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A Study of Carbon Emission Driving Factors of a Metal Chemical Enterprise in China Based on the LMDI Model

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Abstract: The chemical industry is a typical high-carbon emitting industry, and achieving the goal of net zero emissions by 2050 is challenging. Therefore, metal chemical enterprises have to explore a special path of low-carbon development. This article conducted a case study on a Chinese metal chemical production enterprise with a processing scale of 28,000 t/year. Starting from the analysis of energy consumption carbon emissions, this article used available statistical data at the enterprise level to build a carbon emission estimation model for the enterprise combining different emission categories. Moreover, we also calculated the carbon emissions and carbon emission intensity of the enterprise from 2014 to 2022. Further quantitative analyses on the impact of production scale, energy efficiency, energy structure, and emission coefficient on carbon increment were also conducted using a logarithmic mean divisia index (LMDI) model. The results showed that the reduction in carbon emissions of the enterprise during the research period was due to the improvement of energy efficiency, while the production scale and energy structure served as important driving factors. Based on the results, this article proposes some policy suggestions on the future direction and focus of the enterprise's carbon reduction work.

Keywords: carbon accounting; energy consumption; energy conservation and emission reduction; factor analysis

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1. Introduction

According to the Sixth Assessment Report (AR 6) [1] of the Intergovernmental Panel on Climate Change (IPCC), the concentration of greenhouse gases reached an annual average amount of 410 ppm of carbon dioxide in 2019, and it has been continuously rising since 2021, mainly due to direct emissions from fossil fuel combustion. It is imperative to achieve the Paris Agreement's goal of controlling the temperature increase within 1.5 °C, and building a sustainable low-carbon future, even to meet net-zero CO_2 emissions by around 2050 [2]. According to statistics, China's carbon emissions reached 9.83 billion tons in 2019, accounting for 28.8% of total global carbon emissions [3]. China faces the double challenge of reducing CO_2 emissions and ensuring economic growth simultaneously. In this context, in September 2020, China proposed a "double carbon" target, aiming to achieve "carbon peaking" by 2030 and "carbon neutrality" by 2060 [4]. China's chemical industry is booming as a result of its rapid economic growth, and greenhouse gas emissions (GHG) will further rise in the near future [5]. The chemical industry is closely related to human life, including more than 95% of manufactured products [6]. Undoubtedly, the chemical industry consumes a huge amount of energy, pollutes the environment, and increases GHG emissions. As of 2013, the chemical industry accounted for 5.5% of the world's CO_2

emissions and 17% of industrial CO_2 emissions [7], which is the third-largest source of industrial emissions [8]. In the processes of production, consumption, and other aspects, the chemical industry plays a critical role in reducing carbon emissions and actively responds to the government's call to plan and reduce carbon emissions. Chemical enterprises urgently need to explore a path of low-carbon development.

Carbon emissions estimate is not only the foundation of related research on carbon emissions but is also the first step in achieving carbon reduction goals. It provides data support for subsequent driver analysis, carbon reduction measures development, and emission reduction effect assessment [9]. Carbon emission intensity effectively reflects the relationship between an enterprise's carbon emissions and reduction efforts. At present, the commonly applied methods include the following: i, the emission factor method from the production perspective, compiled by IPCC's "*IPCC National Greenhouse Gas Inventory Guidelines*" [10]; ii, the life cycle assessment (LCA) from a consumption perspective [11]; iii, the input–output method based on input–output tables [12]; iv, the actual measurement method. The emission factor method is widely used as it is simple and easy to operate [13]. It has simple data requirements, is relatively easy to obtain, and eliminates errors caused by inconsistencies in statistical calibers [14]. Tong et al. [15] used the emission factor method to calculate carbon emissions from China's high-energy-intensive industrial sectors, showing that coal-fired power plants were the main carbon emissions source. Zhang et al. [16] used the emission factor method to calculate the CO_2 emissions of China's coal chemical industry for 2020 and 2030 and explored CO_2 emission change drivers by the logarithmic mean divisia index (LMDI). LCA offers a comprehensive calculation of carbon emissions at each stage, accurately depicting the socio-economic carbon source impact on climate change from human activities [17,18]. Song et al. [19] constructed a CO_2 emission model for China's steel industry from a life cycle perspective, calculating the entire life-cycle CO_2 emissions. This method effectively helps measure precisely carbon emissions across various sectors [20]. However, the life cycle assessment method is constrained by the requirement of a large number of sectors, the difficulty of unifying data standards, the complexity of the calculation process, and the susceptibility to the data accuracy [21]. The input–output method, an analytical method based on input–output within the LCA framework, is widely applied in greenhouse gas assessments for industrial sectors [22]. Jiang et al. [23] used the energy consumption model and input–output analysis to study the structural carbon emissions on the energy supply side energy system and the energy demand side of China's industry from 2002 to 2015. The actual measurement method has fewer intermediate links with more accurate results, but it is difficult to obtain the data, and the results are easily interfered with by the selected measurement samples and measurement accuracy [24]. Several methods can assess greenhouse gases, and choosing the correct one is crucial. This study aims for the estimation of carbon emissions of metal chemical enterprises. Considering the variety of manufacturing processes, the complexity of physicochemical reactions, and the challenges of data acquisition, the emission factor method is the most appropriate method for carbon emission estimation in metal chemical enterprises.

Factor analysis of carbon emissions is not only an extension of carbon emission estimation but is also necessary for a better understanding of changes in carbon emissions. Some scholars have found that economic growth [25], energy consumption [26], non-renewable energy sources [27], and electricity consumption [28] drivers aggravate GHG emissions. Deep research into the driving factors of GHG in the chemical industry can help formulate policies to achieve emission reduction targets [29]. Generally speaking, factor decomposition is the mainstream analysis method in China. Factor decomposition, which includes the Structural Decomposition Analysis (SDA) and Index Decomposition Analysis (IDA) [30], allows for quantitative analysis of the impact of driving factors and has been widely used to explore the relationship between energy consumption and the environment [31]. Xu et al. [32] used SDA to decompose the influencing factors of the CO_2 emission increase in Jiangsu Province and found the drivers of carbon emissions. SDA is based on the input–

output table, so its decomposition can only be summed [33,34], which limits its application. The Logarithmic Mean Divisia Index (LMDI) method, one of the IDA methods, was first proposed by Yoichi Kaya [35]. It has the advantages of perfect decomposition, no residuals, and is easy to understand and consistently aggregated [36]. Therefore, many scholars used the LMDI method to study the factors influencing energy-related CO_2 emissions at the national [30], administrative region [37], or industry level [38]. The LMDI method can analyze the change in CO_2 over time from the perspective of industrial structure, and decompose the changes into several influencing factors, to study the contribution of a certain factor to the change in CO_2 during this period [39]. Serrano-Puente [40] used input–output LMDI decomposition to determine the efficiency and intensity of energy use in Spain, allocating energy demand and carbon emissions to various sectors. Jiang et al. [41] decomposed GHG emissions into six driving factors and showed that the proposed method achieved a perfect decomposition. Previous research has found that LMDI is suitable for exploring the driving factors of GHG emissions in the chemical industry and can provide appropriate mitigation measures [5]. However, related studies on enterprises are still in the early stage. Therefore, in order to gain an in-depth understanding of the degree of influence of different factors on the carbon emissions of chemical enterprises in the context of energy conservation and emission reduction and to identify the main drivers, it is necessary to explore the carbon emission drivers of metal chemical enterprises based on the availability of data and the characteristics of metal chemical enterprises.

In this study, a top–down carbon emission estimation model for metal chemical production enterprises is developed by analyzing the available basic statistical data of chemical enterprises, and then, the LMDI model is constructed to quantify the contribution of production scale, energy efficiency, energy structure, and emission coefficients to the carbon increment. The highlight of this thesis is that the existing studies mainly focused on certain production processes or procedures, but few conducted systematic and comprehensive carbon emission analyses for metal chemical production enterprises. At present, there are still no mature methods and experiences for carbon emission estimation of metal chemical production enterprises at home and abroad, which makes it difficult for enterprises to make decisions for emission reduction. Therefore, in response to the carbon reduction targets, it is necessary to study the carbon emissions, carbon intensity, and drivers of chemical enterprises so as to provide a scientific basis and reference for the carbon reduction policies of chemical enterprises.

2. Materials and Methods

2.1. Accounting Boundary Determination

The metal chemical producer in this study is located in western China with a production capacity of 28,000 t/year and develops, produces, and sells chemical products mainly through chemical methods of deep processing. It is a typical metal chemical production enterprise with high pollution and high emission. Given the complexity and diversity of the chemical industry, to fully consider GHG emission sources, emission boundaries should be determined before calculating GHG emissions from chemical enterprises [5]. "*Greenhouse Gas Emission Accounting and Reporting Requirements Part 10: Chemical Production Enterprises*" [42] is a GHG accounting methodology guide for the chemical industry, which requires accounting for emissions from CO_2 and N_2O in the chemical industry. The study boundary of this metal chemical enterprise is illustrated in Figure 1. In this study, the production area of chemical enterprises is defined as the accounting boundary, and the GHG emissions generated by all units in the enterprises are calculated and summarized. There are many types of pollutant gases produced in the production processes of metal chemical enterprises. All of the same importance, all of them can be harmful to the environment. The metal chemical enterprises in this study are not involved in the production process of nitric acid or adipic acid, so N_2O emissions are not considered. In consideration of the availability of data at this stage and the characteristics of the research object, only CO_2 emission is explored and studied in this study.

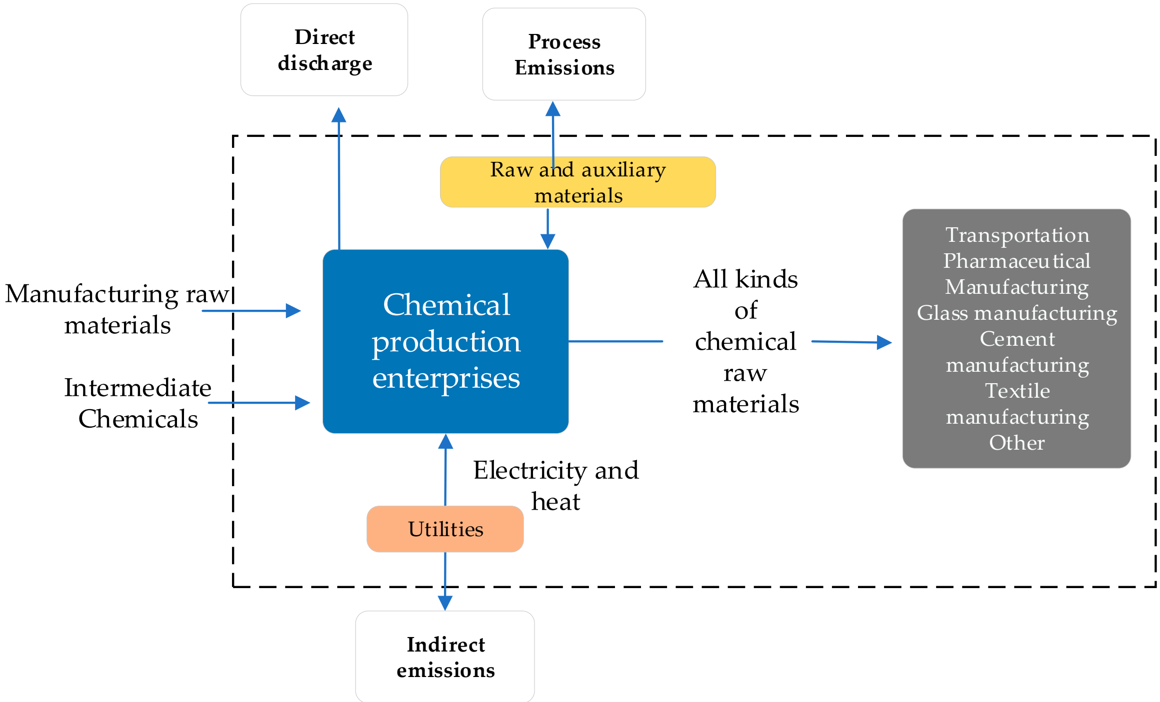

Figure 1. Carbon accounting boundary of the metal chemical enterprise.

The optimization and upgrading of equipment may have a considerable contribution to carbon emission changes at a particular point in the phase, but it is not a frequent occurrence. As a result, transportation operations are taken into account in the calculations for this study, while changes in carbon emissions brought on by equipment optimization and upgrading are not.

2.2. Emission Sources

As early as 2011, the Chinese local government mandated that the scope of emissions, when companies account for GHG emissions, include direct and indirect emissions [43]. Thus, in this paper, carbon emissions include direct carbon emissions from the production of chemical products and energy combustion and indirect carbon emissions from the consumption of purchased electricity by chemical plants. Figure 2 illustrates the emission sources of the metal chemical enterprise, which produces carbon emissions in two ways, energy processing (steam generation through coal-fired boilers) emissions and chemical product production emissions. Carbon emissions from metal chemical enterprises can be divided into three categories: direct emissions from fuel combustion; process emissions; and indirect emissions. There are two primary direct emissions from fuel combustion: one is CO_2 emissions from the complete combustion with oxygen in various fixed or mobile combustion equipment of chemical enterprises; the other is the sale and transportation of products and raw materials, such as purchased fuel and internal raw material transportation. Process emissions can be further divided into two types of CO_2 emissions: i, caused by fossil fuels and other hydrocarbons used as raw and auxiliary materials; ii, caused by carbonate utilization. Indirect emissions are those resulting from the consumption of purchased electricity and heat.

2.3. CO_2 Emission Calculation

The general idea of the accounting method is shown in Equation (1): the total carbon emission of the whole enterprise is the sum of the carbon emission of each industrial process, which is the sum of the carbon emission of fuel combustion, production process, and electricity and heat source.

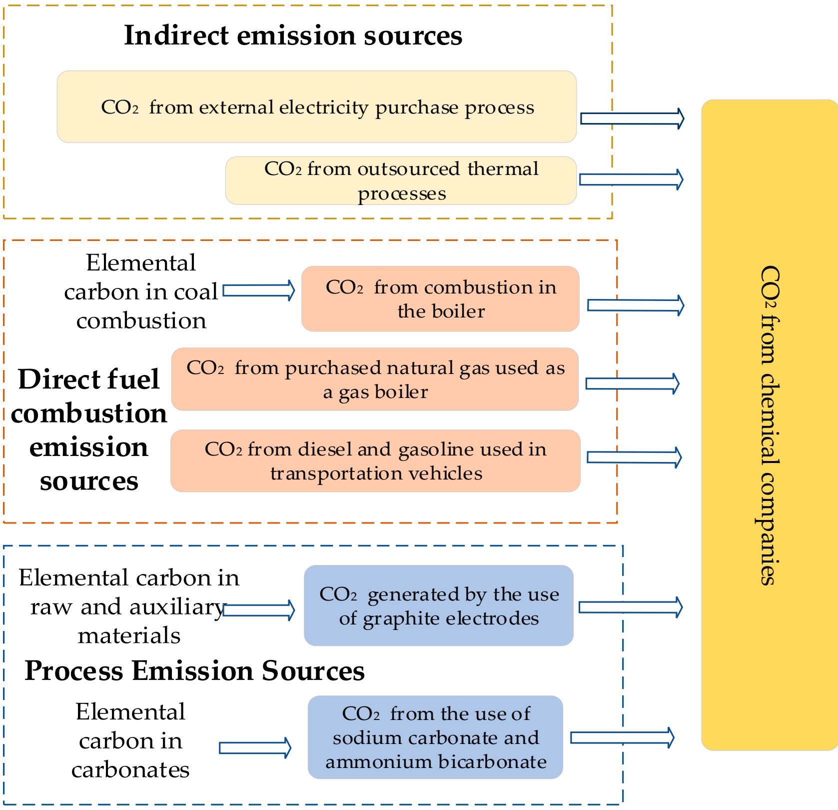

Figure 2. Sources of carbon emissions from this metal chemical enterprise.

$$E_{enterprise,total} = \sum_i E_i \tag{1}$$

$$E_i = E_{rs,i} + E_{gc,i} + E_{jj,i} \tag{2}$$

where E_i is the carbon emissions from an industrial process i, tCO_2; $E_{rs,i}$, $E_{gc,i}$, and $E_{jj,i}$ are industrial process i fuel combustion source, production process source, and electric heat source emissions, respectively, tCO_2.

2.3.1. Fuel Combustion Source

This metal chemical enterprise consumes crude oil, coal, natural gas, and other energy sources for refining and reactions and consumes diesel and gasoline for their transportation activities. Fuel combustion emissions include emissions from natural gas, diesel, lignite, and petrol used in boilers and machinery throughout the enterprise, with the relevant variables defined in Table 1 and calculated as follows:

$$E_{rs} = \sum_i \left(AD_i \times CC_i \times OF_i \times \frac{44}{12} \right) \tag{3}$$

Table 1. Definition of variables related to direct emissions from fuel combustion.

Symbol	Description
E_{rs}	Total GHG emissions from fossil fuel combustion, unit: t
i	Types of fossil fuels
AD_i	Fossil energy consumption (solid fuels in tons, gas fuels in million Nm^3)
CC_i	The carbon content of fossil fuel *i* (in tons of carbon per ton of fuel for solid fuels and tons of carbon per million for gaseous fuels Nm^3)
OF	The carbon oxidation rate of fossil fuel, unit: %
44/12	The ratio of the relative molecular mass of carbon dioxide to carbon

2.3.2. Process Emission Sources

The process emissions of this metal chemical enterprise are shown in Equation (4). It is mainly carbon dioxide from the decomposition process of carbonates and carbon dioxide from the reaction of carbon-containing raw and auxiliary materials. The relevant variables are defined in Tables 2 and 3, and the specific calculation equation are as follows:

$$E_{gc} = E_{tsy} + E_{yfl} \tag{4}$$

$$E_{tsy} = \sum\nolimits_i (AD_i \times EF_i \times PUR_i) \tag{5}$$

$$E_{yfl} = \sum\nolimits_i (AD_i \times EF_i \times CC_i) \tag{6}$$

Table 2. Definition of variables related to process emissions from carbonate consumption.

Symbol	Description
E_{tsy}	Carbon dioxide emissions during the use of carbonates, unit: t
AD_i	Carbonate consumption, unit: t
EF_i	i-th carbonate emission factor, unit: tCO_2/(Tons of carbonate)
PUR_i	The i-th carbonate purity, unit: %

Table 3. Definition of variables related to process emissions from graphite consumption.

Symbol	Description
E_{yfl}	Carbon dioxide emissions during the use of carbonate ores, unit:t
AD_i	Carbon dioxide emissions during the use of carbonate ores, unit:t
EF_i	The *i*-th carbonate ore emission factor, unit: tCO_2/(Tons of material)
CC_i	The carbon content of raw and auxiliary materials (in tons of carbon per ton of fuel for solid fuels and tons of carbon per million for gaseous fuels)

2.3.3. Indirect Emission Sources

Indirect emissions, as shown in Equation (7), are mainly carbon dioxide generated by the net external purchase of electricity and heat by metal chemical enterprises. The relevant variables are defined in Table 4, calculated as follows:

$$E_{jj} = E_{dl} + E_{rl} \tag{7}$$

$$E_{dl} = AD_{dl} \times EF_{dl} \tag{8}$$

$$E_{rl} = AD_{rl} \times EF_{rl} \tag{9}$$

Table 4. Definition of variables related to indirect emissions.

Symbol	Description
E_{dl}	Total CO_2 from net purchased electricity, unit: t
AD_{dl}	Enterprise net power purchases, unit: MWh
EF_{dl}	Average regional grid power supply emission factor, unit: tCO_2/MWh
AD_{rl}	Net purchased heat, unit: GJ
EF_{rl}	Annual average heating emission facto, unit: tCO_2/GJ

2.4. Drivers of Carbon Emissions

To explore in depth the critical factors of carbon emissions of this metal chemical enterprise and the correlation between carbon emissions and these factors, in this study, the factor decomposition formula of energy consumption and carbon emission of metal chemical enterprises was established by the LMDI decomposition method. The main factors on the carbon emissions of metal chemical enterprises were analyzed, including energy structure and its efficiency, production scale, and fossil energy emission coefficient [44]. According to the LMDI principle, the factor decomposition of metal chemical enterprises is:

$$C = \sum\nolimits_f C_f = \sum_f \left(\frac{C_f}{E_f} \times \frac{E_f}{E} \times \frac{E}{P} \times P \right) \tag{10}$$

where C is the total energy-related carbon emissions for chemical enterprises, in t; C_f is the carbon emissions of the fuel type f used, in tCO_2; E is the total energy consumption, in kgoe; E_f is the consumption of fuel f, in kgoe; P is the production of chemical products, in t. The fuel types include lignite, natural gas, diesel, gasoline, electricity, and heat.

The formula can be further expressed as follows:

$$C = \sum\nolimits_f (C_k \times S_f \times B \times P) \tag{11}$$

where C_k is the emission factor for energy type f, i.e., the ratio of carbon emissions from fuels to fuel consumption, in tCO_2/kgoe; S_f is the ratio of energy f consumption to total energy consumption and represents the energy mix factor, in kgoe/t; B is the ratio of total energy consumption of chemical process to the output of chemical products, representing the energy intensity factor; P represents the production scale factor, in t.

Then, the incremental carbon emissions of metal chemical enterprises in the r year and the base year are

$$\Delta C = C_r - C_0 = \Delta C_k + \Delta S_f + \Delta B + \Delta P \tag{12}$$

where ΔC_k represent from year r to the base year, incremental corporate carbon from changes in emission factors only, with other factors (energy efficiency, energy structure, and production scale) holding constant; ΔS_f represent from year r to the base year, incremental corporate carbon from changes in energy structure only, with other factors (energy efficiency, production scale, and emission factors) holding constant. ΔB represent from year r to the base year, incremental corporate carbon from changes in energy efficiency only, with other factors (production scale, energy structure, and emission factors) holding constant; ΔP represent from year r to the base year, incremental corporate carbon from changes in production scale only, with other factors (energy efficiency, energy structure, and emission factors) holding constant.

$$\Delta C_k = \sum\nolimits_f \left(\frac{C^r - C^0}{\ln C^r - \ln C^0} \ln \frac{C_k^r}{C_k^0} \right) \tag{13}$$

$$\Delta S_f = \sum\nolimits_f \left(\frac{C^r - C^0}{\ln C^r - \ln C^0} \ln \frac{S_f^r}{S_f^0} \right) \tag{14}$$

$$\Delta B = \sum\nolimits_f \left(\frac{C^r - C^0}{\ln C^r - \ln C^0} \ln \frac{B^r}{B^0} \right) \tag{15}$$

$$\Delta P = \sum\nolimits_f \left(\frac{C^r - C^0}{\ln C^r - \ln C^0} \ln \frac{P^r}{P^0} \right) \tag{16}$$

2.5. Data Source

The data of the metal chemical enterprise in this study were all obtained from its purchasing records and measurement data. In addition, emission factors and alternative calculation parameters were obtained from "*Greenhouse Gas Emissions Accounting and Reporting Requirements Part 10: Chemical Manufacturing Enterprises*" [42] and General Guidelines for Accounting and Reporting of Greenhouse Gas Emissions from Industrial Enterprises [45] or the physical statistics of enterprises. The direct emission factors, process emission factors, and electric thermal emission factors used in this study are listed in Tables 5–7.

Table 5. Direct emission-related reference data.

Type	Low Calorific Value [a]	Calorific Value Unit	Carbon per Unit Calorific Value [a]	Carbon Oxidation Rate [a]	Conversion Coefficient between Carbon and CO_2
lignite	14.080	GJ/t	0.0280	96%	44/12
natural gas	389.31	GJ/t	0.0153	99%	44/12
diesel oil	43.330	GJ/t	0.0202	98%	44/12
gasoline	44.800	GJ/t	0.0189	98%	44/12
kerosene	44.750	GJ/t	0.0196	98%	44/12

[a] Fossil fuel characterization parameters from the General Guidelines for Greenhouse Gas Emissions and Reporting by Industrial Enterprises [45].

Table 6. Process emission-related reference data.

Type	Carbon Content	Emission Factor [b]	Purity [c]
Sodium carbonate	/	0.415	0.980
Ammonium bicarbonate	0.152	3.663	/
Graphite electrode	0.999	3.663	/

[b] Emission factors are derived from "*Greenhouse Gas Emission Accounting and Reporting Requirements—Part 10: Chemical Manufacturing Enterprises*" [42]. [c] Carbonate purity from enterprise physical statistics.

Table 7. Implied carbon emission-related reference data.

Type	Emission Factor [d]
Net purchased power	0.527
Net purchased heat	0.110

[d] The emission factor comes from the emission factor of China Southern Power Grid released in 2012.

2.6. Carbon Dioxide Evaluation Index

This study used a number of indicators to analyze the CO_2 emissions of metal chemical enterprises, which are listed in Table 8.

Table 8. Carbon dioxide emission index in this study.

Index	Target	Equation	Unit
Direct discharge	Product K	$E_{rs} = \sum_i \left(AD_i \times CC_i \times OF_i \times \frac{44}{12}\right)$	tCO_2
Process emission	Product K	$E_{gc} = E_{tsy} + E_{yfl}$	tCO_2
Indirect emission	Product K	$E_{jj} = E_{dl} + E_{rl}$	tCO_2
Total emission	factory-wide	$E_{enterprise,total} = \sum_i E_i$	tCO_2
Carbon emission intensity per unit product	factory-wide	E_i/P	tCO_2/t
Carbon emission intensity per unit of gross industrial output	factory-wide	E_i/M	tCO_2/million yuan
Energy efficiency factor	factory-wide	E/P	t
Energy structure factor	factory-wide	E_f/E	t
Emission factor	factory-wide	C_f/E_f	tCO_2
Production scale factor	factory-wide	P	t

3. Results and Discussion

3.1. Carbon Emissions

It is very important to classify and analyze CO_2 emissions. In previous estimates of carbon emissions, it is mostly the fuel combustion emissions and indirect emissions that were considered [5]. In this study, we discussed not only direct emissions from fuel combustion caused by fossil energy consumption but also process emissions caused by carbonates and indirect emissions from electricity and heat. It is more systematic and comprehensive and, thus, improves the accuracy of estimation. The emissions of nine emission sources of metal chemical enterprises from 2014 to 2022 are illustrated in Figure 3. In general, the proportion of lignite, natural gas, electricity, and heat changes more obviously. As can be seen from Figure 4, direct emissions were the main form of carbon emissions in this chemical enterprise until 2019, accounting for about 95.62% on average, and direct electricity and heat emissions account for 4.06%. Fuel combustion is the dominant cause of direct emissions. From the contribution rate of each emission source in Figure 4, the structure of the contribution of each emission source to the carbon emission of the metal chemical enterprise before and after 2019 is largely changed.

From 2014 to 2022, there was some fluctuation in the carbon emissions of this metal chemical enterprise. During this period, from 2014 to 2017, the overall trend of carbon emissions of chemical enterprises increased year by year, and the amount increased from 21,800 t in 2014 to 23,600 t in 2017, in total, by 8.25%, with an average annual growth of 2.75%. The early 21st century witnessed a rapid development of China's economy. Since most Chinese enterprises were in the initial stage of development at that time, the industrial structure and technological innovation both lagged behind [46]. As a result, the national economy overly relies on traditional fossil energy, which leads to a rapid increase in carbon emissions [47].

From 2017 to 2021, the carbon emissions of chemical companies decreased from 23,600 t to 15,900 t, a decrease rate of 32.6% with an average annual growth rate of −8.16%. However, the change in the total number of chemical products processed was not significant. This is because chemical companies replaced coal-fired boilers with gas boilers and biomass boilers from 2017 to 2020, demonstrating the important role of adjusting the energy structure in reducing carbon emissions. The whole sector change is related to a series of emission reduction policies formulated by the Chinese government to tackle global climate change. Enterprises under these policies continued to optimize and upgrade their production line, transform the industrial structure, and improve technological innovation capabilities, and therefore controlling the total amount of carbon emissions [48,49].

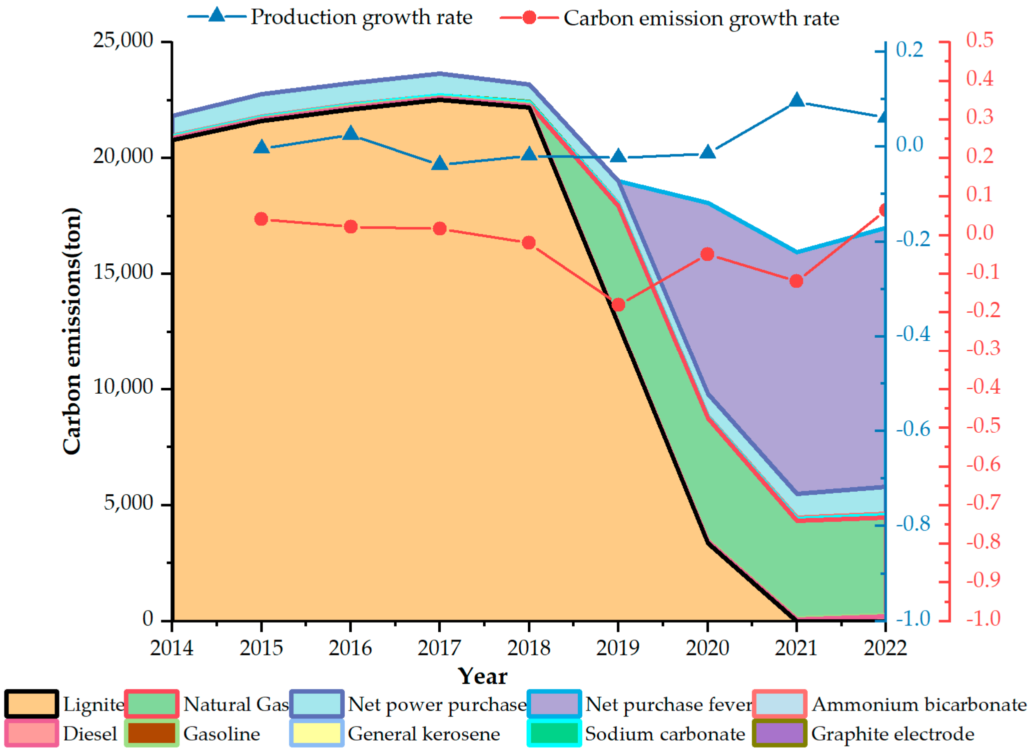

Figure 3. Carbon emissions and growth rate of chemical enterprises from 2014 to 2022.

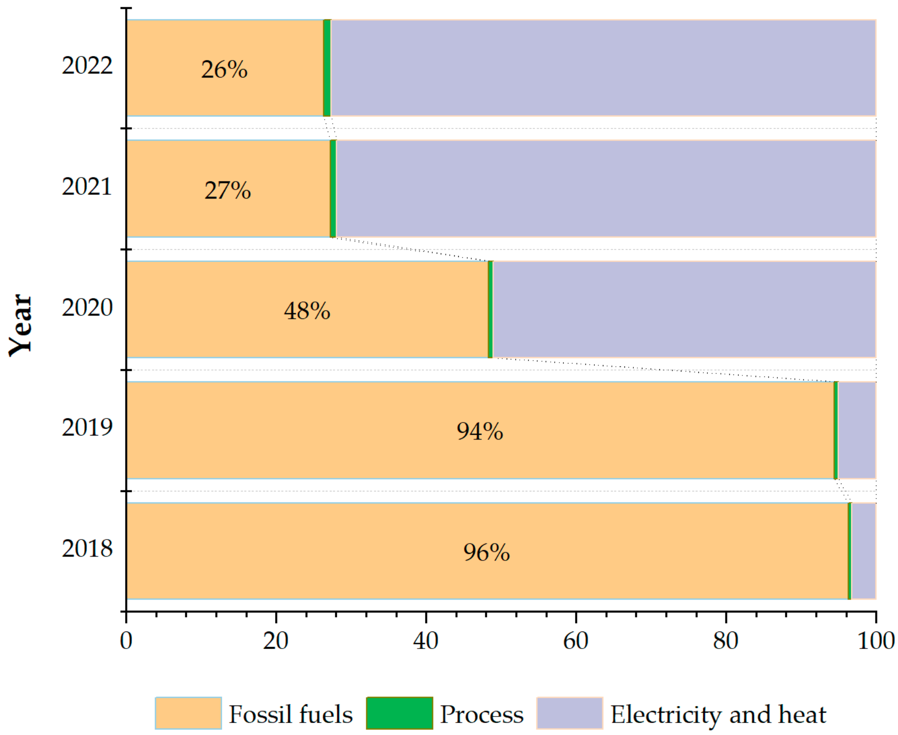

Figure 4. Carbon Emission contribution of each emission source from 2018 to 2022.

As illustrated in Figure 5, this metal chemical enterprise's carbon emissions from fuel combustion changed widely, with a slight increase from 2014 to 2017, reaching the highest value in 2017 and then a significant decrease from 2017 to 2021. From the fuel types' perspective, carbon emissions mainly come from lignite combustion, which accounted for more than 95% of the total fossil fuel emissions in 2014–2017.

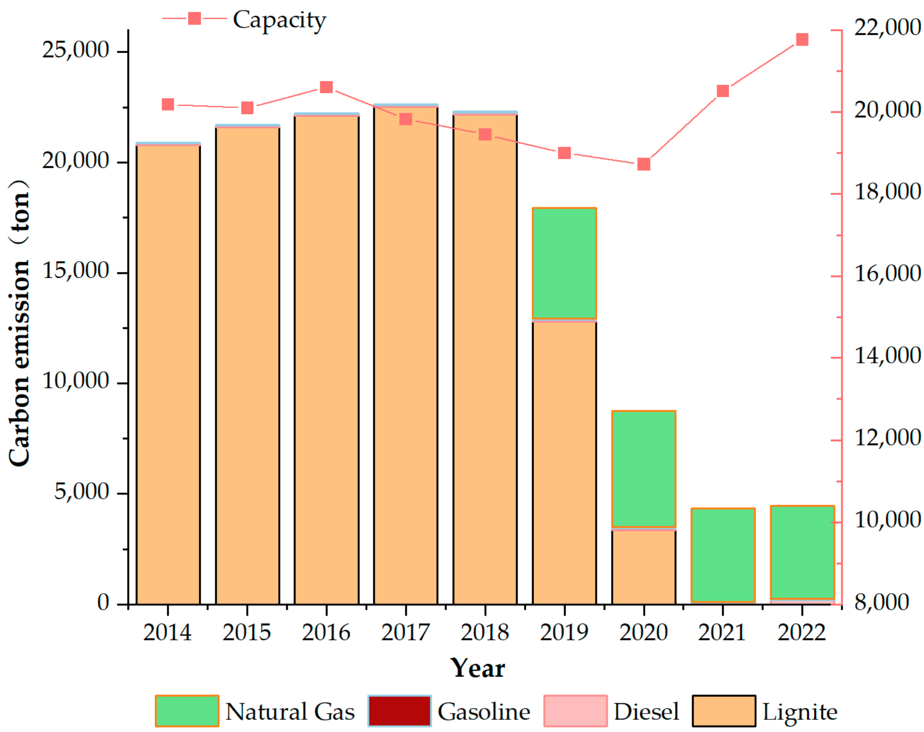

Figure 5. Direct emissions and production of chemical enterprises from 2014 to 2022.

It can be seen that the growth rate of carbon emissions from 2015 to 2018 is similar to the change in fuel combustion emissions, which resulted from the fact that fuel combustion emissions were the leading cause of carbon emissions during this period. An increase in the growth rate of carbon emissions but a decrease in fuel combustion emissions can be seen for 2019–2021. Figure 6 illustrates that the proportion of lignite decreases from 95.7% to 0 and natural gas increases from 0 to 26.4% for 2018–2021 due to three boiler conversions in metal chemical enterprise during this period, from coal-fired boilers to gas-fired boilers, electric fusion boilers, and biomass boilers. The fuel lignite was replaced by cleaner energy, natural gas, electricity, and heat. The decrease in fuel combustion emissions in 2019, 2020, and 2021 is, respectively, up to 4376.05 t, 9197.11 t, and 4406.46 t.

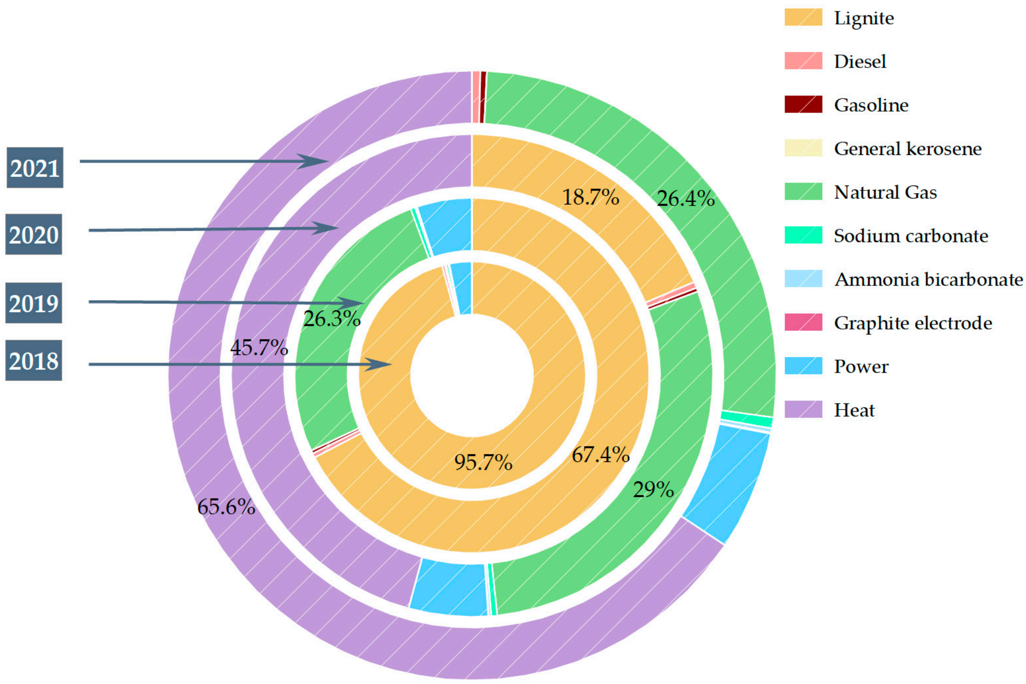

Figure 6. Change in the share of each emission source from 2018 to 2021.

As illustrated in Figure 7, the process carbon emissions of this metal chemical enterprise vary little, with a small increase from 2014 to 2021, reaching the highest value in 2021. In terms of type, it is mainly the carbon emissions brought by sodium carbonate reagents, in which sodium carbonate occupies more than 65% of the total process emissions. It can be seen that the changes in production and process emissions from 2015 to 2016 are similar in magnitude, and the increase in process emissions during this period is mainly due to the increase in sodium carbonate reagents as a result of the production increase. It can be seen that the production volume decreased in 2016–2019, but the process carbon emissions increased, which may result from the adjustment of the production ratio of different chemicals leading to the increase in carbonate used. In 2019–2022 production volume and process emissions changed in a similar magnitude, but there was a certain change in the proportion of each process source situation, which may be due to the new increase in chemical production in metal chemical enterprise, and the new use of materials led to a new change in the proportion of carbon emissions.

As illustrated in Figure 8, the indirect carbon emissions of this metal chemical enterprise changed a lot and reached the highest value in 2022. In terms of type, it comes from carbon emissions from the net purchase of electricity and the net purchase of heat. It can be seen that the increase in electricity from 2019 to 2020 was not significant, but the newly added net purchased heat accounted for a large proportion. Figure 6 illustrates that during this period, the proportion of net purchased heat increased from 0 to 45.7% due to the conversion of coal boilers to biomass boilers by the enterprise.

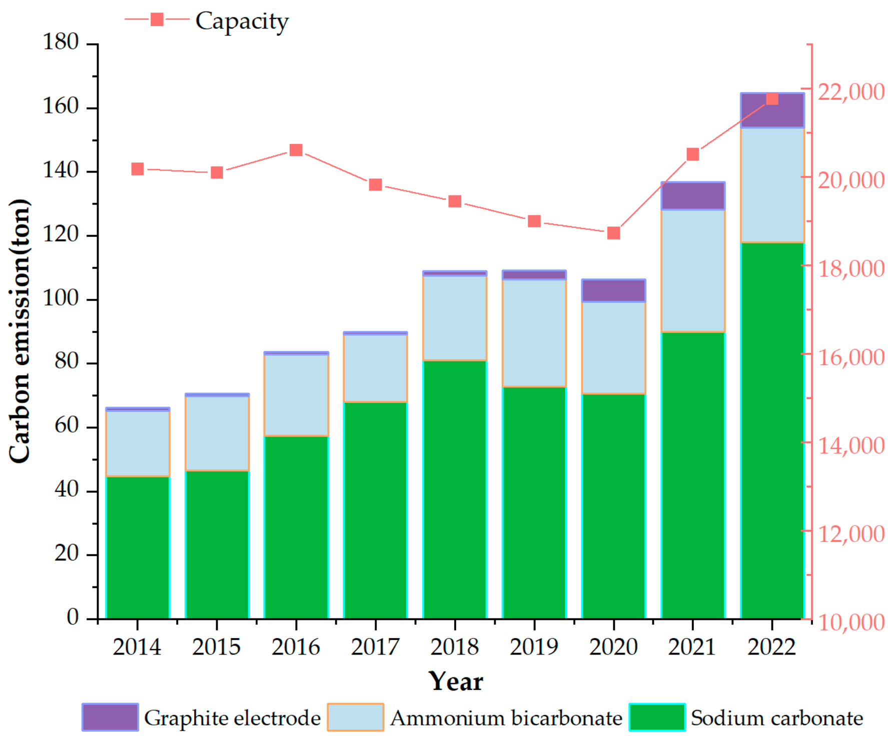

Figure 7. Process emissions and production of chemical enterprises from 2014 to 2022.

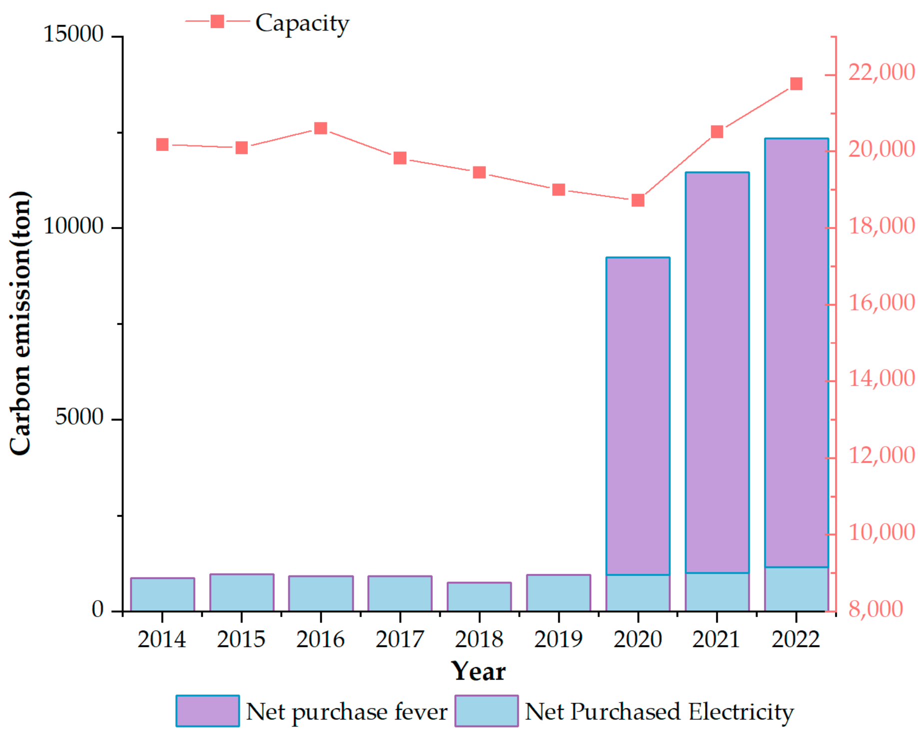

Figure 8. Indirect emissions and production of chemical enterprises from 2014 to 2022.

From 2020 to 2022, the proportion of net purchased heat exceeded 89.57% of the indirect total emissions, and the change in production and indirect emissions was similar. The main reason for the increase in indirect emissions during this period was the increase in production, which led to the increase in net purchased heat. This reflects the important role of production scale in carbon reduction targets.

3.2. Carbon Emission Intensity

The total carbon emission intensity (ratio of carbon emission to the total output value) and carbon emission intensity per unit product (ratio of carbon emission to total production) of this metal chemical enterprise from 2014 to 2022 are illustrated in Figure 9. The carbon emission intensity per unit of product is used to measure the relationship between the products and the carbon emissions [50], while the total carbon emission intensity is used to measure the relationship between the economy and the carbon emissions [51], and it can reflect the energy and economic benefits more accurately [52].

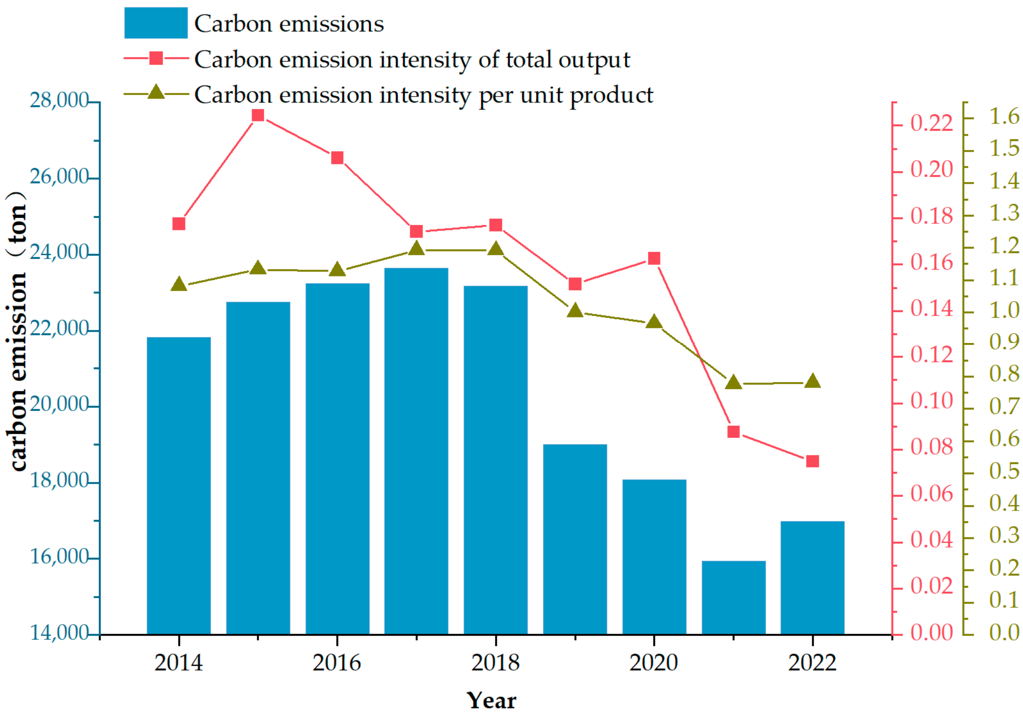

Figure 9. Carbon emission intensity per unit product and carbon emission intensity of total output value of chemical enterprises from 2014 to 2022.

From 2014 to 2022, the total carbon emission intensity shows the characteristic of "increase first, and then decrease". After the increase in total carbon emission intensity from 2014 to 2015, it then decreased from 2015 to 2017, further fluctuated and increased from 2017 to 2018, and, finally, showed a relatively stable decreasing trend after 2018. During that period, there were significant decreases in 2017, 2019, and 2021, presumably related to the enterprise energy transformation and price changes of chemical products, which would lead to a decrease in carbon emission intensity when the sales volume of chemical products is high, and the product price is high. In terms of carbon emission intensity per unit product, the overall trend from 2014 to 2018 is significantly increasing. Among them, there was a significant increase in 2017, which is presumed to be related to the increase in chemical product types, and the diversified chemical products led to a significant change in carbon emission intensity per unit product. After 2018 it shows a stable decreasing trend because of the change in energy proportion and the improvement of management. The comprehensive energy consumption of metal chemical enterprises rose from 6052.8 kgoe/t to 9455.96 kgoe/t during 2018–2022. However, the carbon emission intensity of the total output value decreased in this phase despite the increasing output. The pattern indicates that factory scale has a positive relationship with energy saving and emission reduction. Moreover, it reflects that companies in this period have entered a higher level compared with 2014–2017 in terms of improving quality and efficiency.

3.3. The Contribution of Carbon Emission Impact Factors

Previous studies mainly focused on carbon emission estimation methods. Though these methods can effectively evaluate the overall emissions, they only work as "statistical" functions [53]. Therefore, it is impossible to learn about the influencing factors of carbon emissions and propose efficient emission reduction measures with these accounting methods. Based on the above carbon emission accounting results and enterprise analysis from 2014 to 2022, the carbon emission contribution of production scale, energy efficiency, energy structure, and emission factors in 2014–2022 is quantified using the dynamic factor decomposition method. The production scale is the processing capacity of chemical enterprises. The larger the processing volume of chemical products, the more carbon emissions are produced inevitably. Energy efficiency, i.e., the amount of energy consumed per unit of chemical processed, represents the change in the level of energy use brought about by factors such as energy network optimization and technology enhancement. Energy structure means the ratio of different types of energy consumption to total energy consumption. The higher proportion of clean energy contributes more to carbon emission reduction. The carbon emission factors refer to the carbon emissions caused by different types of energy. Quantitative analysis of the contribution of each influencing factor can verify the progress and effect of emission reduction measures in the enterprises and provide some theoretical basis for the subsequent carbon emission reduction focus, emission reduction target, and policy formulation of metal chemical enterprises [54]. According to the above accounting formula, the contribution of the four factors to the annual average carbon increment of metal chemical enterprises from 2014 to 2022 is illustrated in Figure 10.

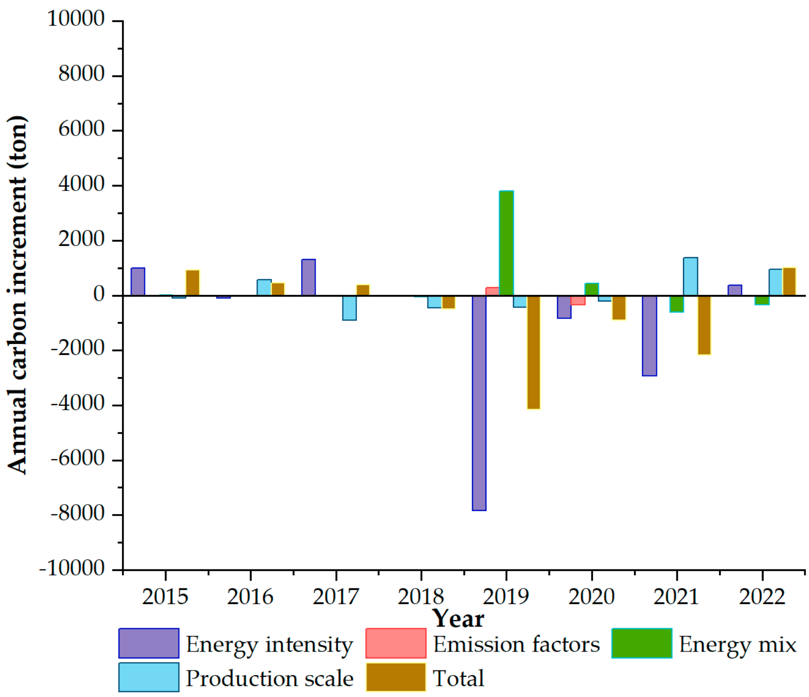

Figure 10. Contribution of different influencing factors to the annual average carbon increment.

Figure 10 indicates the slow growth in 2015–2017 and the decrease in carbon increment in 2018–2021, with the most significant changes in 2019 and 2021 and an increase in 2022.

3.3.1. Energy Efficiency Factors

Figure 10 illustrates that from 2017 to 2021, energy efficiency change had the most significant contribution to carbon increment: the data decreased annually by 0.07%, −188.21%, −92.34%, and −135.27%, respectively. In the early period, energy efficiency had a positive value and contributed significantly to increasing carbon emissions. In the later period, the consumption of chemicals decreased, and the number became negative, with a significant effect of reducing carbon emissions. The positive value in the first period indicates that the energy consumption of tons of chemicals in 2017 was greater than the value of this indicator in 2016. Further analysis of the data reveals that the main reason is that the lignite consumption per ton of chemical in 2017 increased year by year. Figure 9 also indicates that the carbon emission efficiency per unit of product and carbon emission efficiency of total output value both started an upward trend at that moment, which also mutually verifies the accuracy of the quantification results of enterprise carbon accounting results and impact factors. The period of 2018–2021 shows a negative value because the change in energy ratio led to a change in energy efficiency. The contribution of energy efficiency to carbon increment increased in 2022, from inhibiting effect to promoting effect, which indicates that the current means of improving energy efficiency has gradually failed to meet the development needs of enterprises, which raises higher requirements for the improvement of energy efficiency.

3.3.2. Energy Structure Factors

The contribution of the energy mix to the carbon increment is relatively small, and the practical value changed insignificantly in the early period, being positive in 2019 and 2020 and negative in 2021 and 2022. In Figure 11 it analyses the specific energy structure. In the years from 2014 to 2018, lignite consumption accounted for more than 95% of all energy consumption in businesses. The percentage started to drop sharply in 2018. The decline in lignite use was the primary factor in the reduction in carbon emissions, with a contribution of −2.09% to the suppression effect. In the years 2018–2021, the energy ratio was changed, with fuel oil consumption sharply decreasing while natural gas, electricity, and heat consumption rising. By 2020, the energy occupation of heat surpassed that of lignite and became the main source of energy for carbon emissions, forming a new energy structure dominated by heat and supplemented by natural gas and electricity. As a result, energy structure gradually functioned to suppress the growth of carbon emissions from promoting.

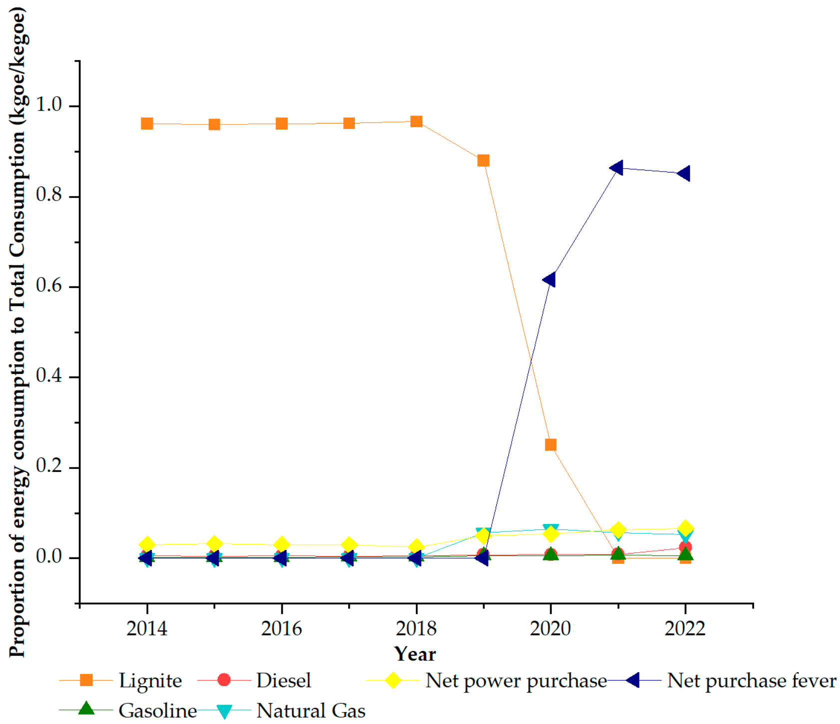

Figure 11. Energy consumption from 2014 to 2022 as a percentage of total consumption.

Overall, in the former period, the large share of lignite led to a rise in carbon emissions, and in the latter period, a reduction in the share of lignite and an increase in the share of electricity and heat contributed to the decrease in carbon emissions. As of right now, the overall carbon emissions tend in a downward direction, proving the notion that electricity, heat, and natural gas are cleaner energy sources compared with lignite and that the adjustment of energy structure can significantly reduce carbon emissions.

3.3.3. Other Factors

The contribution of the carbon emission factors to the annual average increment is not obvious enough. The change in the production scale is consistent with the change in carbon increment except for 2017 and 2021, which, to some degree, reflects that at this stage, production is an important influencing factor of carbon emission. Therefore, it is very important to reasonably control the expansion of new chemical projects, strengthen the regulation on the existing stock and surplus increment, and encourage industrial cooperation, especially in the situation of increased overcapacity [55].

4. Conclusions and Policy Suggestions

4.1. Conclusions

This study aims to quantify CO_2 emissions and the contribution of driving factors to carbon increment in a Chinese metal–chemical enterprise. By analyzing the emission characteristics of a metal–chemical enterprise, a CO_2 calculation model is proposed based on the classification of emission categories. With the LMDI model, we can have a deep comprehension of the impact of different factors on the carbon emissions of chemical enterprises and provide directions for further steps in carbon emission reduction in the future. The main conclusions are as follows:

This study established a set of carbon emission estimation methods suitable for metal chemical enterprises with a complete and systematic analysis of metal chemical enterprises. Compared with previous studies, this model is more comprehensive, systematic, and simple. Not only the direct emissions of fuel combustion caused by fossil energy consumption but also the process emissions caused by carbonates and indirect emissions of electricity and heat energy are considered;

This study highlighted the importance of enterprise air pollution control strategies in mitigating CO_2 emissions. This metal chemical enterprise has successfully reduced CO_2 emissions by replacing coal-fired boilers with more efficient and cleaner technologies. However, direct emissions from fuel combustion remain a significant contributor to the increase in CO_2 emissions in recent years, necessitating the adoption of advanced technologies for CO_2 emission control and the use of clean alternative energies to resolve issues in the near future;

This study also quantified the contribution of various influencing factors to carbon increment by constructing the LMDI model. The result shows that energy efficiency and energy structure are important driving factors affecting CO_2 emissions, and adjusting energy structure makes a difference in carbon emission reduction;

Overall, this study provides valuable insights into the CO_2 emissions of metal chemical enterprises and sheds light on research methods for estimating carbon emissions so as to better understand the characteristics and impacts of carbon emissions. It underscores the need for continued research on carbon emission calculation models and analysis of driving factors for metal chemical enterprises to promote more effective energy conservation and emission reduction.

4.2. Policy Suggestions

The growing energy demand of the Chinese chemical industry has exacerbated carbon emissions [5]. Therefore, based on the above-mentioned studies, we should explore new policies and suggestions to reduce the carbon emissions of metal chemical enterprises in more depth in order to reduce their negative impact on the environment.

1. Coordinate the development plan of the enterprise and make future capacity development plans by combining the enterprise's own development plan and market situation, evaluate its own level, and provide the basis for its own capacity development plan by making horizontal comparisons with the same type of enterprises, make a detailed energy-saving diagnosis, analyze the energy consumption level of the enterprise, and formulate the enterprise's own energy-saving transformation plan according to the current situation of the enterprise in order to promote the sustainable development and transformation of the enterprise;

2. Strengthen the construction of the management system. Establish a management system based on the actual situation of the enterprise itself by clarifying the responsibilities of carbon emission (energy) related departments and related personnel and specifying specific management requirements;

3. Promote basic information management. Establish a comprehensive data and information statistical framework based on the enterprise's situation, considering the current situation of carbon emission (energy), to provide reliable data support for the enterprise's development and planning;

4. Accelerate the construction of an early warning system. Build a rapid inner-enterprise accounting system according to the characteristics of the enterprise's carbon emission sources, and realize automatic early warning of the system by setting the intrusion value, to provide strong support for the enterprise's high-quality development;

5. Optimize the technical equipment of chemical enterprises to improve energy utilization efficiency. Improve the energy structure of chemical enterprises by widely using clean energy and fossil fuels with low emission coefficients and promoting the use and replacement of renewable energy to achieve the goal of green and low-carbon economic development.

However, this paper has a limitation. Although a comprehensive and systematic study of the overall carbon emissions of this metal chemical enterprise has been performed, when the data are more comprehensive and detailed in the future, a more detailed carbon footprint study is also needed for the processes and workshops. In this way, the carbon operation trajectory and migration transformation in the metal chemical enterprise will be clearer, and the carbon emission estimation will be more accurate.

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