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Decoupling China's mining carbon emissions from economic development: Analysis of influencing factors

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Mining provides basic materials and energy for human life and supports economic and social prosperity and development. The decoupling of mining carbon emissions from economic development is an important way of achieving China's carbon peaking and carbon neutrality goals. This study uses the Tapio decoupling model to measure the relationship between China's economic development and carbon emissions from 2001 to 2018. It analyzes the overall industry as well as its subdivisions and identifies the factors driving carbon emissions with help from the improved Kaya identity and LMDI decomposition models. The results show that, except for the unstable situation in the oil and natural gas mining industry, the other mining divisions have attained strong decoupling and have become stable, showing a continuous positive trend. On the whole, the mining product smelting and processing industry has achieved a major transformation, moving from negative decoupling to weak decoupling, but there are great differences between different sub-sectors. The overall consumption of China's mining products, and the incremental carbon emissions have continued to decline, while economic development has shifted from inefficient expansion to high-quality economic development, although without reaching the ideal state. The economic factor and energy intensity effects are the key factors in increasing and restraining carbon emissions, respectively, and their influence should not be ignored. This study aims to provide a decision-making basis for China's mining industry, that it might carry out carbon emission reduction planning, and promote the clean and efficient construction of the industry and the green and high-quality development of the economy.

Keywords: carbon emissions, economic growth, mining, Tapio decoupling, LMDI decomposition

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INTRODUCTION

Global warming is an urgent problem faced by the whole world. In 2020, global greenhouse gas emissions continued to rise, with the global average temperature about 1.2°C higher than the pre-industrial level (World Meteorological Organization, 2020), and atmospheric CO_2 concentration exceeding 415ppm (Guo, 2019). As the world's largest CO_2 emitter, in response to climate change China announced in September 2020 that its CO_2 emissions would peak by 2030, and that it would strive to achieve carbon neutrality by 2060 (Xinhua Network, 2020). In March 2021, China included the goals of carbon peaking and carbon neutrality in the overall layout of its "ecological civilization" plan (Xinhua News Agency, 2021), and integrated ecological and environmental governance with ecological civilization construction, and produced a balanced development plan for an ecologically sustainable environment and high-quality economic growth.

As a pillar industry in China, the mining industry has caused serious damage to the ecological environment, while simultaneously promoting rapid economic growth. This is especially true of the coal-based mining industry, due to the massive scale of the mining, processing, and consuming of fossil fuels, resulting in the continuous and rapid growth of CO_2 emissions, which have in turn caused a series of environmental problems with a serious impact on the natural environment and the economic development of China (Blöcher et al., 2018; Liu et al., 2021a). In 2020, China's coal production was about 3.9 billion tons, with total annual energy consumption of about 4.98 billion tons of standard coal. Although China's total coal consumption control effect is obvious, and the total share of primary energy consumption continues to decline, in 2020 the proportion of primary energy consumption of coal, oil, and natural gas, were, in turn, 56.8%, 18.9%, and 8.3%, respectively. At the same time, the carbon emissions of these three sources accounted for 67.4%, 22.4%, and 5.4%, respectively (Zhang et al., 2022). Fossil energy dominated by coal still plays the main role in the structure of energy consumption. Energy structure adjustment is the first means of solving traditional energy exhaustion and environmental pollution (Deng et al., 2022). The mining industry supports more than 70% of China's national economy. Against the background of the new normal of economic development, China's economy is shifting from high-speed growth to high-quality development, and the mining industry needs to follow the principles of scientific and sustainable development, deepen structural reform on the supply side, and promote low-carbon and high-quality economic development in the process of achieving carbon peaking and carbon neutrality goals (Ju and Qiang, 2017; Wu and Tu, 2019; Hu and Xiao, 2020; Qiang et al., 2021).

Under the new normal, climate change and low-carbon economic development further produce new and higher requirements for mining. Various studies on economic growth and carbon emissions have recently been conducted. Gao and Ge (2020) pointed out the spatial and temporal characteristics of China's economic growth and energy carbon emissions, based on the evolutionary trends of decoupling China's economy and energy carbon emissions between 2001 and 2015. Han et al. (2021) described the regional differences in carbon emissions in China's provinces from 2005 to 2017 and showed the evolving trend of the decoupling index. Climent and Pardo (2007) analyzed the decoupling of Brazil's economic growth and energy-induced carbon emissions from 2004 to 2009 and conducted an exponential decomposition analysis on the variations in carbon emissions. Wu et al. (2019) studied the decoupling effect of China's provinces from 2001 to 2015 and pointed out that 30 provinces in China generally realized the transition from weak decoupling to strong decoupling. Based on a BP neural network model, Liu et al. (2005) studied the decoupling of carbon emissions and GDP growth in China's nonferrous metals industry from 1995 to 2010, providing a reference for the industry's low-carbon transition. Based on the decoupling model, Luo and Wu (2018) analyzed the carbon emissions from the energy consumption of the mining industry in China from 1994 to 2015, and the results show that the dominant status is weak decoupling. Ramachandra et al. (2017) analyzed the relationship between energy carbon emissions and economic gaps in Bangalore, India, indicating that the economic level is an important factor influencing energy consumption and greenhouse gas emissions in India. Sun and Zhou (2017) constructed a spatial measurement model of carbon emissions from 1996 to 2014, showing that energy intensity and economic development levels are the main factors influencing the decoupling index. Zhang et al. (2019) analyzed the factors affecting carbon emissions in Pakistan from 1971 to 2014, and their results showed that population, fossil energy, and GDP per capita are the main factors affecting carbon emissions in Pakistan.

As for the analysis of the decoupling state and the influencing factors of energy and the economy, most studies are carried out at a single level or in different spatial regions. Few studies have produced a multi-stage and deep analysis based on a long time series, combining the general and local aspects of the whole life cycle. The green, low-carbon, and sustainable development of the mining industry is the main driving force behind China's economic construction and high-quality development. Therefore, this study takes the whole life cycle of carbon emissions and economic growth of the mining industry as the research object; carries out research into the decoupling of carbon emissions and GDP; measures the decoupling effect of carbon emissions in each stage of the mining industry based on the Tapio decoupling model; explores the decoupling characteristics of carbon emission in each industry at each stage of the mining industry; and further adopts the LMDI decomposition model to systematically analyze the influencing factors of carbon emission. The innovation of this study is found in its decomposition of the carbon emission process over the whole life cycle of the mining industry from 2001 to 2018; in the way it carries out carbon emission characterization and analysis of each industry at different stages; and in the way it provides accurate and rapid solutions for pollution traceability. Based on a long time series, a combination of local and general approaches are used to carry out year-by-year and cumulative annual carbon emission driver analysis, which clearly shows the influence results of each factor in each time period. It is expected this work will provide references for understanding the intrinsic mechanism of carbon emission changes, for predicting the future trend of carbon emissions (Lv, 2019), for exploring the path of high-quality economic growth, for adjusting the energy structure, and for formulating and implementing differentiated carbon emission reduction policies in the mining industry.

TABLE 1 | Decoupling state classification.

Type	E(C, D)	△C	△D	Decoupling state
1	(-∞, 0)	<0	>0	Strong decoupling
2	[0, 0.8)	>0	>0	Weak decoupling
3	(1.2, ∞)	<0	<0	Recessive decoupling
4	[0.8, 1.2]	>0	>0	Expansive coupling
5	[0.8, 1.2]	<0	<0	Recessive coupling
6	(1.2, ∞)	>0	>0	Expansive negative
7	(-∞, 0)	>0	<0	Strong negative decoupling
8	[0, 0.8)	<0	<0	Weak negative decoupling

METHODS AND DATA SOURCES

Tapio decoupling model

The Tapio decoupling model is an elastic analysis, and the calculated results have strong stability (Song, 2021; Weng et al., 2021), The decoupling index between GDP growth and carbon emissions is calculated as **Eq (1)**:

$$E_{(C,D)} = \frac{\frac{\Delta C}{C}}{\frac{\Delta D}{D}} \tag{1}$$

where $E_{(C,\ D)}$ is the decoupling index, $\triangle C$ is the amount of change in carbon emissions from the mining industry, $\triangle D$ the amount of change in gross domestic product (GDP), and C and D are total carbon emissions and GDP. Decoupling indices and decoupling types are given in **Table 1**.

LMDI method

The modified Kaya constant equation (**Eq. 2**) and the LMDI (**Eq. 3**) decomposition method are chosen to analyze the influence factors behind carbon emissions from the mining industry, and the Kaya constant equation of carbon emissions from energy consumption is as follows:

$$C = \sum_n \frac{C_n}{E_n} \times \frac{E_n}{D} \times \frac{D}{M} \times \frac{M}{P} \times P = \sum_n f_n \times p_n \times \varphi \times \lambda \times \theta \tag{2}$$

where C is the total carbon emissions of the mining industry; C_n is the nth industrial energy consumption carbon emissions; E_n is the energy consumption of the nth industry; D is the total energy consumption; M is the GDP; P is the total population; f_n is the carbon emission factors; P_n is the energy structure; φ is the energy intensity; λ is the economic factor; and θ is the population size.

Decomposing the amount of carbon emission changes according to the additive form in the LMDI model, assuming that C_o and C_t are the total carbon emissions in the base year, and

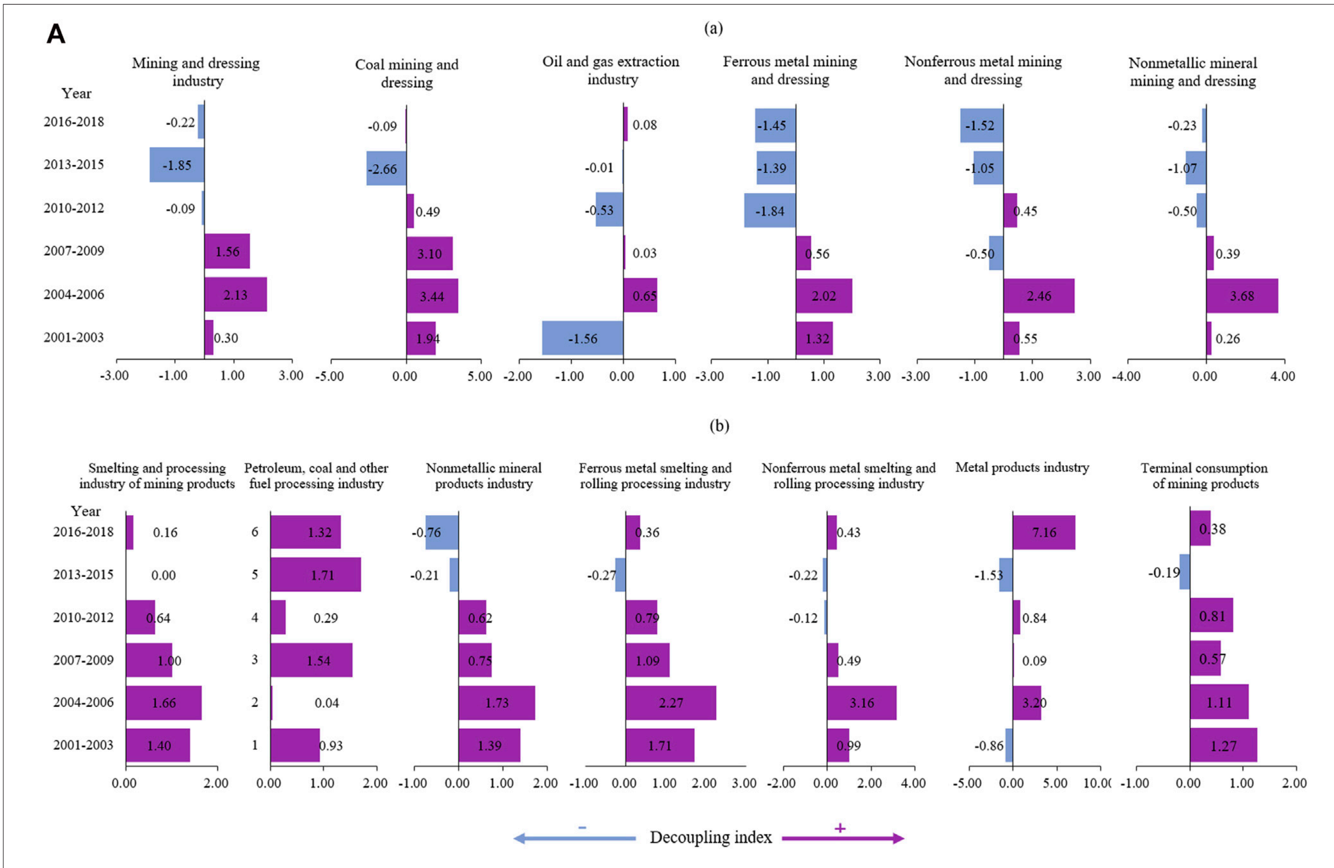

FIGURE 1 | (Continued).

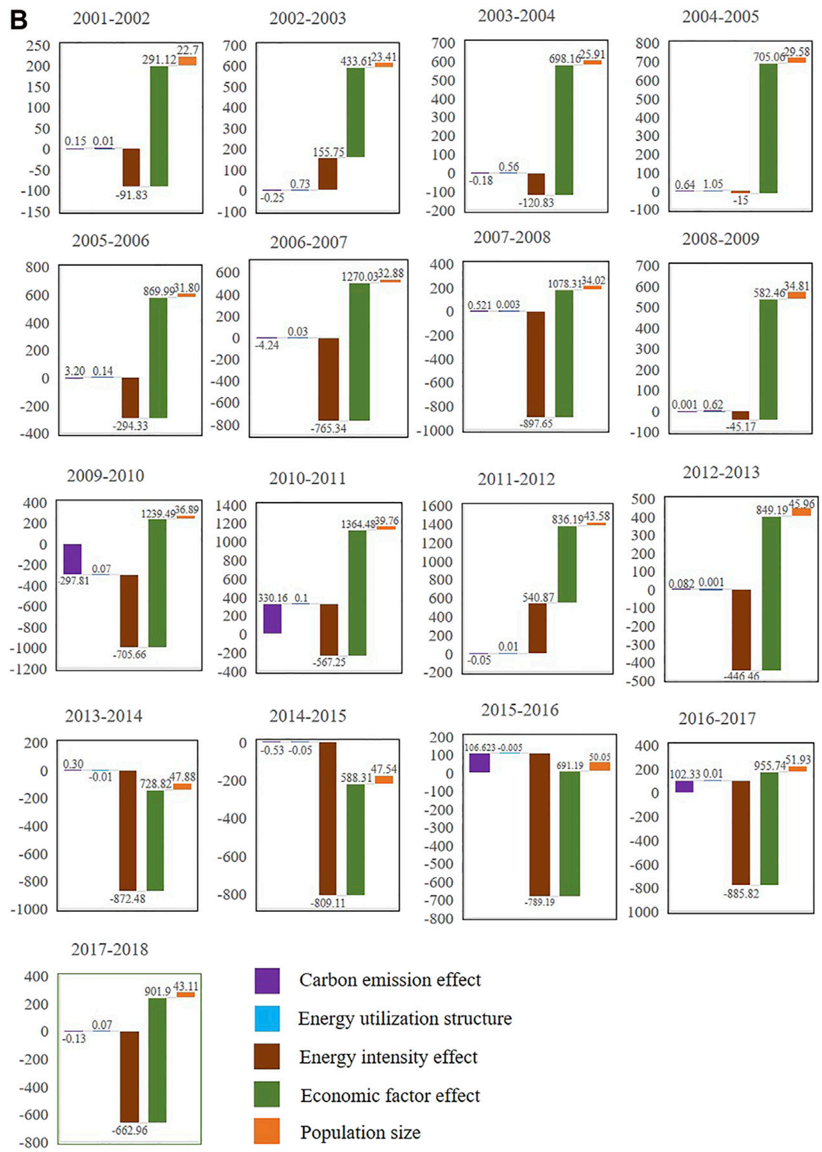

FIGURE 1 | (Continued). Decoupling index of various industries. **(Aa)** Changes in carbon emission decoupling trends in mining and dressing industry, 2001–2018. **(Ab)** Changes in carbon emission decoupling trends in the smelting and processing industry of mining products and in terminal consumption of mining products, 2001–2018. **(B)** Effects of five factors on carbon emissions of China's mining industry. Annual effects of various factors on mining carbon emissions, 2001–2018.

the total carbon emissions in the target year t, respectively, the equation is as follows:

$$\Delta C = C_t - C_o = \Delta C_f + \Delta C_p + \Delta C_\varphi + \Delta C_\lambda + \Delta C_\theta \qquad (3)$$

where $\Delta C_f + \Delta C_p + \Delta C_\varphi + \Delta C_\lambda + \Delta C_\theta$ indicate carbon emission intensity of the mining industry, energy utilization structure, energy intensity effect, economic effect, and population size. The calculation formula of each decomposition factor is as follows:

$$\Delta C_f = \sum_n \frac{C_n^T - C_n^o}{ln\, C_n^T - ln\, C_n^T} \times \left(ln\, f_n^T - ln\, f_n^o \right) \qquad (4)$$

$$\Delta C_p = \sum_n \frac{C_n^T - C_n^o}{ln\, C_n^T - ln\, C_n^T} \times \left(ln\, P_n^T - ln\, P_n^o \right) \qquad (5)$$

$$\Delta C_\varphi = \sum_n \frac{C_n^T - C_n^o}{ln\, C_n^T - ln\, C_n^T} \times \left(ln\, \varphi_n^T - ln\, \varphi_n^o \right) \qquad (6)$$

$$\Delta C_\lambda = \sum_n \frac{C_n^T - C_n^o}{ln\, C_n^T - ln\, C_n^T} \times \left(ln\, \lambda_n^T - ln\, \lambda_n^o \right) \qquad (7)$$

$$\Delta C_\theta = \sum_n \frac{C_n^T - C_n^o}{ln\, C_n^T - ln\, C_n^T} \times \left(ln\, \theta_n^T - ln\, \theta_n^o \right) \qquad (8)$$

Data resource

The data of GDP and the GDP index in this study are from the China Statistical Yearbook (after accounting). In order to ensure comparability, the GDP is treated at constant prices based on

2001. Carbon emissions from the mining industry are mainly divided into three aspects: the mining industry, the smelting and processing industry, and the terminal consumption of mining products. This study focuses on energy products, and the carbon emission data of each industry comes from the CEADS database and the National Bureau of Statistics.

RESULTS AND DISCUSSION

Decoupling analysis of carbon emissions from mining and dressing industry

The changing trend of the overall carbon emissions from the mining and dressing industry (**Figure 1Aa**) reflects a decoupling status and transformation from weak decoupling, to negative decoupling, and then to strong decoupling. During 2001–2009, carbon emissions and economic levels grew rapidly. Then, with the active promotion of China's green mining industry and circular economy, China's economy achieved rapid growth from 2010 to 2018, while the growth of carbon emissions from the mining and dressing industry gradually stabilized, and decreased year by year (Luo and Wu, 2018). In terms of the development status of each sub-sector, in 2010 and 2007, coal and ferrous metal mining and dressing industries reached a strong decoupling state, respectively, and have remained in a stable state, realizing the transformation from high carbon to low carbon development. The mining and dressing industries of nonferrous metals and nonmetallic minerals were in a weak decoupling state during 2001–2003, and in a negative decoupling state from 2004 to 2006, but then attained a strong decoupling state. The decoupling state of the oil and gas extraction industry has gone from strong decoupling to weak decoupling and is in an unstable state. Although the growth rate of carbon emissions is lower than the economic growth rate, this unstable development state is not conducive to the transition to low-carbon industry and brings potential pressure to high-quality economic development. The above results show that China's mining and extraction industry has achieved structural optimization as a whole, but the oil and natural gas extraction industry has room for improvement. Unit intensity control targets should therefore be strengthened to further reduce unit energy consumption (Tian and Xu, 2012). Continuing to promote green and low-carbon transformation is an inevitable direction for the sustainable development and healthy economic growth of China's mining and dressing industry (Liu et al., 2021a).

Decoupling analysis of carbon emissions from the mining product smelting and processing industry

As a whole, the mining product smelting and processing industry (**Figure 1Ab**) has realized the transformation from negative decoupling to weak decoupling, which has altered the traditional development mode to a large extent. However, the industry has been in a state of weak decoupling since 2010, and as an industry with high CO_2 emissions, there is still a large gap before low-carbon development will be realized. The development status of each sub-mining product in the smelting and processing industry reveals petroleum, coal, and other fuel processing is in a relatively poor condition, with the growth rate of CO_2 emissions at a high level, and the economic growth rate significantly lower. From 2001 to 2018, economic growth and carbon emissions were in a relative state, with a slight improvement in the middle, but with little effect, and there has been a lengthy negative decoupling state of expansion since 2013. The nonmetallic mineral products industry has achieved benign development by realizing the transition from negative decoupling of carbon emissions and economic development to weak decoupling, and then to strong decoupling. The ferrous and nonferrous metal smelting and rolling processing industries also showed a better development trend, with expansion of the negative decoupling state to weak and strong decoupling occurring, with carbon emissions still increasing, but by and large effectively controlled. As of 2018, the metal products industry had poor emission reduction and an unstable development status. The trend of decoupling carbon emissions and economic growth is unclear and there is an obvious alternation phenomenon. As the demand for metal products in society continues to expand, the metal products industry needs to actively comply with the low-carbon trend and enhance the strength and sustainability of carbon reduction.

The mining products smelting and processing industry is an important part of China's mining industry. China's mineral resources are gradually shifting from shallow to deep mines, while resource endowment, backward processing technology, low efficiency of production equipment, resource uncertainty and dynamics, etc. pose serious challenges to the low-carbon transformation of the industry. Therefore, as the backbone of the whole life cycle of the mining industry, we should strengthen digitalization, intelligence, and automation, and upgrade the industry in terms of safety, efficiency, the economy, and green and sustainable development (Liu et al., 2021b).

Decoupling analysis of carbon emissions from mining product end consumption

From **Figure 1Ab**, it can be seen that from 2001 to 2018, the incremental carbon emissions from the end consumption of mining products in China, which by and large are in a continuous downward trend, achieved a shift from negative decoupling to weak decoupling, indicating that with the development of the economy and the optimization and upgrading of the mining structure, the utilization efficiency of mineral products improved continuously, and the value creation capacity was increasingly enhanced. There was a brief rebound during 2010–2012, after which the low-carbon state was gradually restored and stabilized, but economic growth and carbon emissions did not achieve coordinated development, and the process of achieving high-quality economic growth needs further improvement.

Rational and efficient utilization of mineral resources is the basis of high-quality economic development. Currently, China is in the stage of rapid industrialization and urbanization. The

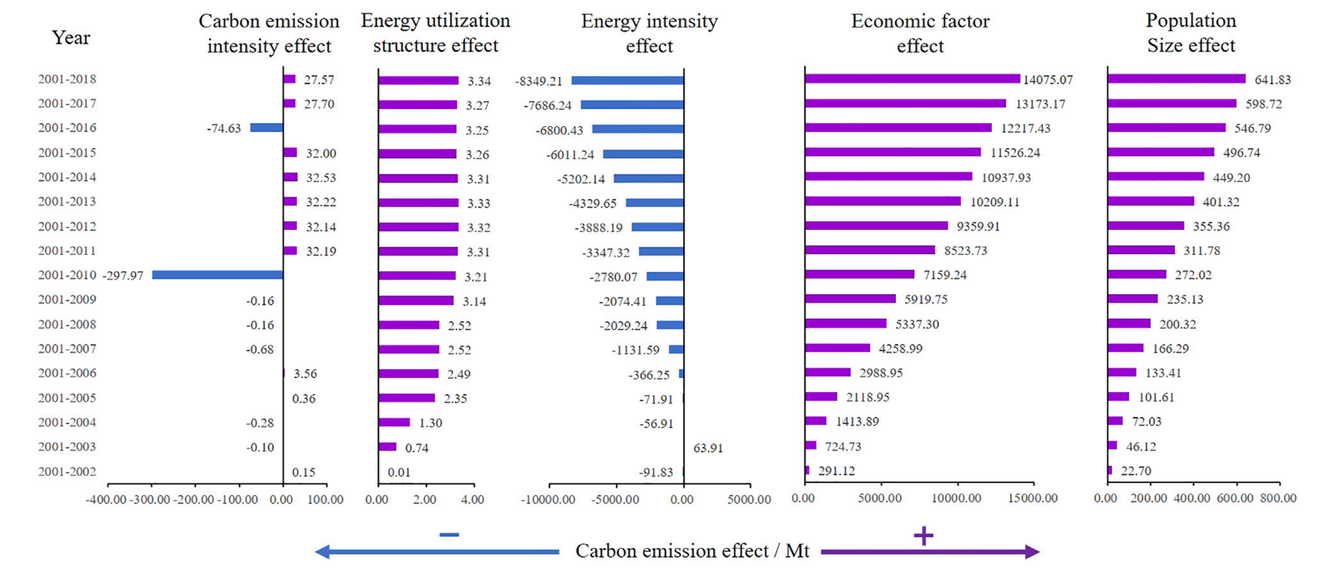

FIGURE 2 | Effects of five factors on carbon emissions of China's mining industry. Cumulative effects of various factors on mining carbon emissions, 2001–2018.

demand for mineral resources continues to grow, and promoting the comprehensive utilization and clean and efficient use of mineral resources has become a top priority (Shang et al., 2022). CO_2, generated by the consumption of energy products, accounts for more than 85% of total carbon emissions. Accelerating the adjustment of the energy consumption structure (Li et al., 2022), reducing the proportion of fossil energy with high carbon emissions, and continuously increasing the proportion of clean energy are important ways to realize the transition from weak decoupling of consumption carbon emissions and economic growth, to strong decoupling (Li, 2022).

Decomposition analysis of carbon emission drivers in the mining industry

The factors influencing carbon emissions from China's mining industry from 2001 to 2018 were decomposed by the LMDI model into a carbon intensity factor, an energy utilization structure factor, an energy intensity factor, an economic effect factor, and a population size factor. From the results of the year-by-year effect of the model's operation (**Figure 1B**), we can clearly see the driving or inhibiting effects of these five factors on carbon emissions in each part of the study period, and the different time changes in the same factors. The carbon intensity factor was consistently stable and mostly suppressed carbon emissions from the mining industry during the period 2001–2009, although there were two large fluctuations during the periods 2009–2012, and 2015–2018. Except for the period 2013–2016, the energy structure factors are positively correlated, and the other periods are relatively stable, with all of them showing the inhibition effect on carbon emissions. Energy intensity factors play a dominant role in inhibiting CO_2 growth, and only in 2002–2003 are they positively correlated with carbon emissions, being negatively correlated for the remainder of the period. Carbon emission reduction reached 8.9764 million tons during 2007–2008. The contribution of economic effects to carbon emissions was promoted from 2001 to 2018. Due to China's previous high-speed economic development model and its large share in the overall emission situation, there are higher requirements for carbon emission reduction. The population size factor continues to have a positive effect on carbon emissions, with a low share during the study period, and as the population size continues to increase, the consumption of resources also expands, thus leading to an increase in CO_2 emissions.

The trend of the cumulative effect of each factor on carbon emissions of energy consumption in China's mining industry from 2001 to 2018 can be seen in **Figure 2**. From an overall perspective, the cumulative effect of carbon intensity alternates positively and negatively during the study period, had a low impact on carbon emissions, and, most of the time, CO_2 emissions increased with a small positive value. During the analysis period, the cumulative effect of energy utilization continued to grow slowly with a positive value, reflecting that China's previous energy utilization structure was relatively unified, leading to an increase in CO_2 emissions. The cumulative effect of energy intensity is the greatest contributor to mining emissions reduction, showing a significant effect on curbing CO_2 emissions by a large amount each year. The effect of economic factors is positively correlated with the decomposition of carbon emissions from the mining industry, both year-by-year, and cumulatively, and contributes most significantly to the increase in carbon emissions throughout the study period. The cumulative effect of the population size factor also continues to stimulate the increase of CO_2 emissions at a faster rate. Although the cumulative effect of the population size factor now accounts for a smaller share in emissions, its influence should not be ignored given the rapid increase in population, the desire for a high quality of life, and increasing carbon emissions from personal energy consumption.

In conclusion, China's economic development transition is still occurring, and energy consumption per unit of GDP is still at a relatively high level, about 1.46 times the world average (Li, 2022). Energy utilization is mainly based on coal (Zhuang and Yan, 2017) and a relatively unified energy structure. China has a large population base, and with the development of a well-off society in an all-around way, and people's yearning for a better life, energy consumption will greatly increase, and the scale of carbon emission activities will gradually expand (Gao et al., 2021). The COVID-19 epidemic has also impacted China's economic development. Energy is the foundation of economic development, and economic recovery after the epidemic reveals a huge gap in energy supply. Therefore, it is of great significance to build a circular economic system decoupling economic growth from resource consumption (Meng et al., 2021), to expand the influence of energy intensity on carbon emission reduction, and to master the driving factors of carbon emissions for the green development of China's mining industry.

CONCLUSION

Based on data on China's economic development and mining carbon emissions from 2001 to 2018, and using the Tapio decoupling state analysis model and improved Kaya identity and LMDI decomposition model, this study explores the decoupling relationship between mining carbon emissions and economic development in China. Related factors affecting mining carbon emissions were decomposed and analyzed based on time patterns. The main conclusions are as follows:

(1) The overall development of China's mining and extraction industry has achieved a major shift, with the decoupling index dropping from 0.304 to −0.266, achieving and continuing to develop a strong decoupling state since 2010. The carbon emissions of coal mining and dressing, ferrous metal mining and dressing, nonmetallic mining and dressing, and nonferrous metal mining and dressing have been greatly controlled. The decoupling index decreased from 1.938, 1.318, 0.259, and 0.553 in the early stage to −0.088, −1.452, −0.226, and −1.525 in the later stage, respectively, reflecting the harmonious development of the mining and extraction industry and the economy. However, the development of the oil and natural gas mining industry is unstable, with the decoupling index alternating between positive and negative, showing a repeated situation of strong decoupling and weak negative decoupling. Therefore, this industry sector needs to strengthen carbon emission reduction actions and improve the space for green and low-carbon development.

(2) CO_2 emissions from the mining products smelting and processing industry were effectively controlled at the overall level, and the decoupling index changed from the previous 1.402 to the later 0.16, thus achieving a shift from negative decoupling to weak decoupling. This indicates that the overall industrial structure is optimized, and is gradually transforming from a high-energy consumption industry to a low-energy consumption industry. The nonmetallic mineral products industry, and nonferrous metal smelting and rolling processing industries, all achieved low-carbon development, with decoupling values ranging from-0.5 to 1.4, hence successively achieving a strong decoupling development state. The ferrous metal smelting and rolling processing industry also achieved better development, with the decoupling value between −0.3 and 1.8, showing a downward trend on the whole, and changing the state of inefficient expansion of the industry. The development of petroleum, coal, other fuel processing industries, and the metal products industry is not as positive, with the former decoupling index in 2007 remaining above 1.5, and the decoupling index of the latter alternating between positive and negative, with a wide floating range, and still a large gap before strong decoupling is achieved.

(3) China's energy end consumption has achieved a shift from high consumption and high carbon emissions to low carbon emissions and green economic development, with a decoupling index between −0.2 and 1.3, although it has not yet reached the ideal state. Based on the time pattern, China's energy carbon emissions are on a growth trend. As China's fossil energy consumption accounts for a relatively large proportion of emissions, it is difficult to achieve a rapid restructuring of the mining industry over a short period of time. Therefore, in order to achieve green and low-carbon development in China, increasing the proportion of clean energy, and adjusting the energy consumption structure are important ways forward.

(4) In the analysis of annual effect and annual cumulative effect, economic factors promoting CO_2 emission have the greatest impact on CO_2 emissions every year. Production reached a peak of 1,364.48 million tons (Mt) in 2011, which was the main factor in promoting carbon emission. While the effect of energy intensity fully shows the advantages of suppressing CO_2 emission, the restraining effect was small in 2001–2006. There was an obvious restraining effect from 2007, with the restraining amount reaching a peak of 885.82 Mt in 2017. Most of the time carbon intensity shows positive and negative alternation in a widely fluctuating range. At the same time, this will be an important aspect of carbon reduction and emission reduction in the future. The effect value of the population factor is positive year by year, and it keeps increasing at an annual growth rate of about 0.04%. The annual effect value of the energy utilization structure is -0.15~1.1 (Mt). Although this

accounts for a small proportion of the total, its impact should not be ignored.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

WS contributed to all aspects of this work; SR conducted data analysis; SR and KL wrote the manuscript text; CZ gave some useful suggestions and comments to this work. All authors reviewed the manuscript.

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REFERENCES

Blöcher, M., Zimmermann, G., Moeck, I., Brandt, W., Hassanzadegan, A., and Magri, F. (2018). Carbon emission decoupling and decomposition of energy consumption in mining industry of China. *Resour. Industries* 20 (01), 61–67. doi:10.13776/j.cnki.resourcesindustries.20180212.010

Climent, F., and Pardo, A. (2007). Decoupling factors on the energy–output linkage: The Spanish case. *Energy Policy* 35, 522–528. doi:10.1016/j.enpol.2005.12.022

Deng, M. J., Ming, B., Li, Y., Huang, Q., Li, P., and Wu, M. (2022). Pathways towards a cleaner energy system for Xinjiang under carbon peak and carbon neutrality goals. *J. Nat. Resour.* 37 (05), 1107–1122. doi:10.31497/zrzyxb.20220501

Gao, C. C., Ge, H. Q., Lu, Y. Y., Wang, W. J., and Zhang, Y. J. (2021). Decoupling of provincial energy-related CO_2 emissions from economic growth in China and its convergence from 1995 to 2017. *J. Clean. Prod.* 297, 126627. doi:10.1016/J.JCLEPRO.2021.126627

Gao, C., and Ge, H. (2020). Spatiotemporal characteristics of China's carbon emissions and driving forces: A five-year plan perspective from 2001 to 2015. *J. Clean. Prod.* 248, 119280–120127. doi:10.1016/j.jclepro.2019.119280

Guo, Y. N. (2019). Atmospheric CO_2 concentration reaches historic peak. *Ecol. Econ.* 35 (07), 5–8.

Han, M. Y., Liu, W. D., Xie, Y. T., and Jiang, W. B. (2021). Regional disparity and decoupling evolution of China's carbon emissions by province. *Resour. Sci.* 43 (04), 710–721.

Hu, Z. Q., and Xiao, W. (2020). Some thoughts on green development strategy of coal industry: From aspects of ecological restoration. *Coal Sci. Technol.* 48 (04), 35–42. doi:10.13199/j.cnki.cst.2020.04.002

Ju, J. H., and Qiang, H. Y. (2017). The trend and direction of green development of the mining industry in China. *China Min. Mag.* 26 (02), 7–12.

Li, H., Pang, B., Zhu, F. H., Sun, X. L., Xu, J. X., and Wang, S. (2022). *Comparative energy consumption structure and mode between China and major energy consuming countries under the background of carbon emission reduction*. Springer, 1–13. doi:10.13227/j.hjkx.202112065

Li, J. (2022). Research on the relationship and impact of energy consumption and high-quality economic development in China. *Mod. Econ. Res.* 2022 (04), 11–20+132. doi:10.13891/j.cnki.mer.2022.04.006

Liu, G. X., Jia, F. R., Yue, Q., Ma, D. Z., Pan, H. D., and Wu, M. (2005). Decoupling of nonferrous metal consumption from economic growth in China. *Environ. Dev. Sustain.* 18 (1), 221–235. doi:10.1007/s10668-015-9635-0

Liu, X. J., Hou, H. L., Sun, Y. X., and Zhou, P. (2021a). Thinking about the connotation and realization path for green mining in China. *Min. Res. Dev.* 41 (10), 180–186. doi:10.13827/j.cnki.kyyk.2021.10.031

Liu, X. J., Hou, H. L., Wu, Q., Tian, X., Wu, S. K., and Huang, J. (2021b). Spatial pattern of the green development of mining industry in the Yangtze river economic belt and its driving mechanism. *Min. Res. Dev.* 41 (04), 176–182. doi:10.13827/j.cnki.kyyk.2021.04.033

Luo, S. X., and Wu, X. (2018). Carbon Emission Decoupling and Decomposition of Energy Consumption in Mining Industry of China. *Resour. Ind.* 20 (1), 61–67. doi:10.13776/j.cnki.resourcesindustries.20180212.010

Lv, Q. (2019). *Study on spatiotemporal dynamic characteristics and reduction strategy of energy consumption carbon emissions in China*. Beijing: China University of Mining & Technology. [master's thesis].

Meng, X. Y., Wang, Y., and Zheng, X. Z. (2021). Circular economy strategy for the target of carbon neutralization: Management experience and enlightenment from turku. *Finl. Environ. Prot.* 49 (12), 76–80. doi:10.14026/j.cnki.0253-9705.2021.12.003

Qiang, H. Y., Gao, B., Guo, D. Y., and Wang, X. Y. (2021). Options for sustainable development of mining industry under the background of carbon neutrality. *Nat. Resour. Econ. China* 34 (04), 4–11. doi:10.19676/j.cnki.1672-6995.000603

Ramachandra, T. V., Bajpai, V., Kulkarni, G., Aithal, B. H., and Han, S. S. (2017). Economic disparity and CO2 emissions: The domestic energy sector in greater Bangalore, India. *Renew. Sustain. Energy Rev.* 67, 1331–1344. doi:10.1016/j.rser.2016.09.038

Shang, M., Wang, R. R., and Hu, Z. (2022). Study on spatial and temporal evolution and driving mechanism of carbon emissions from provincial energy consumption in China - the analysis based on the perspective of environmental regulation. *Environ. Pollut. Control* 44 (04), 529–534+551. doi:10.15985/j.cnki.1001-3865.2022.04.020

Song, Z. G. (2021). Economic growth and carbon emissions: Estimation of a panel threshold model for the transition process in China. *J. Clean. Prod.* 278, 123773. doi:10.1016/j.jclepro.2020.123773

Sun, Y. F., and Zhou, M. (2017). Decoupling and driving factors analysis between the energy carbon emissions and economic growth in China. *Rev. Econ. Manag.* 33 (06), 21–30. doi:10.13962/j.cnki.37-1486/f.2017.06.003

Tian, F., and Xu, X. F. (2012). Mechanism analysis about exploitation of oil and gas resources in China under low-carbon economy. *Future Dev.* 35 (01), 48–50+55.

Weng, G. M., Li, C. H., Pan, Y., and Li, J. P. (2021). Decoupling Effect and Influencing Factors of Carbon Emissions in China's Tourism Industry. *Geogr. Geo-Inf. Sci.* 37 (2), 114–120.

World Meteorological Organization (2020). *WMO state of the global climate 2020 (provisional report)*. Geneva: WMO.

Wu, Q., and Tu, K. (2019). Analysis on the dual constraints of energy and environment to the development of China and countermeasures. *Chin. Sci. Bull.* 64 (15), 1535–1544. doi:10.1360/n972018-01057

Wu, Y., Tam, V. W. Y., Shuai, C., Shen, L., Zhang, Y., and Liao, S. (2019). Decoupling China's economic growth from carbon emissions: Empirical studies from 30 Chinese provinces (2001–2015). *Sci. Total Environ.* 656, 576–588. doi:10.1016/j.scitotenv.2018.11.384

Xinhua Network (2020). President Xi Jinping delivered an important speech at the general debate of the 75th session of the UN General Assembly. Available at: https://www.mfa.gov.cn/ce/ceus/eng/zgyw/t1817766.htm.

Xinhua News Agency (2021). President xi jinping presided over the ninth meeting of the central finance and economics commission. *Budg. Manag. Account.* 1 (04), 4–5.

Zhang, K., Miao, M., and Zhang, L. Q. (2022). Carbon peaking and carbon neutrality goals and reflections on China's energy transition Part II——fossil energy in energy transition. *Sino-Global Energy* 27 (04), 1–7.

Zhang, Q. Y., Zhang, Y. L., and Pan, B. B. (2019). Influence factor to carbon emissions in Pakistan. *South Asian Stud. Q.* 2019 (02), 50–57+5. doi:10.13252/j.cnki.sasq.2019.02.07

Zhuang, Z. Q., and Yan, W. L. (2017). The contribution of technical innovation capability to optimize the structure of energy utilization in China: A theoretical and empirical analysis. *Nanjing J. Soc. Sci.* 2017, 24–31. doi:10.15937/j.cnki.issn1001-8263.2017.10.004

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