Carbon Flow Analysis of Hunan Province from 2012 to 2020 Based on Material Flow Analysis

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Abstract. With the continuous growth of greenhouse gas CO_2 emissions, climate change led by human activities has affected all regions of the world, so it is of great significance to scientifically and effectively grasp the temporal and spatial dynamics of regional carbon flow for regional mitigation of climate change and the realization of the "dual carbon" goal. In this study, we combined the available energy statistics and material flow analysis methods, took Hunan Province as an example, analyzed the carbon flow in the region, drew carbon flow maps in 2012 and 2020, and compared the carbon flow trend according to the total carbon flow, industrial sector and process carbon emissions. The results showed that the total energy-related carbon emissions in Hunan Province in 2012 and 2020 were 420.8039 million tons and 354.3196 million tons, respectively, which decreased by 30.34% in 2020 compared with 2012. In 2020, the total CO_2 emissions of processes in Hunan Province were 72,216,400 tons, of which the CO_2 emissions of ferrous metals, chemical industries and non-metallic mining processes accounted for 16%, 1% and 64% of the total CO_2 emissions of the industry, respectively. This study can provide data reference and theoretical basis for the implementation of the "dual carbon strategy" of relevant regional departments.

Keywords: Carbon flow diagram; Material flow analysis method; Carbon emissions; Hunan Province.

1. Introduction

In the past century, human beings have used a large number of fossil fuels (such as coal, oil, etc.), emitting a large amount of CO_2 and other greenhouse gases, resulting in more and more serious global warming. In 1981~1990, the global average temperature increased by 0.48 °C compared with 100 years ago, and the average temperature in the world climbed by about 0.6 °C in the 20th century. In order to stop the trend of global warming, the United Nations specially formulated the United Nations Framework Convention on Climate Change in 1992, which was signed and entered into force in the Brazilian city of Rio de Janeiro in the same year. In September 2020, China clearly proposed the goals of "carbon peaking" in 2030 and "carbon neutrality" in 2060, aiming to maintain global temperature stability by reducing carbon dioxide emissions.

The current phase of research related to CO_2 emissions in China focuses on a broad discussion on whether the stated goal of carbon reduction [1] can be achieved and how to achieve this target [2]. At the national level, scholars account for national carbon emissions and analyze their contributing factors. Li [3] et al. used the logarithmic average Di Index (LMDI) method to evaluate the driving factors of China's CO_2 emissions, and concluded that GDP growth is the main reason for the increase in carbon emissions, and both energy intensity and carbon emission coefficient are conducive to CO_2 emission reduction. At the regional level, scholars propose appropriate and desirable carbon emission reduction strategies based on the industrial and energy characteristics of each region and on the premise of ensuring stable economic growth. Liu Yang [4] et al. proposed a new comprehensive measurement method to evaluate the common prosperity of 30 provinces in China from 2006 to 2019. Further, we use systematic generalized moment estimation (SYS-GMM) to investigate the impact of common prosperity on carbon emissions. It is concluded that common prosperity significantly reduces carbon emissions, and that common prosperity has a greater impact on carbon emissions in provinces with higher and lower carbon emission levels.

The existing literature has systematically studied China's CO_2 emissions at the national and regional levels. However, they all focus on macro and a few megacities, ignoring other regions and their industrial characteristics, and most studies lack accounting for process CO_2 emissions from the production process. Therefore, from the perspective of industry, the material flow analysis method is used to analyze the carbon flow in Hunan and calculate the energy-related CO_2 and process CO_2 emissions in Hunan Province. Finally, combined with the energy balance sheet of Hunan Province and the Guidelines for the Preparation of the 2006 IPCC National Greenhouse Gas Emission Inventory (hereinafter referred to as the IPCC Emission Inventory), the carbon flow maps of 2012 and 2020 reflecting the carbon flow of the energy conversion process and the final consumption sector are drawn, which provides a useful reference for the formulation of relevant policies for achieving the "dual carbon" goal in Hunan Province.

2. Materials and methods

2.1 Data sources and classification methods

The data used in this article are mainly from the 2013-2021 Hunan Statistical Yearbook and the IPCC emission inventory. The data on various fuel consumption in the final consumption sector from 2012 to 2020 comes from the Hunan Provincial Bureau of Statistics. The classification method of the end-consuming sector in the Hunan Statistical Yearbook and the classification method of the IPCC emission inventory were integrated (Table 1), and the CO_2 emissions of Hunan Province were accounted for based on this.

Table 1. Classification of end-consuming sectors

numbering	IPCC emissions inventory	Hunan Provincial Bureau of Statistics
1	Ferrous	Smelting and pressing of ferrous metals
2	nonferrous metal	Smelting and pressing of non-ferrous metals
3	chemical industry	Manufacture of chemical raw materials and chemical products, chemical fibers, pharmaceuticals, rubber and plastic products
4	Pulp, paper and printing industry	paper and paper products; Reproduction in print and recording media
5	Food processing, beverages and tobacco products	agro-food processing; food manufacturing; production of wine, beverages and refined teas; Tobacco products
6	Non-metallic mining	Manufacturing of non-metallic mineral products
7	Transportation equipment	automobile manufacturing; Manufacture of railway, ship, aviation and other transportation equipment
8	Machine	Manufacture of general machinery, special-purpose machinery, electrical and electrical appliances, computers, communications and other electronic equipment, as well as measuring instruments and machinery
9	Mining industry	Mining industry
10	Wood and wood products	Manufacture of wood and wood, bamboo and other grass products; Furniture manufacturing
11	Textiles & Leather	Manufacture of textiles, textiles and apparel, apparel, leather, fur, feathers and other related products and footwear
12	Industry-specific	the manufacture of cultural, aesthetic, sports and recreational supplies; metal product manufacturing; Other manufacturing; utilization of waste resources; metal products, machinery maintenance services; Production and supply of water

2.2 Substance flow analysis

In this paper, the material flow analysis method was used to analyze the carbon flow in Hunan Province. Substance flow analysis is an effective means of industrial metabolism research on a specific substance in a country or region [5-6], which shows us the flow pattern of an element in the region, and can be used to evaluate the impact of various processes in the life cycle of the element on the environment. Through material flow analysis, the input and flow of toxic and harmful substances can be controlled, the total amount and degree of use of material flow can be analyzed, and new methods and perspectives can be provided for environmental policy [7-8], and provide reference for decision-makers to make decisions on resources and environment.

2.3 Calculation method for energy-related CO_2 emissions

Calculation method for energy-related CO_2 emissions:

$$CP_{mn}^{k} = \sum P_{mn}^{k} \times PF_{n}(1 - CS_{n}^{k})\ O_{n} \times \frac{44}{12} \quad (1)$$

In the formula: m represents the industrial sector, n represents the fuel, k represents the time (year), CP_{mn}^{k} represents the carbon emissions generated by the m industry in k year with n as fuel (ten thousand t), P_{mn}^{k} is the total energy consumption (TJ) of the m industry in k year with n as fuel, PF_n represents the carbon emission coefficient of the nth fuel (t C/TJ), CS_{n}^{k} is the proportion of the nth fuel that has not been oxidized, O_n represents the oxidation rate of fuel n (Table 2), and $\frac{44}{12}$ represents the ratio of CO_2 to carbon molecular weight. In this paper, the fuel used as raw material for manufacturing products is excluded from the total energy consumption, so CS_{n}^{k} it is always 0.

Table 2. Carbon emission factors and carbon oxidation rates for each fuel

Fuel	carbon emission factor	Carbon oxidation rate	Fuel	carbon emission factor	Carbon oxidation rate
raw coal	25.8	0.90	fuel oil	21.1	0.98
Bituminous coal	26.1	0.93	gasoline	18.9	0.98
Briquettes	33.6	0.90	diesel fuel	20.2	0.98
Coal washing	25.4	0.93	kerosene	19.6	0.98
coke	29.5	0.93	NGL	17.2	0.98
Other coking products	29.5	0.93	Other oils	20.0	0.98
crude	20.1	0.98	natural gas	15.3	0.99

2.4 Process CO_2 emission calculation method

The expression of CO_2 in the cement and calcium carbide industry is:

$$E_{co_2} = AD \times EF \quad (2)$$

Where: E_{co_2} indicates the process CO_2 emissions, AD indicates the production of industry substances, and EF represents the carbon emission coefficient of the industry, as shown in Table 3.

Table 3. Carbon emission factors of cement and calcium carbide industries

Industry	Output	Carbon Emission Factor (t CO_2/t)
Cement	Cement clinker output (excluding calcium carbide slag)	0.538
calcium carbide	calcium carbide production	1.154

The expression of process CO_2 emissions in the steel industry is:

$$E_{co_2} = AD_p \times EF_p + AD_q \times EF_q + (AD_b \times F_b - AD_d \times F_d) \times \frac{44}{12} \quad (3)$$

Where: AD_p is the consumption of limestone as a solvent, EF_p is the emission coefficient of limestone as a solvent, AD_q is the consumption of dolomite as a solvent, EF_q is the emission coefficient of dolomite as a solvent, AD_b is the amount of pig iron required for steelmaking, F_b is the average carbon rate of pig iron, AD_d is the average carbon rate of steel production, F_d is the average carbon rate of steel products, see Table 4 for details.

Table 4. Carbon emission coefficient and average carbon rate of the steel industry

Category	Carbon emission factor (t CO_2/t)	Category	Average carbon rate (%)
Limestone (solvent)	0.430	pig iron	4.1
Dolomite (solvent)	0.474	Steel products	0.248

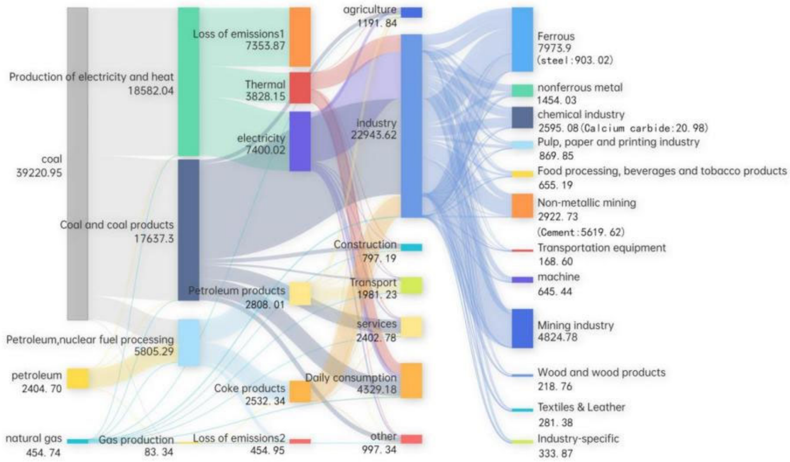

Fig. 1 Carbon flow map of Hunan Province in 2012 (10,000 tons)

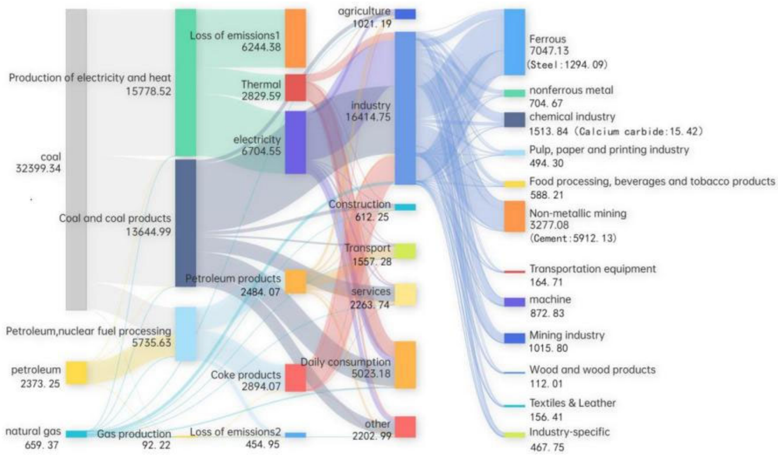

Fig. 2 Carbon flow map of Hunan Province in 2020 (10,000 tons)

3. Results and analysis

3.1 CO_2 emissions and analysis on the energy supply side

The energy supply side consists of coal, oil and gas. In 2012 and 2020, the CO_2 carbon emissions generated by coal consumption reached 392.2095 million tons and 323.9934 million tons, accounting for 93.21% and 91.44% of the total respectively, and the carbon emissions generated by coal consumption in 2020 decreased by 17.39% compared with 2012, indicating that the carbon emission structure of Hunan Province's energy supply side is single, mainly coal, supplemented by oil and gas. The CO_2 carbon emissions generated by oil consumption remained basically stable from 24.047 million tons in 2012 to 23.7325 million tons in 2020, indicating that the exploration of oil in Hunan Province is still in progress, and the total amount of oil imported from abroad remains stable. CO_2 emissions from natural gas consumption increased by 44.5% from 4,547,400 tons in 2012 to 6,593,700 tons in 2020, indicating that Hunan Province is increasing the use of natural gas energy.

3.2 CO_2 emissions and analysis in processing and conversion

The processing and conversion process consists of the production of electricity and heat (hereinafter referred to as electric heat production), the processing of coal products, petroleum processing, the production of coking and nuclear fuel, and the production of gas. In 2012 and 2020, the total CO_2 emitted by electric heat production was 185.8204 million tons and 157.7852 million tons, respectively, according to the calculation of Figure 1 and 2, accounting for 44.16% and 44.53% of the total carbon emissions, respectively, of which the total CO_2 emissions from power production were 74.0002 million tons and 67.0455 million tons, respectively, indicating that Hunan Province should focus on CO_2 emission reduction in the electric heating sector. The total amount of CO_2 lost in the processing and conversion process1 is equivalent to the total CO_2 emitted by power production, reaching 73.5387 million tons and 62.4438 million tons in 2012 and 2020 respectively, with huge carbon emissions, indicating that Hunan Province should increase the investment of relevant scientific research resources, rely on scientific and technological progress, and improve the technology of energy application.

3.3 CO_2 emissions and analysis in the end-consuming sector

3.3.1 Energy-related CO_2 emissions

According to Figures 1 and 2, the proportion of CO_2 emissions from the final consumption sector in Hunan Province in 2020 was calculated. Among them, ferrous metals, domestic consumption and non-metallic mining accounted for 70.4713 million tons, 50.2318 million tons and 32.7708 million tons of CO_2 emissions in the final consumption sector, accounting for 24.22%, 17.27% and 11.26% of carbon emissions, respectively, ranking the top three. The total CO_2 emissions of the service industry and other industries were 22,637,400 tons and 22,029,900 tons, respectively, accounting for 7.78% and 7.57% of carbon emissions, respectively. In addition, there are agriculture, transportation, chemical industry and mining industry and other sectors with carbon emissions of more than 10 million tons. It shows that in addition to the CO_2 produced in the process of industrialization in Hunan Province, agriculture, transportation, services, daily consumption and others will produce a certain amount of CO_2. Among them, the CO_2 emissions generated by domestic consumption are particularly significant, accounting for the second place in the total CO_2 emissions of the final consumption sector.

3.3.2 Process CO_2 emissions

In 2012 and 2020, the total process CO_2 emissions in Hunan Province were 65.4362 million tons and 72.2164 million tons, respectively. Among them, the CO_2 emissions of ferrous metals, chemical industries and non-metallic mining processes accounted for 10%, 1% and 66% of the total CO_2 emissions in the industry in 2012. In 2020, the CO_2 emissions of ferrous metals, chemical industries and non-metallic mining processes accounted for 16%, 1% and 64% of the total CO_2 emissions of the industry, respectively. In addition to the low proportion of process CO_2 emissions in the chemical industry, process CO_2 emissions from ferrous and non-metallic mining account for a considerable proportion. In 2020, the proportion of CO_2 emissions of ferrous metal processes increased by 6 percentage points compared with 2012, the proportion of CO_2 emissions of chemical industry processes remained unchanged, and the proportion of CO_2 emissions of non-metallic mining processes decreased by 2 percentage points. Among them, although the CO_2 emissions of ferrous metal processes account for relatively small, they have a growth trend, accounting for 16% in 2020, and their total carbon emissions account for the largest proportion in the end-consumption sector, so the process CO_2 emissions of ferrous metals are still large. Process CO_2 emissions in non-metal mining have exceeded energy-related CO_2 emissions, reaching 59,121,300 tons in 2020.

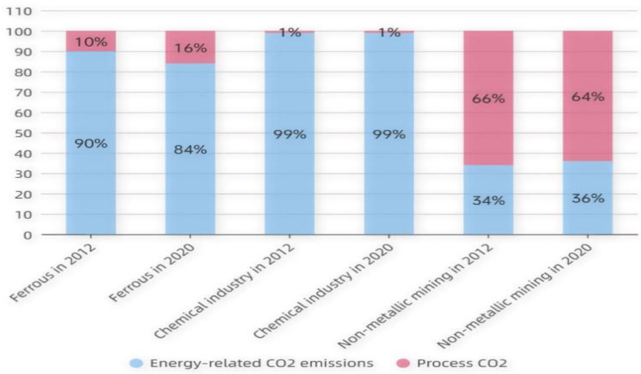

Fig. 3 Comparison of energy-related and process CO_2 emissions across the three sectors in 2012 and 2020

4. Conclusion and discussion

The results show that coal supply is the main energy supply in Hunan Province, the utilization degree of natural gas is low, and the carbon emission structure is single. The CO_2 emissions generated by the power production process in the processing and conversion links are huge in scale, and the carbon emissions losses in each link are serious. The carbon emissions brought by residents' daily consumption in the end-consumption sector are large and still increasing, and the carbon emission structure of each end-consumption sector is different. The process CO_2 emissions of ferrous metal and non-metal mining industries are large, accounting for a certain proportion of the total carbon emissions of the industry.

Based on the above analysis, the paper puts forward the following reference suggestions for Hunan Province to achieve the "dual carbon" goal: (1) actively develop hydropower, steadily develop nuclear power, and develop new energy sources such as biogas, solar energy, wind energy, and geothermal energy according to local conditions, and (2) the power sector adopts effective measures such as reducing line losses, establishing an effective energy-saving evaluation system and improving load utilization to promote energy conservation and emission reduction of the power system. (3) Increase the investment of relevant scientific research resources, rely on scientific and technological progress, improve the technology of energy application, and let the fuel be fully burned to reduce heat loss. (4) Advocate residents to implement the concept of "green consumption" and advocate low-carbon life. (5) Formulate diversified and targeted countermeasures based on the carbon emission structure of each end-consuming sector, taking into account energy-related CO_2 emission reduction in each sector and process CO_2 emission reduction in some sectors.

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