic hierarchy process (AHP), and ecological footprint (EF).

LCA is a broadly applied decision support tool used to assess the potential environmental impacts and resource use of a system throughout its life cycle (cradle-to-grave). The LCA has successfully been applied to integrate environmental issues like climate change and cleaner production [24]. Blackett et al. used LCA to determine the environmental impacts of materials used in various stages of high voltage transmission in different national grid systems [25]. Roy et al. applied LCA to improve the production process by comprehensively evaluating the environmental impacts of different stages of food production, and clarified the link that most impacted the environment [26]. Cherubini et al. paid attention to the waste management stage in industrial production and introduced various schemes for waste disposal to minimize environmental pollution by applying LCA [27]. Turconi et al. used LCA to quantify the potential environmental impacts of different types of power generation at different life cycle stages [28]. Olivares et al. compared the environmental impact of a solar air conditioning cooling system and a commercial cooling system in each life cycle stage from construction, operation, to end of life, and found that the use of a solar cooling system can significantly reduce the impact on the environment [29]. However, the final results of LCA are based on subjective evaluations as LCA leaves the choice of the impact assessment to the analyst [30].

AHP is a decision-making method that divides elements related to cleaner production into objectives, criteria, and schemes, and is used to conduct qualitative and quantitative comprehensive analysis. Researchers have completed in-depth analyses in multiple industries. Tseng et al. used AHP to discuss how different decision criteria (such as organization, system and technology, measurement, and feedback) affect the efficiency of cleaner production during the manufacturing process of water pressure plates in the hydropower industry [31]. Tong et al. adopted AHP to formulate a comprehensive index system of water saving and waste reduction in the textile printing and dyeing industry [32]. However, weighting scoring systems are often based on expert judgement and can sometimes be extremely biased, so the fuzzy analytic hierarchy process (FAHP) model was introduced. Peng and Li used the FAHP model to evaluate cleaner production in the aviation industry and to identify the causes of high energy consumption and pollution [33]. Jia et al. established a comprehensive index framework and evaluated the cleaner production in the vanadium extraction industry using the FAHP model [34]. Zhu and Huang used the FAHP model to analyze the production of the fuel ethanol industry in terms

of production technology characteristics, resource and energy use, comprehensive use, and pollutant generation [35]. Canan et al. evaluated the sustainability of grid electrolysis (electricity from fossil fuels), wind electrolysis, photovoltaic (PV) electrolysis, nuclear thermochemical water splitting cycles, solar thermochemical water splitting cycles, and photoelectrochemical cells using fuzzy AHP [36].

Another commonly used comprehensive evaluation method is the ecological footprint (EF) method, which is used to convert the resources consumed and the waste produced into a unified ecological productive area to quantitatively describe and evaluate the carrying capacity of the regional environment and the degree of sustainable development. Chavezrodriguez et al. compared the greenhouse gas emissions of four fossil fuels (ethanol in sugarcane, ethanol in corn, gasoline in traditional crude oil, and gasoline in oil sands) to determine the low-carbon cleanliness of different fossil fuels by applying EF method [37]. Cerutti et al. used a fruit production system as an example and quantified the environmental impacts associated with four different units based on the EF method [38]. Mikulčić et al. used the EF method to measure energy consumption and CO<sub>2</sub> emissions from different cement production processes [39]. Guerrero et al., selecting the urbanization and housing construction in Andalusia as an example, calculated the ecological footprint of the construction projects in the stages of urbanization, construction, decoration, or demolition, and then used the general language in the industry to control the environmental impact [40]. However, the EF method is based on a single indicator compared to the AHP model, so fails to comprehensively depict the sustainability aspects of a system.

Although the above comprehensive evaluation methods achieve the synthesis from different perspectives, synthesizing all inputs and outputs is difficult because the analyzed objects cannot be summed up. The emergy analysis method established by Odum [41] effectively solves the above problem. Emergy analysis is a method based on thermodynamic laws, general system theories [42], energetics [43], and measuring both the productivity of natural resources and human socio-economic resources. To conduct an emergy analysis, a system is converted into a network of energy streams and a measure of solar emergy assigned to energy flows [44]. Solar emergy represents the total amount of available solar energy that was directly or indirectly used to generate or support a given product or service, and it is calculated in solar equivalent joules (sej) [45].

Since the beginning of the 21st century, emergy analysis has been widely used in environmental impact assessment. Liu et al. used emergy analysis to quantitatively measure the ecological environmental losses caused by industrial solid waste (ISW) and provided recommendations on how to properly determine ecological compensation standards [46]. Geber and Björklund used emergy analysis to compare the resource requirements of different wastewater treatment systems [47]. Nimmanterdwong et al. applied emergy analysis to evaluate the CO<sub>2</sub> capture process from a sustainability perspective [48].

Since the emergy analysis method can be used to comprehensively evaluate economic factors and environmental factors, some scholars applied emergy analysis to measure the cleanliness of industry systems, such as the power industry. Caruso et al. used the emergy function to evaluate the cleanliness of the Italian power system [49]. Luo and Ding used emergy analysis to evaluate the energy purification of biomass power generation systems [50]. Riposo evaluated the cleanliness of wind power production using emergy theory [51].

However, emergy analysis was originally designed to be applied to ecological systems. Due to the natural differences between industrial and ecological systems, improving the suitability of the emergy indices for sustainability analysis and the evaluation of industrial systems is necessary [52]. Environmental load rate (ELR) and emergy sustainability index (ESI) are a pair of commonly used emergy indicators reflecting the environmental load and sustainability capability of the system. Due to their universality and applicability, scholars have improved and applied these indicators. Mu et al. stated that traditional ELR is not consistent with the notion that implementing waste management should lead to less environmental stress, and accounted for investment of waste treatment by improving the ELR indicator [53]. Lu et al. proposed that the quality and energy of waste discharged from

industrial systems also have a certain value, and improved ELR and ESI to better evaluate the sustainability of industrial systems [54]. Ma et al. explored the sustainability of the steel production system and classified ELR and ESI in a more detailed group [55]. The most important characteristic of emergy analysis is that it can be used to develop a link between economic and ecological systems. This method can integrate different types of inputs and outputs from the perspective of material flow to lay a methodological foundation for the production cleanliness evaluation of clean energy.

In the existing power dispatch method, environmental aspects are the important factors that restrict power dispatch decisions. However, power dispatch encounters the following problems when considering environmental aspects: (1) due to the complexity of environmental factors, only a portion of environmentally regulated pollutants (mainly SO<sub>2</sub> and NO<sub>x</sub>) are used as emission constraints in current power dispatching models; (2) power dispatch model rarely considers emissions that indirectly impact the environment and have a high level of importance, such as CO<sub>2</sub>, because China's coal-fired power plants do not have clear carbon emission standards; (3) the environmental aspects of the power dispatch are relatively simple, with only minimum emissions as environmental constraints and long-term sustainability constraints are lacking; and (4) the final decision on power dispatch is economic cost, and a separate amount of environmental value for reference is lacking.

The purpose of this study was to construct a cleanliness evaluation model that can comprehensively reflect the coal-fired power generation environmental aspects, thus providing a reference for clean power dispatching. The main contributions of this paper are as follows: (1) the findings enrich the information on the environmental aspects of power dispatch, and carbon emission constraints and sustainability constraints based on existing environmental regulatory policy; (2) the model presented in this paper considers all pollutants that are currently regulated by the Chinese environmental protection department; (3) in the absence of clear carbon emission standards, we calculated the upper limit of CO<sub>2</sub> emissions, so that CO<sub>2</sub>, which has no clear regulatory requirements but significantly impacts the environment, can be included in the power dispatch environmental constraints; and (4) we considered all the inputs and outputs of the coal-fired power plant and built an emergy-based environmental value added (EEVA) value that comprehensively reflects the production cleanliness, providing a separate environmental value for power dispatch.

The rest of the paper is organized as follows: Section 2 introduces the method used and the case study background, Section 3 provides the results of the case study and relevant discussion, and Section 4 outlines the conclusion.

## 2. Materials and Methods

In this section, a comprehensive production cleanliness evaluation model for coal-fired power generation is constructed. The inherent logic of the model is that the unit must first meet three environmental constraints (pollutant concentration, carbon emission, and sustainability constraints) to participate in the clean dispatching plan. Only units that meet the three conditions simultaneously are eligible to participate in the cleaning dispatching plan. Secondly, the EEVA values of all units meeting the above constraints are calculated, and the production cleanliness is ranked according to EEVA values. Finally, the cleaning dispatcher arranges the power generation sequence according to the cleanliness of the units.

### 2.1. Background and Data Collection

We selected the CD Power Plant as a research target, located in Hebei Province, China. The CD Power Plant is a coal-fired combined heat and power (CHP) power plant, mainly supplying electricity for heating in North China and Southern Hebei. The CD power plant has two 600 MW subcritical units and two 660 MW supercritical units. It is a large and modern power plant with management with extensive experience. The power plant uses Shenfu low-sulfur coal and has high-efficiency electrostatic precipitator, and synchronously uses a flue gas desulfurization device to reduce the impact on the environment.

The main data of this paper were obtained from the 2018 Environmental Protection Operation and Pollutant Discharge Statistics Report, Environmental Statement, and Production Telecommunications Express provided by the CD Power Plant. Data on pollutant emissions were tested and certified by external environmental companies and monitored by the local environmental protection department. Financial data and production data were audited by Klynveld Peat Marwick Goerdeler (KPMG), one of the top four accounting firms in the world. The CO<sub>2</sub> emission data were calculated by a third-party organization according to the Requirements of the Greenhouse Gas Emission Accounting and Reporting (Part 1: Power generation enterprise).

## 2.2. Methods

In this study, the comprehensive production cleanliness evaluation model of coal-fired power generation was constructed using the emergy method. The model calculates the EEVA value of different power generating units based on three basic environmental constraints. Here, we define clean electric energy as low-pollution, low-carbon, and sustainable. This means that electricity production should not only meet the emission requirements of environmental protection departments, but also control carbon emissions and meet the requirements of sustainable development. Therefore, we adopted emission, carbon emission, and sustainability constraints as the basic environmental constraints. The following sections in this chapter provide a detailed description of the comprehensive production cleanliness evaluation model.

### 2.2.1. Environmental Constraints

#### Pollutant Concentration Constraint

In China's coal-fired power industry, environmental regulation plays an important role in increasing the cleanliness of production and clean energy development [56]. The environmental policy of China's coal-fired power industry is mainly the Emission Standard of Air Pollutants for Thermal Power Plants GB13223-2011 (hereinafter referred to as the Standard). The Standard is regarded as the most stringent environmental regulation standard in the history of the thermal power industry. The Standard stipulates corresponding emission requirements for both existing and new thermal power construction projects. The Standard specifies the upper limit of emission concentration for major atmospheric pollutants such as soot, SO<sub>2</sub>, and NO<sub>x</sub>.

The coal-fired power plant entrusts a third-party to measure the concentration of atmospheric pollutants and report it to the environmental protection department. Therefore, for constraint 1, the pollutant concentration monitoring report reported by the coal-fired power plant to the environmental protection department can be used as the basis for evaluation.

$$\text{Constraint 1 : } E_{dij} \leq \bar{E}_{dj}$$

where  $E_{dij}$  represents the emission concentration of pollutant  $j$  of generating unit  $i$  (mg/Nm<sup>3</sup>) and  $\bar{E}_{dj}$  represents the standard emission concentration of pollutant  $j$  according to the requirement of environmental regulation departments (mg/Nm<sup>3</sup>).

#### Carbon Emission Constraint

Unlike strict regulatory standards for air pollutant emissions, no universal regulatory policy exists for CO<sub>2</sub> emissions [57]. The accounting of China's coal-fired power plants' CO<sub>2</sub> only considers key enterprises, and they rely on enterprises to report data themselves [58]. The lack of stringent carbon policies has indirectly led to the lack of carbon capture technology in China's coal-fired power plants [59].

Talaq et al. suggested that the relationship between atmospheric pollutant emissions and unit output can be expressed as a quadratic function [60]. Zhang et al. proposed a CO<sub>2</sub> emission function

in the coal-fired unit electricity distribution optimization model [61]. Based on Talaq et al. [60] and Zhang et al. [61], we established a CO<sub>2</sub> emission upper limit model to calculate the maximum CO<sub>2</sub> emissions under certain unit output conditions. In the absence of CO<sub>2</sub> regulatory standards, the upper limit of CO<sub>2</sub> emissions from power plants can be based on the maximum emissions calculated from Model (1):

$$\begin{aligned} \max E &= \sum_{i=1}^n \sum_{t=1}^T (\alpha_i + \beta_i Q_{it} + \gamma_i Q_{it}^2) \\ \text{s.t. } &\begin{cases} Q_{i,\min} \leq Q_{it} \leq Q_{i,\max} \\ \sum_{i=1}^n \sum_{t=1}^T (\alpha_i + \beta_i Q_{it} + \gamma_i Q_{it}^2) \leq E^{\max} \end{cases} \end{aligned} \quad (1)$$

where  $E$  is the system CO<sub>2</sub> emission (kg);  $\alpha_i$ ,  $\beta_i$ , and  $\gamma_i$  are the CO<sub>2</sub> emission coefficient of unit  $i$  in t/h, t·MW<sup>-1</sup> h<sup>-1</sup>, and t MW<sup>-2</sup> h<sup>-1</sup>, respectively;  $Q_{i,\min}$  and  $Q_{i,\max}$  are the upper and lower limits of the unit's output per unit time (MW), respectively; and  $E^{\max}$  is the upper limit of the unit's CO<sub>2</sub> discharge in the period  $t$  (kg). The CO<sub>2</sub> emissions of different units are related to fuel quality, consumption, and whether decarbonization technology is used.

For the second condition, we used the CO<sub>2</sub> emission intensity (t/MWh) to constrain the limit of CO<sub>2</sub> emission. When the actual emission intensity exceeds the upper limit emission intensity, the CO<sub>2</sub> emissions do not meet the standard.

$$\text{Constraint 2 } E_{ci} \leq \bar{E}_{ci}$$

where  $E_{ci}$  indicates the CO<sub>2</sub> emission intensity of generating unit  $i$  (t/MWh) and  $\bar{E}_{ci}$  represents the upper limit of the CO<sub>2</sub> emission intensity of generating unit  $i$  (t/MWh).

### Sustainability Constraint

Although electricity is a relatively clean and safe source of energy, its production processes cause direct or indirect environmental pollution [62], such as emissions of air pollutants, greenhouse gases, and solid waste from coal-fired power generation. The advantage of the emergy analysis is that all the substances consumed and produced by the coal-fired power generation process can be converted into the same unit through the emergy transformations. The emergy analysis lays a measurement basis for the comprehensive evaluation of the production cleanliness of coal-fired power generation. Emergy is calculated by multiplying the unit of a product or service by the transformation, as shown in Equation (2):

$$U = \sum_{i=1}^n E_i \times Tr_i \quad (2)$$

where  $U$  is the total emergy calculated over all independent input flows (sej),  $E_i$  is the available energy or exergy, and  $Tr_i$  is the solar transformation of the  $i$ th input flow of a product or service (sej/units).

The research target was a coal-fired power electricity production system, as shown in Figure 1, whose boundary is the area of the coal-fired power electricity plant. Coal-fired power production consumes many resources and generates various wastes. Based on the emergy algorithm, we abbreviate the renewable resources as  $R$ , the non-renewable resources as  $N$ , resources from human economic system as  $F$ , and the product for human economic system as  $Y$ . By converting different materials into uniform units, all materials in the system can be added, enabling the construction of comprehensive emergy evaluation indices. Figure 1 shows a schematic of the emergy framework for a system.

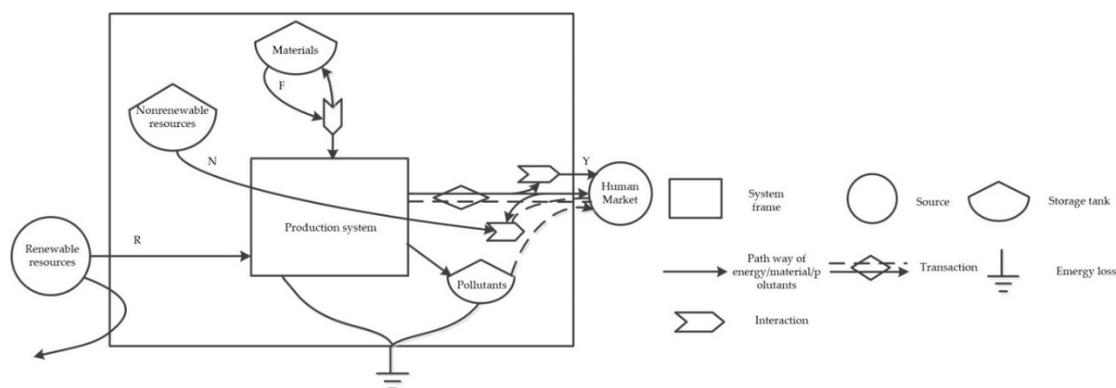


Figure 1. Energy analysis map.

The global energy baseline calculated by Odum is  $9.44 \times 10^{24}$  sej/year [41]; Odum updated the data to  $15.83 \times 10^{24}$  sej/year [63]. The emergy transformation is based on Odum's research in 2000 and subsequent studies [64–66], or multiplied by 1.68 based on Odum's 1996 research results.

A key step in the emergy evaluation process is to calculate emergy indices. Among the basic emergy indices proposed by Brown and Ulgiati [67], the indices reflecting the environmental sustainability are mainly EYR, ELR, and ESI. The formulas for these indices are shown in Table 1.

Table 1. Traditional emergy indicators.

Emergy Indices	Formula
EYR	$Y/F$
ELR	$(F + N)/R$
ESI	$EYR/ELR$

EYR is the ratio of the total output emergy  $Y$  to the input emergy  $F$ . It is an indicator of the efficiency of input and output. The ELR is the environmental loading ratio, which reflects the pressure on the local ecological environment due to production activities. ESI is the environmental sustainability indicator; the higher the ESI, the higher the sustainability of the system.

However, as an analytical method of ecological economics, the above-mentioned emergy indicators have certain limitations when applied to industrial ecological analysis. First, the emergy analysis assumes that all inputs are positive. In industrial ecosystems, some systems are waste and sewage treatment systems, the input of which is a harmful negative output, playing an environmental value-adding role in the process of converting a negative output into a positive output. For the above production system, the input is theoretically expected to be larger than the output, so the result of the conventional EYR may be different from the actual situation. Second, for the general ecosystem, the total output ( $Y$ ) is positive and less waste is produced, so traditional emergy indicators can be used to evaluate the efficiency of the ecosystem. However, industrial systems produce a portion of waste and pollution emissions while producing positive outputs. If waste and pollution emissions are included in  $Y$ , the output emergy may be too optimistic because the output  $Y$  contains some invalid emergy.

The traditional output emergy  $Y$  containing part of the invalid emergy (waste and emission) leads to the contradiction between emergy analysis and industrial sustainability analysis. In this paper, when measuring the environmental impact and environmental sustainability of industrial systems, the total output  $Y$  is recalculated using the EEVA as shown in Equation (3). The EEVA value is determined by dividing the environmental value created by the system into two parts: the value that is beneficial to

the ecological environment, and the environmental load that is harmful to the ecological environment and requires environmental management.

$$EEVA = \sum_{i=1}^n NPEOAT_i - \sum_{j=1}^n NNEO_j \tag{3}$$

where EEVA is the system environment adding value measured using energy (sej), NPEOAT<sub>i</sub> (net positive emergy output after treatment) indicates the positive output emergy after environmental treatment (including positive products and other environments) (sej), and NNEO<sub>i</sub> (net negative emergy output) is the emergy of the *i*th negative output (sej).

Based on Peng and Li [25] and Pan et al. [55], we improved the traditional emergy indices based on the EEVA value for the production cleanliness evaluation of the coal-fired power industry, as shown in Table 2.

**Table 2.** Improved emergy indices. EEVA, emergy-based environmental value added.

Improved Emergy Indices	Implications	Formula
IEYR	Improved emergy yield ratio	EEVA/(R + N + F)
IELR	Improved environmental loading ratio	(N + R)/EEVA
IESI	Improved environmental sustainability ratio	IEYR/IELR

To prevent coal-fired power units from neglecting long-term environmental sustainability in pursuit of short-term production targets, we used emergy indices to assess the environmental sustainability of coal-fired power plants. This is the ratio of emergy-based environmental value added (EEVA) to all environmental inputs which include renewable resources (R), non-renewable resources (N) and resources from human economic system (F). It is a short-term production efficiency indicator. IELR is the ratio of total natural resource input including renewable resources (R) and non-renewable resources (N) to emergy-based environmental value added (EEVA). IESI is the ratio of IEYR to IELR and represents a long-term environmental sustainability indicator. From the perspective of sustainable development and environmental regulation, coal-fired power units should not increase production efficiency at the expense of long-term environmental sustainability. Therefore, the criteria for judging the condition can be achieved by comparing the relationship between IESI and IEYR.

$$\text{Constraint 3 : } IEYR_i \leq IESI_i$$

where IEYR<sub>i</sub> is the improved emergy yield ratio of generating unit and IESI<sub>i</sub> is the improved emergy sustainability index of generating unit *i*.

### 2.2.2. Comprehensive Production Cleanliness Evaluation Model

After the coal-fired power unit meets the above three constraints, it is ranked according to the unit EEVA value, and the unit with the largest unit EEVA value receives the priority power generation rights. Based on environmental constraints 1–3 and emergy theory, we established a coal-fired power unit production cleanliness evaluation model:

$$EEVA = \sum_{i=1, g=1} NPEOAT_{ig} - \sum_{i=1, q=1} NNEO_{iq}$$

$$\text{s.t. } \begin{cases} E_{dij} \leq \bar{E}_{dj} \\ E_{ci} \leq \bar{E}_{ci} \\ IEYR_i \leq IESI_i \end{cases} \tag{4}$$

where  $NPEOAT_{ig}$  represents the emergy of positive output  $g$  of generating unit  $i$ ,  $NNEO_{iq}$  represents the emergy of negative output  $q$  of generating unit  $i$ ,  $E_{dij}$  represents the emission concentration of pollutant  $j$  of generating unit  $i$  ( $\text{mg}/\text{Nm}^3$ ),  $\bar{E}_{dj}$  represents the standard emission concentration of pollutant  $j$  according to the requirement of environmental regulation departments, ( $\text{mg}/\text{Nm}^3$ ),  $E_{ci}$  indicates the  $\text{CO}_2$  emission intensity of generating unit  $i$  ( $\text{t}/\text{MWh}$ ),  $\bar{E}_{ci}$  represents the upper limit of the  $\text{CO}_2$  emission intensity of generating unit  $i$  ( $\text{t}/\text{MWh}$ ),  $IEYR_i$  represents the improved emergy yield ratio of generating unit  $i$ , and  $IESI_i$  represents the improved emergy sustainability index of generating unit  $i$ .

### 3. Results and Discussion

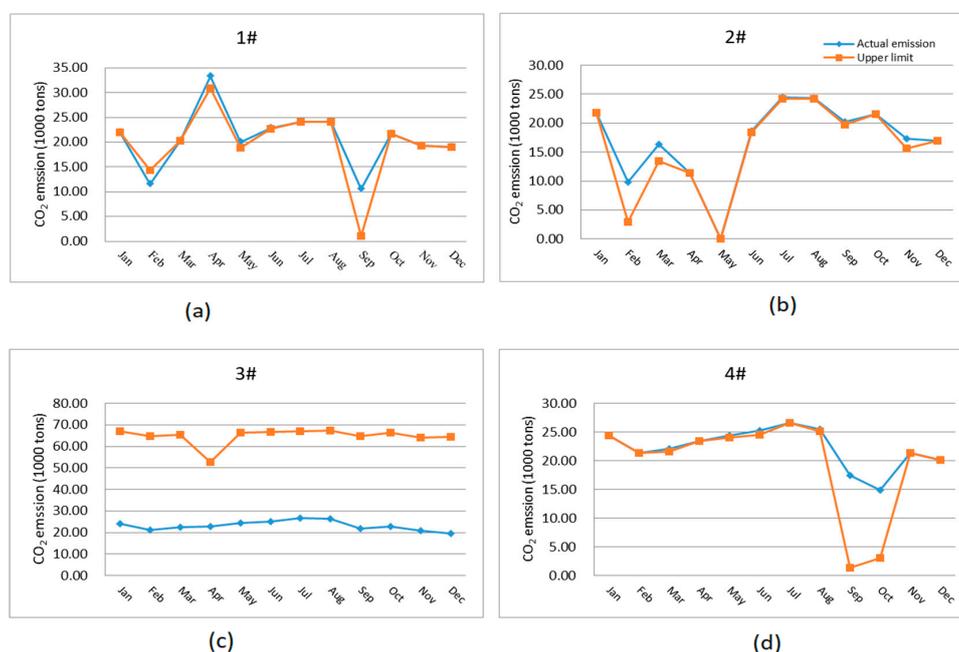
This section provides the calculation results and discussion of the coal-fired power production cleanliness evaluation model. The cleanliness of the coal-fired power unit is evaluated based on the whether it is clean, low-carbon, and sustainable, and then the production cleanliness is ranked according to the environmental added value created by the coal-fired power unit. Therefore, we first calculated three constraints that reflect sustainability: the concentration of pollutants, the intensity of carbon emissions, and the compliance of emergy indices. Among them, the pollutant regulation standard is the basis for judging whether the coal-fired power production meets the policy requirements of the environmental regulation department. At present, the requirements of the environmental regulation department for coal-fired power plants are mainly reflected in the concentration of atmospheric pollutant discharge. However, no regulatory standards exist for carbon emissions. In the absence of carbon emission regulation policies, Model (1) is used to calculate the theoretical upper limit of  $\text{CO}_2$  emissions under certain working conditions, and we compared it with actual emissions to determine whether carbon emissions exceed the standard. In judging whether coal-fired power production meets environmental sustainability requirements, we used the emergy analysis method to convert all input and output materials into the same unit of measurement, and analyzed emergy using improved emergy indices, as shown in Table 2.

As shown in Table 3, the concentration of atmospheric pollutants discharged by the four units was far below the environmental regulation standards because the power plant has undertaken ultra-low emission modification of environmental treatment equipment for the above-mentioned air pollutant discharge process.

Table 3. Air pollutant discharge.

$E_{dij}$												$\bar{E}_{dj}$	
Soot ( $\text{mg}/\text{Nm}^3$ )													
Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1	1.5	1.98	1.98	1.56	2.26	2.29	2.12	2.16	2.04	2.05	1.91	1.75	30
2	1.3	1.00	1.00	1.83	/	2.47	2.47	2.36	1.67	1.74	2.61	2.61	
3	1.23	1.15	1.15	1.31	1.54	1.72	1.73	2.18	1.50	2.26	2.22	2.54	
4	1.34	1.55	1.55	2.04	2.27	2.35	2.49	2.53	1.85	6.71	1.99	1.95	
SO <sub>2</sub> ( $\text{mg}/\text{Nm}^3$ )													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1	16.41	17.47	17.47	14.18	16.84	18.11	17.07	16.98	14.46	14.81	16.57	17.47	100
2	17.33	17.43	17.43	16.83	/	15.11	14.42	14.43	11.00	14.14	14.57	15.26	
3	18.88	19.09	19.09	22.76	23.47	20.30	24.11	20.66	18.04	21.84	22.20	25.04	
4	16.38	14.82	14.82	16.16	17.88	17.57	20.43	18.98	18.65	17.63	17.31	19.36	
NO <sub>x</sub> ( $\text{mg}/\text{Nm}^3$ )													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1	27.63	25.16	25.16	30.27	31.81	30.15	22.9	24.85	28.59	28.5	27.34	23.18	200
2	23.98	72.8	72.8	28.64	/	31.19	24.25	24.31	22.73	26.59	24.52	19.99	
3	27.86	26.44	26.44	34.06	33.47	31.45	28.51	31.22	31.49	37.89	36.54	36.7	
4	29.87	27.06	27.06	35.2	34.56	36.45	39.3	40.7	38.18	217.64	30.02	26.02	

In this study, we used Lingo software to calculate the upper limit of CO<sub>2</sub> emission under certain working conditions. The calculation results are shown in Figure 2, the relevant performance parameters of the units are shown in Table 4.



**Figure 2.** Actual CO<sub>2</sub> emissions and CO<sub>2</sub> upper limits. Note: (a)Actual CO<sub>2</sub> emissions and CO<sub>2</sub> upper limits of unit 1, (b)Actual CO<sub>2</sub> emissions and CO<sub>2</sub> upper limits of unit 2, (c)Actual CO<sub>2</sub> emissions and CO<sub>2</sub> upper limits of unit 3, (d)Actual CO<sub>2</sub> emissions and CO<sub>2</sub> upper limits of unit 4.

**Table 4.** Performance parameters of the units.

Unit Number	Unit Capacity (MW)	Coal Consumption Rate (g/KW h)	Unit Output		Unit Emission Parameter		
			Minimum Output (MW)	Maximum Output (MW)	$\alpha$ (t/h)	$\beta$ (t MW <sup>-1</sup> h <sup>-1</sup> )	$\gamma$ (t MW <sup>-2</sup> h <sup>-1</sup> )
1	600	281.82	350	600	593,830.338	-2871.238	4.278
2	600	282.05	300	600	149,738.287	-463.955	1.203
3	660	290.03	370	660	97,159.567	-3333.705	3.583
4	660	288.49	370	660	1,248,820.644	-4609.993	4.966

Figure 2 shows that the actual CO<sub>2</sub> emissions of unit 1 exceeded the emission limit in April, May, June, and September. Since unit 2 was shut down for maintenance in May, no carbon dioxide was emitted during the month. However, the CO<sub>2</sub> discharge of unit 2 exceeded the upper limit in seven months of the year. The actual CO<sub>2</sub> emissions of unit 4 exceeded the emission limit in March, May, June, August, September, and October. Compared with the above three units, unit 3 did not have excessive carbon dioxide emissions at any point in the year.

Since China does not have regulations for CO<sub>2</sub> emissions in the electricity industry, the above calculation results provide a basis for evaluating the performance of coal-fired power carbon emissions and lay a foundation for the comprehensive evaluation of coal-fired power production cleanliness. As shown in Table 5, except for unit 3, the CO<sub>2</sub> emissions of other units were not up to standard within one year, which means that the above units are not allowed to participate in the cleaning schedule during that month. Among them, unit 1 showed non-compliance in April, May, and September. The carbon emissions of unit 2 were the worst because the unit did not meet carbon emission standards for seven of the 12 months. The situation of unit 4 is slightly better than that of unit 2, which has a carbon emission intensity that did not exceed the standard for half the year. Compared with the above three units, unit 3 met carbon dioxide emission standards throughout the whole year.

Table 5. CO<sub>2</sub> emission intensity.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1#												
Actual Emission Intensity (t/MWh)	0.701	0.749	0.743	0.423	0.725	0.732	0.737	0.736	0.752	0.686	0.735	0.682
Upper Limit Intensity (t/MWh)	0.701	0.929	0.743	0.393	0.688	0.728	0.737	0.736	0.081	0.686	0.735	0.682
2#												
Actual Emission Intensity (t/MWh)	0.695	0.749	0.746	0.139	0.000	0.729	0.733	0.736	0.747	0.685	0.729	0.666
Upper Limit Intensity (t/MWh)	0.695	0.220	0.616	0.139	0.000	0.721	0.725	0.731	0.728	0.685	0.662	0.666
3#												
Actual Emission Intensity (t/MWh)	0.713	0.755	0.758	0.187	0.740	0.747	0.749	0.746	0.777	0.698	0.753	0.721
Upper Limit Intensity (t/MWh)	1.966	2.298	2.219	0.429	2.010	1.974	1.882	1.891	2.301	2.036	2.307	2.359
4#												
Actual Emission Intensity (t/MWh)	0.716	0.753	0.758	0.190	0.742	0.746	0.747	0.749	0.766	0.697	0.754	0.712
Upper Limit Intensity (t/MWh)	0.716	0.753	0.742	0.190	0.730	0.726	0.747	0.740	0.062	0.144	0.754	0.712

Table 6 demonstrates the raw data and emergy calculation results of four units in the year according to Equation (2). The emergy analysis method considers material input and economic input as well as all positive output and negative output.

As shown in Figure 3, electricity, limestone, and liquid ammonia are consumed the most in the total input emergy. Although the main raw material of coal-fired power generation is coal, the emergy consumption of coal is less than the total emergy input of the above three materials. This is mainly due to China's coal-fired power plants being currently installed or later rebuilt with environmental protection equipment to meet the requirements of the environmental regulation department. Therefore, in addition to the main raw material (coal), the plants also consume a large amount of resources for environmental management. The environmental protection equipment of the CD Power Plant mainly includes electric dust removal equipment, desulfurization equipment and denitration equipment. The CD Power Plant also adopts wet electrostatic precipitation (WESP) technology, selective catalytic reduction (SCR) technology, and limestone-gypsum desulfurization (FGD) technology to treat major coal-fired pollutants such as soot, NO<sub>x</sub>, and SO<sub>2</sub>.

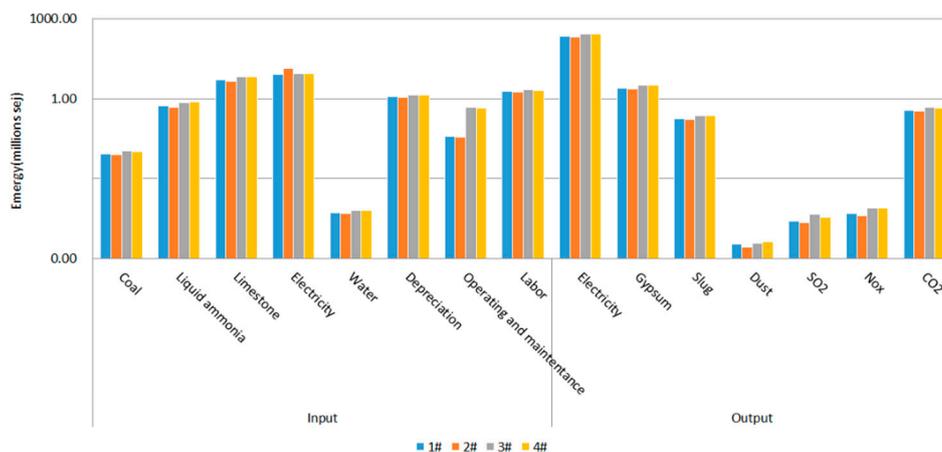


Figure 3. Emergy input/output analysis of coal-fired power units.

Table 6. Energy input/output results.

		1#		2#		3#		4#		
		Raw Data (Units)	Emergy (Sej)	Transformation (Sej/Unit)						
Input	Coal	$1.25 \times 10^{12}$	$8.38 \times 10^{16}$	$1.16 \times 10^{12}$	$7.76 \times 10^{16}$	$1.60 \times 10^{12}$	$1.07 \times 10^{17}$	$1.53 \times 10^{12}$	$1.02 \times 10^{17}$	$6.69 \times 10^{04}$ [54]
	Liquid ammonia	$3.73 \times 10^{08}$	$5.52 \times 10^{18}$	$3.18 \times 10^{08}$	$4.71 \times 10^{18}$	$4.91 \times 10^{08}$	$7.27 \times 10^{18}$	$5.04 \times 10^{08}$	$7.46 \times 10^{18}$	$1.48 \times 10^{10}$ [54]
	Limestone	$1.36 \times 10^{10}$	$4.97 \times 19$	$1.24 \times 10^{10}$	$4.50 \times 10^{19}$	$1.87 \times 10^{10}$	$6.79 \times 10^{19}$	$1.85 \times 10^{10}$	$6.73 \times 10^{19}$	$3.64 \times 10^{09}$ [54]
	Electricity	$5.03 \times 10^{14}$	$8.05 \times 10^{19}$	$8.32 \times 10^{14}$	$1.33 \times 10^{20}$	$5.23 \times 10^{14}$	$8.37 \times 10^{19}$	$5.48 \times 10^{14}$	$8.77 \times 10^{19}$	$1.60 \times 10^{05}$ [55]
	Water	$7.95 \times 10^{08}$	$5.28 \times 10^{14}$	$7.41 \times 10^{08}$	$4.92 \times 10^{14}$	$9.93 \times 10^{08}$	$6.59 \times 10^{14}$	$9.59 \times 10^{08}$	$6.37 \times 10^{14}$	$6.64 \times 10^{05}$ [55]
	Depreciation <sup>1</sup>	$3.54 \times 10^{06}$	$1.23 \times 10^{19}$	$3.30 \times 10^{06}$	$1.14 \times 10^{19}$	$4.00 \times 10^{06}$	$1.38 \times 10^{19}$	$3.83 \times 10^{06}$	$1.33 \times 10^{19}$	$3.46 \times 10^{12}$ [29]
	Operating and maintenance <sup>1</sup>	$1.11 \times 10^{05}$	$3.84 \times 10^{17}$	$1.03 \times 10^{05}$	$3.58 \times 10^{17}$	$1.34 \times 10^{06}$	$4.63 \times 10^{18}$	$1.28 \times 10^{06}$	$4.44 \times 10^{18}$	$3.46 \times 10^{12}$ [29]
Output	Labor <sup>1</sup>	$5.46 \times 10^{06}$	$1.89 \times 10^{19}$	$5.08 \times 10^{06}$	$1.76 \times 10^{19}$	$6.16 \times 10^{06}$	$2.13 \times 10^{19}$	$5.90 \times 10^{06}$	$2.04 \times 10^{19}$	$3.46 \times 10^{12}$ [29]
	Electricity	$1.36 \times 10^{16}$	$2.17 \times 10^{21}$	$1.25 \times 10^{16}$	$2.01 \times 10^{21}$	$1.68 \times 10^{16}$	$2.70 \times 10^{21}$	$1.63 \times 10^{16}$	$2.60 \times 10^{21}$	$1.60 \times 10^{05}$ [55]
	Gypsum	$2.53 \times 10^{10}$	$2.53 \times 10^{19}$	$2.38 \times 10^{10}$	$2.38 \times 10^{19}$	$3.28 \times 10^{10}$	$3.28 \times 10^{19}$	$3.20 \times 10^{10}$	$3.20 \times 10^{19}$	$1.00 \times 10^{09}$ [55]
	Slug	$5.84 \times 10^{09}$	$1.77 \times 10^{18}$	$5.58 \times 10^{09}$	$1.69 \times 10^{18}$	$7.44 \times 10^{09}$	$2.25 \times 10^{18}$	$7.43 \times 10^{09}$	$2.25 \times 10^{18}$	$3.02 \times 10^{08}$ [29]
	Dust	$2.05 \times 10^{07}$	$3.45 \times 10^{13}$	$1.63 \times 10^{07}$	$2.75 \times 10^{13}$	$2.22 \times 10^{07}$	$3.73 \times 10^{13}$	$2.48 \times 10^{07}$	$4.17 \times 10^{13}$	$1.68 \times 10^{06}$ [29]
	SO <sup>2</sup>	$1.53 \times 10^{08}$	$2.59 \times 10^{14}$	$1.35 \times 10^{08}$	$2.27 \times 10^{14}$	$2.72 \times 10^{08}$	$4.59 \times 10^{14}$	$2.15 \times 10^{08}$	$3.63 \times 10^{14}$	$1.69 \times 10^{06}$ [53]
	NO <sub>x</sub>	$2.96 \times 10^{08}$	$5.01 \times 10^{14}$	$2.46 \times 10^{08}$	$4.16 \times 10^{14}$	$4.56 \times 10^{08}$	$7.72 \times 10^{14}$	$4.56 \times 10^{08}$	$7.71 \times 10^{14}$	$1.69 \times 10^{06}$ [53]
CO <sup>2</sup>	$2.19 \times 10^{12}$	$3.71 \times 10^{18}$	$2.03 \times 10^{12}$	$3.43 \times 10^{18}$	$2.79 \times 10^{12}$	$4.7 \times 10^{18}$	$2.67 \times 10^{12}$	$4.51 \times 10^{18}$	$1.69 \times 10^{06}$ [53]	

<sup>1</sup> USD:CNY = 6.8812.

As shown in Table 7, through the calculation of emergy indices, we found that unit 4 had an IESI lower than IEYR in February, which indicated that the unit's environmental benefits in this month were lower than the economic benefits.

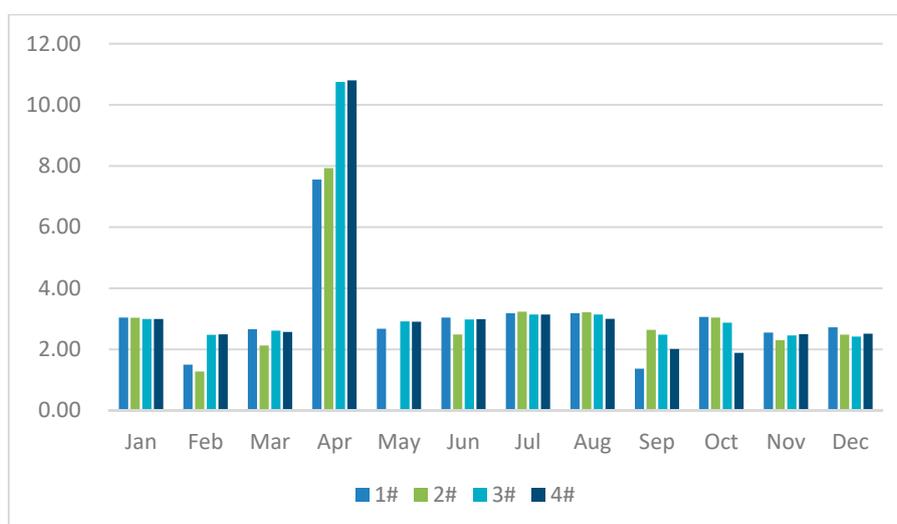
**Table 7.** Emergy indices.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1#	IEYR	10.49	10.15	10.62	53.00	10.49	11.39	11.27	10.56	10.67	12.19	11.99	10.43
	IESI	15.57	13.48	16.44	86.85	14.56	23.48	24.59	19.97	23.86	23.60	23.50	15.15
2#	IEYR	10.77	10.40	10.76	34.67	0.00	11.35	11.22	10.63	10.70	11.51	1.98	10.91
	IESI	15.26	13.05	16.02	54.53	0.00	23.63	24.85	19.79	23.44	23.22	39.88	15.02
3#	IELR	11.06	12.08	11.16	30.20	11.92	11.38	11.40	11.32	11.29	11.95	12.19	10.67
	IESI	11.88	17.47	13.48	31.55	14.85	16.57	18.88	17.76	18.80	16.46	16.94	12.02
4#	IEYR	10.99	9.85	11.21	29.10	11.08	10.81	10.95	10.72	10.65	11.89	11.34	10.41
	IESI	11.92	9.10	13.45	34.64	17.16	18.22	19.88	18.69	20.45	18.68	18.41	12.70

When the coal-fired power unit meets the above three constraints, it is eligible to participate in the evaluation of production cleanliness. We used EEVA values to measure the environmental added value of coal-fired power units. The EEVA value is also an emergy value, which is the embodiment of the environmental effects of production. Figure 4 and Table 8 show the unit EEVA values and comparisons for the four coal-fired power units. Through the above analysis, we identified months where the four units do not meet the constraints of the clean scheduling model. Therefore, from the perspective of clean dispatch, the units that do not meet the conditions are excluded from the monthly dispatching schedule, and the monthly cleanliness rankings of the four units are shown in Table 9.

**Table 8.** EEVA per unit ( $\times 10^{16}$  sej/MW).

Unit Number	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	3.04	1.50	2.66	7.56	2.67	3.04	3.18	3.18	1.37	3.06	2.55	2.72
2	3.04	1.28	2.13	7.93	0.00	2.49	3.23	3.21	2.64	3.04	2.30	2.48
3	2.99	2.48	2.61	10.75	2.91	2.98	3.14	3.14	2.48	2.87	2.45	2.42
4	2.99	2.49	2.57	10.80	2.90	2.99	3.14	3.00	2.01	1.89	2.50	2.51
Units with excessive CO <sub>2</sub> emissions		2	2 3	1	1 4	2 4	2	2 4	1 2 4	4	2	
Units with unqualified emergy indices		4										



**Figure 4.** Comparison of EEVA ( $\times 10^{16}$  sej/MW).

**Table 9.** Monthly production cleanliness rankings.

Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	2	1	\	\	1	1	1	\	1	1	1
2	1	\	\	3	\	\	\	\	\	2	\	3
3	2	1	\	2	1	2	2	2	1	3	3	4
4	2	\	2	1	\	\	2	\	\	\	2	2

As shown in Table 9, unit 1 had the highest production cleanliness ranking for eight months. Unit 2 ranked first with unit 1 only in February. The main reason for this finding is the unqualified CO<sub>2</sub> emission performance of unit 2. Unit 4 ranked first only in April. In addition to carbon emissions not meeting standards in most months, the February emergy indices did not meet sustainability requirements.

In addition, we found that because the environmental regulation department has clear requirements for the concentration of atmospheric pollutants, coal-fired power plants have installed environmental protection facilities to meet the requirements of relevant environmental regulation policies, although environmental protection management activities will incur additional costs. As a result, the concentration of air pollutants is rarely exceeded. Conversely, due to the lack of regulation of carbon dioxide, no mandatory carbon dioxide emission standard exists, so the coal-fired emissions of coal-fired power units are not controlled. We also found that the above-mentioned units achieved sustainable production in all other months except for one unit that did not meet the sustainability requirements in February, indicating that the sustainable production capacity of the coal-fired power units is generally strong. Through emergy analysis, we found that no wastewater is produced in the negative output because the plant uses advanced sewage treatment technology and water circulation technology to achieve 100% recycling of industrial wastewater, which is zero industrial wastewater emission. Second, atmospheric emissions are also extremely low due to environmental regulations. The power plant's fly ash and other solid waste and gypsum by-products have stable recycling manufacturers (mainly sold to cement companies and the construction industry for secondary use). Therefore, the total negative output of the coal-fired power plant is low, and the environmental load caused by the coal-fired power units is small, so the sustainability level is high.

#### 4. Conclusions

Although power dispatch is aware of the importance of the environment, due to the complexity of the environmental elements, power dispatch is concerned with the uniqueness and incompleteness of the environment. This paper proposed a comprehensive evaluation model for determining the cleanliness of production to provide a comprehensive environmental indicator for power dispatch.

We selected a representative coal-fired power plant in China that has four generator units as a research case. According to the comprehensive production cleanliness evaluation model, the cleanliness levels of the four generator units were ranked from the perspective of clean power dispatch. First, we analyzed three environmental constraints and found that not all generating units were eligible to participate in the clean power dispatch schedule. Power generating unit 2 was constantly exceeding carbon emissions for nearly half of the year, whereas unit 4 was the only unit that did not meet the sustainability constraints. By further calculating the EEVA value, we found that unit 1 achieved clean power dispatch participation rights for nine months of the year, and had the highest EEVA value for eight of those months, which indicates that unit 1 has a considerably better clean power dispatch. Although unit 3 received 11 months of participation rights, its EEVA value only ranked first for three months. We found that when environmental regulatory departments have clear emission standards for pollutant emissions, coal-fired power plants try to control the emissions of these pollutants (NO<sub>x</sub>, SO<sub>2</sub>, and dust). However, for emissions that are not explicitly limited but significantly impact the environment (CO<sub>2</sub>), coal-fired power plants have not applied strict measures, which may cause coal-fired power plants to adopt technological means to transfer the emission medium or change the emission form of pollutants.

The research results provide a reference for clean power dispatch in the power industry and could help power companies to more effectively achieve environmental management and improve clean production capacity to improve market competitiveness in the electricity market. Finally, the comprehensive evaluation method proposed in this paper could help guide environmental regulators to develop more targeted environmental regulation policies.

Future research can be conducted in the following three areas: First, scholars can combine economic analysis with technical research to further explore the regulatory standards for CO<sub>2</sub> emissions. Second, the emergy analysis can be applied throughout the life cycle to explore the environmental value-added potential of each stage of production, and to further improve the clean production capacity by evaluating the level of production cleanliness at different life cycle stages. Third, future research could expand this model to renewable energy generation such as hydropower and wind power. By comprehensively evaluating the production cleanliness of different power generation types, a reference for clean dispatching plans of regional power grids could be created.

**Author Contributions:** T.L. and Y.S. designed the research; Y.S. completed the calculations and analyzed the data; Y.S. wrote the original draft; Y.S. and J.S. reviewed and edited the paper. All authors have read and approved the final manuscript.

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