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Original Research

How Does Metal Consumption Decouple? Evidence from Copper Based upon Tapio Theory and LMDI Model

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Abstract

Copper, the cornerstone metal in sustainable energy initiatives, plays a crucial role in applications such as electric vehicles, wind turbines, and other green energy projects. This paper aims to study the evolution and decoupling relationship between copper consumption and economic growth. We first quantified the trends of the Copper Decoupling Index. Utilizing an expanded Kaya identity and logarithmic mean Divisia index (LMDI) decomposition method, the analysis explores the key drivers behind copper consumption. The results are as follows: 1) Developed countries such as the United Kingdom and the United States have showcased an ideal state of strong decoupling between economic growth and copper consumption, whereas Germany and Japan have generally shown signs of negative or weak decoupling. Conversely, in China, the consumption of copper has experienced negative decoupling growth. 2) During China's industrialization process, the primary catalyst for changes in copper consumption was the scale effect, while the structural and efficiency effects exerted negative regulatory influences. 3) Recent structural adjustments in China have highlighted the inhibitory impact of structural changes on electricity consumption growth. From 2006–2022, the influence of industrial structural changes on copper consumption has been predominantly governed by negative regulation, with its intensity increasing year by year since 2014. These research findings offer valuable insights for policymakers globally in developing tailored strategies for copper supply and consumption in varying economic growth scenarios.

Keywords: copper consumption, driving factors, Tapio Decoupling Theory, LMDI factor decomposition model

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Introduction

Metal consumption, especially bulk metal, permeates the entire process of a country's (or region's) industrialization. Copper, as a prominent non-ferrous metal, is extensively used in electrical engineering, light industry, mechanical manufacturing, construction, national defense, and other sectors due to its exceptional conductivity, strength, resilience, and corrosion resistance. Notably, copper has become an indispensable component in electric vehicles, wind turbines, and various alternative energy initiatives. As global demand for low-carbon power generation equipment and new energy infrastructure continues to rise, the need for copper correspondingly increases. Over the years, China has emerged as the world's largest consumer of copper, highlighting the significance of understanding the factors influencing copper consumption in China. This knowledge is crucial for the sustainable development of the copper industry during the new stage of post-industrialization, the promotion of emissions reduction in end-use applications, and the support of strategic emerging industries.

According to the latest statistics released by the International Copper Study Group in 2023, global refined copper production increased by approximately 2.8% in 2022. Of the total consumption of 25.97 million tons, China accounts for 58%, solidifying its position as the world's largest consumer of refined copper. Moreover, the EU 15 countries and the United States contribute 12% and 7%, respectively, to the overall consumption, collectively representing about 77% of global copper demand. As the global copper market gradually recovers from the impact of the Corona Virus Disease 2019 (COVID-19) pandemic, a significant increase in overall consumption is anticipated. Currently, we are amidst unprecedented transformations reshaping the world in this century. The escalation of global trade protectionism introduces significant uncertainties and risks to China's industrial chain. In the context of the copper industry chain, production recovery outpaces demand revival. Therefore, studying the factors influencing copper consumption in China is of paramount significance.

The correlation between economic growth and the overall consumption and composition of mineral resources has long been a central focus in resource economics research. Since the 1990s, in pursuit of sustainable development objectives, scholars have increasingly directed their attention toward investigating the interplay between economic growth and the environmental pressures associated with resource utilization. This shift in focus emphasizes theoretical advancements and the application of quantitative methods. Consequently, the introduction of concepts such as the Environmental Kuznets Curve (EKC) and Decoupling Theory, along with corresponding methods and indicators, has provided theoretical frameworks and a broader array of quantitative tools to guide the sustainable management of mineral resources. The "decoupling" analysis method is designed to disentangle the linkage between resource and environmental pressures and economic performance. It not only encapsulates the intrinsic connection between these factors through a straightforward quantitative framework but also effectively discerns the distinct stages and current dynamics of this relationship's evolution. This method enables the analysis of economic growth in conjunction with material resource consumption, energy use, land occupation, environmental degradation, and carbon emissions. In contrast to the EKC hypothesis, which examines the long-term trajectory of resource and environmental pressures stemming from economic advancement, decoupling analysis is oriented towards real-time fluctuations in the interaction between these factors on a short-term basis.

While many scholars have focused on the evolution patterns of energy and mineral resource consumption, there has been a noticeable lack of attention to non-energy mineral resource consumption and a dearth of comprehensive theoretical perspectives. Existing research often fails to consider both long-term trends and short-term real-time variations, and there is a notable gap in analyzing the factors influencing decoupling. Several critical issues remain inadequately addressed, including analysis and interpretation: Given the distinct nature of metal mineral resources compared to energy mineral resources, does their consumption truly decouple from economic growth? What are the unique characteristics of the decoupling process in countries that have achieved decoupling? Are there commonalities and disparities in the decoupling trajectories between developed nations and latecomers? What factors play a pivotal role in driving the decoupling phenomenon?

The aim of this study was to examine the decoupling relationship between copper consumption and economic growth. We show the cumulative copper resource consumption patterns and decoupling state during the industrialization processes in the United Kingdom, the United States, Japan, Germany, and China. This paper takes copper as an example and uses the LMDI method to analyze the factors influencing China's copper consumption. This research contributes to the high-quality development of the copper industry during the new stage of post-industrialization, aids in reducing emissions in end-use applications, and supports the growth of strategic emerging industries. In conclusion, the profound significance of copper across various sectors and China's position as the largest consumer cannot be underestimated. As the demand for green energy intensifies and the global copper market rebounds, it becomes imperative to identify the factors that shape copper consumption in China and strive for the high-quality development of this industry.

Literature Review

At the theoretical level, the relationship between economic growth and the total amount and structure of resource consumption has garnered significant attention in the field of resource economy. Since the 1990s, scholars have predominantly focused on studying the nexus between economic growth, environmental pressures, and resources, emphasizing theoretical deepening and the application of quantitative methodologies. Thus, the introduction of decoupling theories, methods, and indicators provides theoretical guidance and diversified quantitative approaches for investigating sustainable resource development. Presently, numerous studies explore resource-environment variables (e.g., CO_2, energy, urban waste) and short-term local pollutants (e.g., SO_2, SPM, NO_X, and CO), as well as land consumption within the realm of resources and the environment [1]. However, there remains a paucity of research on the decoupling conditions of non-energy mineral resource consumption.

The decoupling analysis approach endeavors to sever the connection between resource and environmental pressures and economic performance. It characterizes the intrinsic relationship between the two through quantitative relations while effectively identifying the specific phases and real-time information pertaining to their evolutionary dynamics. This approach enables an examination of the relationship between economic growth and the consumption of material resources, energy consumption, land occupation, environmental pollution, and carbon emissions. Decoupling analysis focuses on long-term and short-term real-time changes in the interaction between economic development and resource and environmental pressure [2]. Shen et al. (2017) [3] posit that China's economic growth and mineral resource consumption exhibit periodic decoupling and re-coupling. Wang et al. (2020) [4] contend that the decline in total energy consumption stems from the slowdown in economic growth since 2013, the profound adjustment of industrial structure, and the continuous decrease in energy consumption intensity. Ma et al. (2021) [5] discover that China's industrial economic growth and energy consumption demonstrate a robust decoupling state, with energy intensity and industrial structure effects playing pivotal roles in achieving such decoupling. The "dual carbon" goal necessitates accelerated industrial structural adjustments, controlled total energy consumption, enhanced energy efficiency, and the long-term promotion of green, low-carbon, and sustainable development within the energy and mineral industry.

There are many studies on basic metal encompassing aspects of supply security (Zeng et al., 2023; Duan et al., 2021; Sun et al., 2019) [6–8], demand forecasting (Zhang et al., 2015) [9], and consumption intensity (Yang et al., 2015) [10]. Conversely, there exists relatively limited research on the influencing factors and driving forces behind consumption structure. Currently, several approaches are employed to study consumption structure and its impact factors concerning basic metal. One method revolves around input-output sensitivity analysis, using this analysis to examine the structural and technological incentives as well as the driving factors behind consumption growth based on the Leonev input-output model (Yan et al., 2015; Liu et al., 2016; Huang et al., 2018) [11–13]. This method primarily scrutinizes the interrelationships among industrial sectors, with extensive research focusing on carbon emissions. Another method examines the factors influencing long-term and short-term changes in resource consumption through per capita mineral resource consumption analysis. Malenbaum (1978), for instance, conducted a comprehensive study of the long-term shifts in demand for mineral resource consumption in the United States, based on per capita mineral resource consumption. His findings suggested an inverted "U"-shaped relationship between the intensity of mineral resource consumption and per capita income. The Institute of Mineral Resources, Chinese Academy of Geological Sciences, developed an "S" pattern model for per capita copper resource consumption, concluding that per capita GDP constitutes the primary driver for copper consumption. Further research has explored the consumption structure of copper resources in China, revealing a striking resemblance to Japan's trend in copper consumption structure during the 1960s-1970s. Researchers employ regression models to analyze the impact of factors such as population, technology, industrial structure, and wealth on resource consumption (Wiedmann, 2015; Wang et al., 2016) [14, 15]. Econometric models offer a certain degree of explanation regarding the influence of factors like industrial structure, technology, and economic development level on resource consumption costs. However, they fail to elucidate the correlations among industrial sectors. The third approach involves factor decomposition models. This method employs index decomposition and structural decomposition techniques to disentangle the primary driving forces impacting metal consumption at the global and national levels. These forces include economic scale, industrial structure, and intensity effects (Yao et al., 2018) [16]. Factorization models are widely employed in the study of energy and carbon emissions as a primary empirical method for analyzing influencing factors.

Chen et al. (2023) [17] utilized the Kaya identity and the LMDI decomposition method to assess and analyze the implicit carbon emissions generated in the energy consumption process of 30 mainland Chinese provinces (excluding Tibet) from 2003 to 2020, considering both temporal and spatial dimensions. He et al. [18] analyzed the influencing factors of carbon emissions in China's electricity industry based on the combination of LMDI and K-means clustering. Guo et al. [19] used the kaya identity and LMDI decomposition methods to identify the contributions of six factors to NO_X emissions reduction in China's power industry. Quan et al. [20] used the LMDI method to analyze the influencing factors of carbon emissions in China's logistics industry. Liu et al. [21] established LMDI and Tapio models to deeply explore the influence degree of different factors on carbon emissions. De Oliveira-De Jesus [22] and Alajmi [23] analyzed the factors of electricity-related CO_2 emissions in the Latin America and Caribbean (LAC) power sector and greenhouse gas emissions in Saudi Arabia based on the LMDI model.

Since the 1980s, Divisia decomposition has gained prominence in the fields of energy and carbon emissions due to its efficacy in addressing zero-point and residual issues during decomposition. The Divisia decomposition method circumvents the need for input-output tables while providing more rational and scientific explanatory factors, excluding unexplained residual terms. Consequently, the conclusions derived from actual research align more closely with reality and boast wider applicability. Thus, this decomposition method is extensively employed in causal analyses of energy consumption and intensity [24–26]. Fang et al. [27] and Jiang et al. [28] analyzed the influence mechanism of China's electricity consumption and non-residential power consumption based on a multi-period ST-LMDI model and Kaya-LMDI methods. Murni Yetty et al. [29] provided econometric individual time series VEC models and discovered that economic variables were the most significant factors that aggravated the change in household energy consumption based on LMDI. Hasan and Liu [30] used the LMDI to explore the factors influencing natural gas consumption in Bangladesh from 1994 to 2018.

To address the gap in understanding decoupling between fundamental metals and the drivers of economic growth and consumption structure, this paper utilizes copper as an exemplar. To begin with, an analysis of the cumulative copper resource consumption patterns during the industrialization processes spanning over 250 years in the United Kingdom, nearly 230 years in the United States, approximately 150 years in Japan and Germany, and almost 70 years in China reveals a strikingly similar trajectory of evolutionary patterns. Moreover, by applying the Tapio Decoupling Theory, we delve into the intricate relationship between copper consumption and economic growth in major countries. Furthermore, we employ the LMDI factor decomposition model to gain deeper insights into the driving forces behind China's copper consumption. This meticulous approach allows for an exploration of the intrinsic factors influencing the growth of mineral resources during China's middle and late stages of industrialization. Subsequently, we meticulously decompose metal consumption along three pivotal dimensions: the scale effect, structural effect, and efficiency effect. Through this comprehensive analysis, we aim to illuminate the intensity of each effect within China's metal consumption growth process, identify the driving factors fueling economic growth, and provide astute recommendations and countermeasures for the development of the fundamental metal industry within the framework of the "dual carbon" goal.

Experimental

Tapio Decoupling Model

The Tapio decoupling elastic model possesses notable advantages, including stability, accuracy, and resilience to statistical dimensional variations [35]. In this study, we employ this model within the realm of metal and metal consumption to investigate the relationship between economic growth and metal consumption during the process of industrialization. The Tapio decoupling elastic model is constructed as follows:

$$DEI_{t_0,t_1} = \frac{EP_{t_1} - EP_{t_0}}{EP_{t_0}} \Big/ \frac{DP_{t_1} - DP_{t_0}}{DP_{t_0}} \quad (1)$$

Where *DEI* represents the decoupled elastic index, *EP* refers to environmental pressure indicators (in this study, it pertains to metal consumption), and *DP* denotes the economic driving force indicator. Specifically, we utilize per capita GDP as the economic driving force indicator, with t_0 denoting the base period and t_1 representing the current period. Given the lagged relationship between resource consumption and economic growth, a time interval of 5–10 years is necessary for period analysis. Here, we adopt a 5-year time interval. Table 1 classifies Tapio decoupling elasticity into eight levels: strong decoupling, weak decoupling, recession decoupling, strong negative decoupling, weak negative decoupling, growth negative decoupling, growth connection, and recession connection. Among these levels, strong decoupling signifies the optimal state where resource and environmental pressures gradually decrease alongside economic growth, whereas strong negative decoupling represents the worst decoupling state characterized by a negative correlation between economic growth and resource/environmental pressure. The economic implications associated with other states lie along a continuum, as resource and environmental pressures intensify concurrently with recessions.

LMDI Model

Extension of Kaya Identity for Metal Consumption

The Kaya identity, proposed by Japanese professor Yoichi Kaya at the 1989 United Nations Intergovernmental Panel on Climate Change (IPCC) seminar, is commonly employed for analyzing the driving factors behind changes in CO_2 emissions at the national level. According to Professor Yoichi Kaya, CO_2 emissions are primarily determined by population, standard of living, energy use intensity, and carbon emission factors. The specific Kaya identity is formulated as follows:

$$C = \frac{C}{E} \times \frac{E}{Y} \times \frac{Y}{P} \times P \quad (2)$$

$$CE = \frac{C}{E} \quad (3)$$

$$EI = \frac{E}{Y} \quad (4)$$

Where *C* represents total CO_2 emissions, *E* denotes total energy consumption, *Y* signifies gross domestic product, and *P* denotes total population; *CE* represents the ratio of total CO_2 emissions to total energy consumption, reflecting the intensity of CO_2 emissions predominantly determined by energy consumption structure; *EI* stands for the ratio of total energy consumption to GDP, representing a factor of energy consumption intensity that reflects the degree of economic dependence on energy and remains closely linked to industrialization, economic structure, and energy utilization rates; *G* denotes the ratio of GDP to population, representing

Table 1. Decoupling types and meaning of Tapio models.

Decoupling state	Ambient pressure ΔEP	Economic driving force ΔDP	Decoupling index DEI	number	Decoupling type
Negative decoupling	>0	>0	(1.2,+∞)	I	Expansive negative decoupling
	>0	<0	(-∞,0)	II	Strong negative decoupling
	<0	<0	(0,0.8)	III	Weak negative decoupling
Decoupling	>0	>0	(0,0.8)	IV	Weak decoupling
	<0	>0	(-∞,0)	V	Strong decoupling
	<0	<0	(1.2,+∞)	VI	Recessive decoupling
Connection	>0	>0	(0.8,1.2)	VII	Expansive coupling
	<0	<0	(0.8,1.2)	VIII	Recessive coupling

an economic size factor that reflects a country's per capita standard of living; P represents the population size factor, signifying the influence of population on total CO_2 emissions.

The focus of this study lies in metal consumption. It primarily decomposes the factors influencing metal consumption and extends the above equation to obtain:

$$C = \sum_{i=1}^{3} \frac{C_i}{Y_i} \times \frac{Y_i}{Y} \times \frac{Y}{P} \times P \tag{5}$$

$$C = \sum_{i=1}^{3} IU_i \times S_i \times A \times P \tag{6}$$

Where P refers to the population; Y represents GDP; Yi signifies the GDP of tertiary industries, C represents metal consumption in tertiary industries, IU_i denotes the consumption intensity of metal in industry I, S_i represents the fraction of GDP attributed to industry I, and A denotes per capita gross domestic product.

LMDI Decomposition Model for Total Metal Consumption

The core concept of the LMDI decomposition method involves decomposing the total increment into various related influencing factors and quantifying the degree of influence each factor exerts on the total increment [31, 32]. This method has found extensive application in decomposing influencing factors such as carbon emissions, energy consumption, and electricity consumption [33, 34]. In this section, we apply the LMDI method to decompose the factors affecting metal consumption, like copper. It is crucial to consider the industrial characteristics and consumption attributes of different subjects to achieve scientifically reasonable decomposition. In this study, the LMDI method is employed to decompose metal consumption factors across three dimensions [36, 37]: production effects, structural effects, and intensity effects. Specifically focusing on copper consumption, we explore the internal causes and intensities of China's metal consumption growth.

Following the analysis framework established in the first section, according to the LMDI model, the difference in metal consumption between the target year (year T) and the base year (year 0) represents the total effect, denoted as $\Delta C_{tot} = C^T - C^0$. This total effect can be decomposed into three parts: the production effect resulting from scale expansion or reduction (ΔC_α), the structural effects arising from changes in industrial structure during the industrialization process (ΔC_S), and the intensity effect stemming from shifts in metal consumption intensity (ΔC_e).

$$\Delta C_{tot} = \Delta C_a + \Delta C_s + \Delta C_e \tag{7}$$

Among them,

$$\Delta C_a = \sum_{i=1}^{3} L(C_i^T, C_i^0) \ln\left[\frac{a(t)}{a(t-1)}\right] = \sum_{i=1}^{3} \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \ln\left[\frac{a(t)}{a(t-1)}\right] \tag{8}$$

$$\Delta C_s = \sum_{i=1}^{3} L(C_i^T, C_i^0) \ln\left[\frac{S_i(t)}{S_i(t-1)}\right] = \sum_{i=1}^{3} \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \ln\left[\frac{S_i(t)}{S_i(t-1)}\right] \tag{9}$$

$$\Delta C_e = \sum_{i=1}^{3} L(C_i^T, C_i^0) \ln\left[\frac{e_i(t)}{e_i(t-1)}\right] = \sum_{i=1}^{3} \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \ln\left[\frac{e_i(t)}{e_i(t-1)}\right] \tag{10}$$

To accurately reflect the contribution of each factor effect, the degrees of contribution of each factor effect are defined as follows:

$$\eta_a = \frac{\Delta C_a}{\Delta C} \quad (11)$$

$$\eta_s = \frac{\Delta C_s}{\Delta C} \quad (12)$$

$$\eta_e = \frac{\Delta C_e}{\Delta C} \quad (13)$$

Among these components, η_a, η_S, η_e represent the contributions of the per capita wealth effect, industrial structure effect, and resource consumption intensity effect, respectively. List of abbreviation and acronyms used in this paper are shown in Table 3.

In this paper, we utilize the example of copper to decompose the LMDI factor of total copper consumption, thereby discussing the impact of economic growth, structural changes, and efficiency changes on variations in total resource consumption.

Data Collection

For this paper, the sample countries for industrial data were selected from five countries: the United Kingdom, the United States, Germany, Japan, and China. These countries represent typical developed industrial nations, with China being a developing and late industrial power. The focus of the data sample is on copper as the predominant mineral resource type. Consumption data for mineral resources in the United Kingdom, Germany, and Japan from 1848 to 1973 were obtained from the Economic Statistics of Major Capitalist Countries (1848–1960) and the Statistical Summary of the Mineral Industry published annually by the British Geological Survey. Data on mineral resource consumption in the United Kingdom, various countries, and Japan from 1974 to 2019 were sourced from the World Bureau of Metals Statistics published by the British Geological Survey in different years. Data on mineral resource consumption in the United States from 1900 to 2019 were obtained from the United States Geological Survey. Population data for the United States, United Kingdom, Germany, and Japan from 1848 to 1960 were acquired from the Economic Statistics of Major Capitalist Countries (1848–1960), while population data from 1961 to 2019 were obtained from the International Statistical Yearbook. Per capita GDP data for the United States, United Kingdom, Germany, and Japan were sourced from the Groningen Center for Economic Growth and Development (GCDC). Data on copper consumption in China were gathered from the China Nonferrous Metals Industry Association, "New China Nonferrous Metals Industry 60 Years," and the "China Nonferrous Metals Industry Yearbook 2017." Copper consumption data for specific industries within China were sourced from the copper market analysis report of the Antaike Research Center on China Metal Network (www.metalchina.com) over the years. It is worth noting that pre-2006 copper market analysis reports did not include industry-specific consumption data, so this study utilized copper consumption data by industry from 2006 to 2017 as the data source. Annual GDP and industry-specific GDP data were obtained from the "China Statistical Yearbook" and the official website of the National Bureau of Statistics of China.

When using the LMDI factorization method, the consumption of energy and metal across various industries is generally classified using the three-industry classification method or the "total energy consumption by industry" classification method in the annual data from the National Bureau of Statistics. Energy consumption is typically divided into agriculture, forestry, animal husbandry, fishing, industry, construction, transportation, warehousing and postal services, wholesale and retail, and other sectors. Copper, as a bulk non-ferrous metal, exhibits unique consumption patterns. The sectors consuming copper include electricity, air conditioning and refrigeration, electronics, construction, transportation, and other industries. Therefore, when applying the LMDI method for factorization, the data needs to be processed using specific approaches.

Table 3. List of abbreviations and acronyms used in this paper.

Abbreviation	Meaning
LMDI	Logarithmic Mean Divisia index
COVID-19	Corona Virus Disease 2019
EKC	Environmental Kuznets Curve
DEI	decoupling elastic index
EP	environmental pressure indicators
DP	economic driving force indicator
IPCC	Intergovernmental Panel on Climate Change
CE	the ratio of total CO_2 emissions to total energy consumption
EI	the ratio of total energy consumption to GDP
IU	the consumption intensity of metal in the industry I

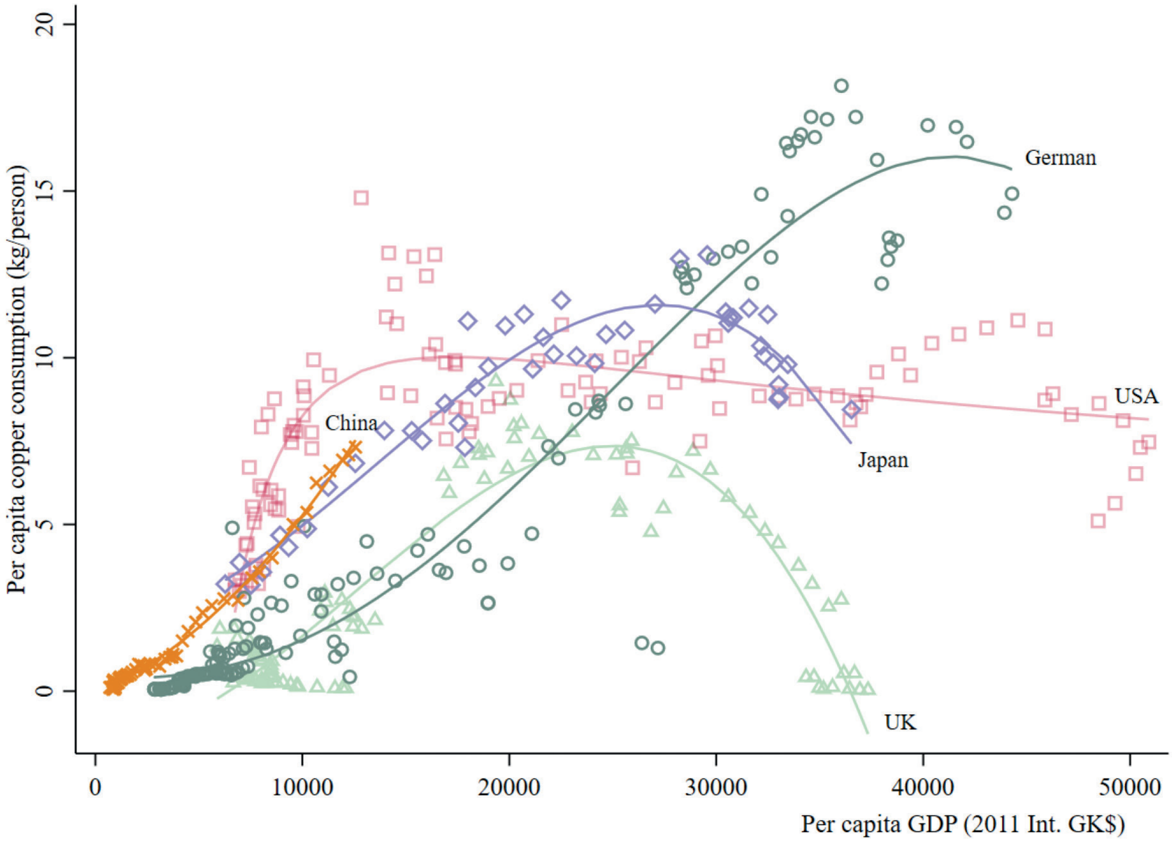

Fig. 1. The correlation between per capita copper consumption and per capita GDP for typical countries during the process of industrialization.

Results and Discussion

Results of the Copper Consumption Decoupling Model

Industrialization serves as the main theme of a country's modernization and constitutes the fundamental path for the ascendance of modern powers. Throughout history, industrialization has spanned over 230 years, with the United Kingdom being the world's first industrialized nation. The United States stands as the most robust industrialized country to date, while Germany has consistently demonstrated a strong capacity for industrialization. Japan experienced significant lag until 1980 but has since witnessed rapid growth. Currently, Japan's level of industrialization is on par with previous countries. Analyzing the evolutionary pattern of GDP growth rates, the United States reached its industrialization peak from 1950 to 1960, followed by Germany from 1960 to 1967 and Japan from 1963 to 1969. During these periods, GDP growth was the fastest, averaging 10.43% and peaking at 12.88%. After 1980, China's GDP growth remained strong, leading to rapid economic expansion. Upon entering the middle and late stages of industrialization, China's economy experienced a slowdown and shifted toward top-quality development.

Considering the development pattern of bulk metal alongside advancing world industrialization, it is evident that the industrialization paths of developed countries share similarities but also exhibit differences due to variations in historical conditions, political factors, economic circumstances, and national industrialization spirits. Similarly, copper consumption reflects distinct patterns influenced by factors such as resource endowments, timing of industrialization, technological conditions, and government intervention. Therefore, this study compares developed countries like the United Kingdom, the United States, Germany, Japan, and China to explore the decoupling process of copper consumption. By examining the evolution of total copper consumption and its structure, we gain insights into consumption patterns and the factors influencing copper consumption in China.

The correlation between per capita copper consumption and per capita GDP for typical countries during the process of industrialization is shown in Fig. 1. Given copper's structural and functional properties, the electrical industry accounted for the largest proportion of copper consumption in early developed countries. Analysis of copper consumption data reveals that in developed countries, copper consumption enters a growth phase when per capita GDP reaches \$3000 to \$3500. During

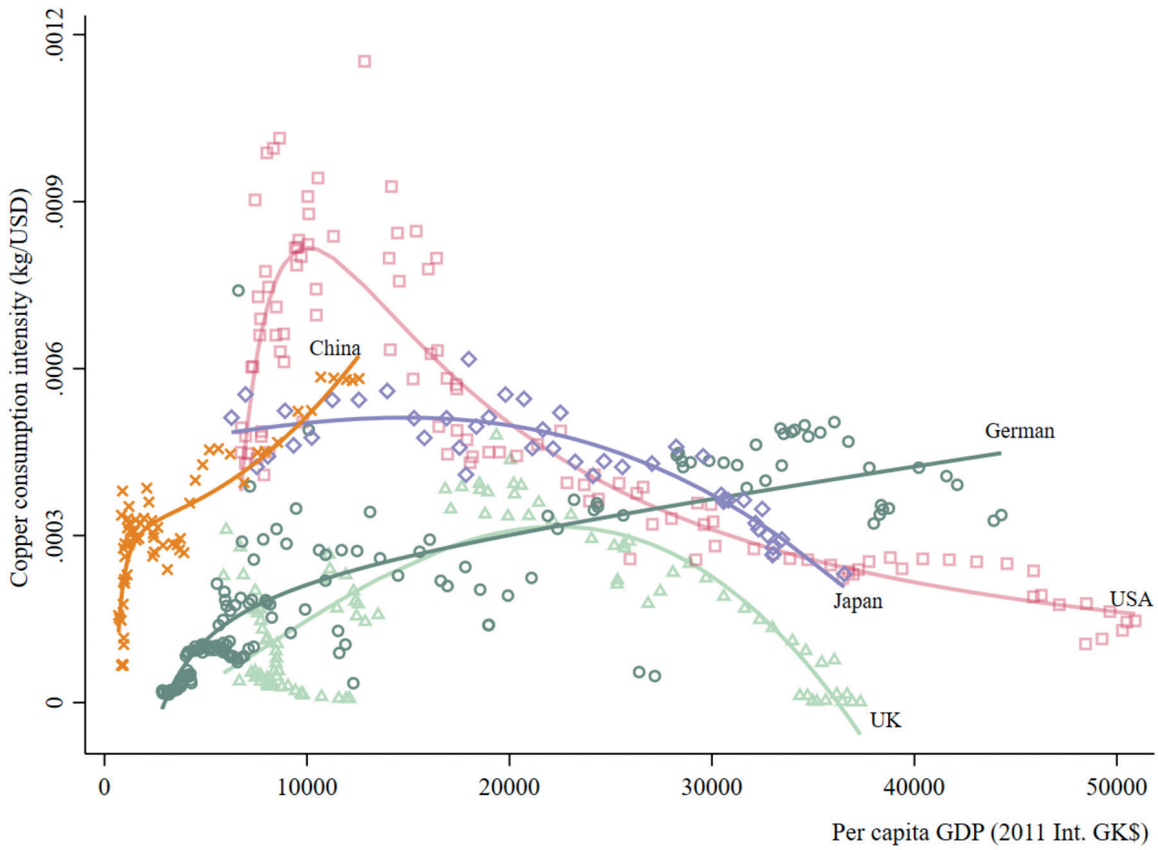

Fig. 2. The comparison of copper consumption intensity in typical countries during the process of industrialization.

Table 2. Decoupling status and segmentation results for copper from 1970 to 2020 in different countries.

Country	1970–2020	1980–1985	1985–1990	1990–1995	1995–2000	2000–2005	2005–2010	2010–2020
UK	V	V	V	V	V	I	VI	V
USA	V	IV	IV	I	I	V	VI	IV
Germany	I	IV	I	I	VII	V	I	V
Japan	IV	IV	VII	V	V	VII	V	V
China	I	I	V	I	I	I	I	I

Note: Due to missing data, the total decoupling elasticity index (DEI) of Chinese copper was calculated from data from 1980 to 2020.

the middle stage of industrialization, metal consumption demonstrates rapid growth, with an accelerated rate of copper consumption. In developed countries, the focus of copper consumption shifts to the construction industry during the middle and later stages of industrialization. Due to copper's structural and functional properties, the peak consumption of copper occurs in the construction sector. The peak years for copper consumption in the United Kingdom, the United States, Germany, and Japan were 1977, 1999, 1998, and 1990, respectively. An in-depth analysis of the relationship between metal consumption and the industrialization process in typical industrialized countries reveals a general trend of "low growth-rapid growth-reaching the peak-tending to decline" between per capita GDP and metal consumption.

Furthermore, an examination of consumption intensity indicators, which measure resource utilization efficiency, shows that copper consumption intensity peaked earlier in the United States, with a per capita GDP peak of $8205. Given that 48% of copper consumption in the United States is attributed to the construction sector, saturation and slowdowns in the housing market significantly impact copper consumption intensity. In Europe, Japan, and China, copper consumption accounts for a significant proportion of the electrical industry. Copper consumption intensity peaks at different per capita GDP levels for Japan ($11433),

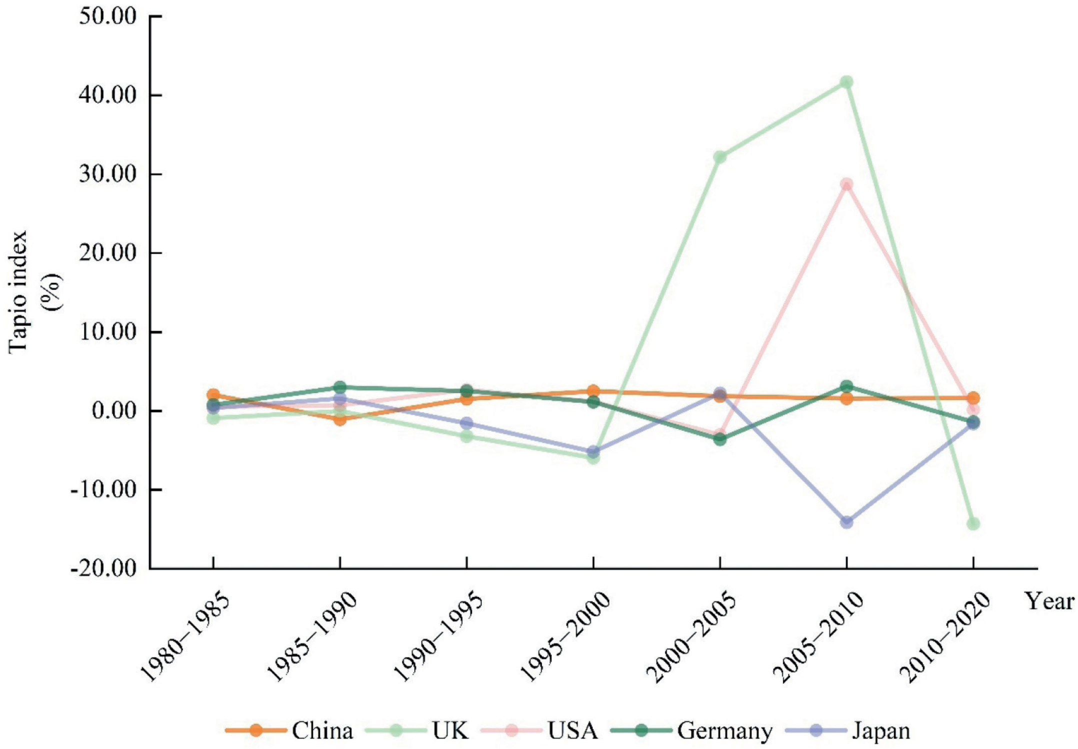

Fig. 3. Trends of the Copper Decoupling Index in major industrial countries from 1980 to 2020.

the United Kingdom ($12383), and Germany ($17299), as shown in Fig. 2. The variation in peak per capita GDP levels arises from the late entry of copper into the economic and social cycle and differences in downstream consumption structures among countries, as well as the development of alternative markets such as aluminum. The relationship between copper consumption intensity and per capita GDP in major industrial countries during the industrialization process generally exhibits a Kuznets inverted "U" curve.

Based on Equation (1), this study calculates the decoupling index between copper consumption and economic growth in China, the United Kingdom, the United States, Germany, and Japan, and presents the trends of the decoupling index in Table 2. For the entire period from 1970 to 2020, copper consumption and economic growth in the UK and the US show a strong decoupling state, achieving complete decoupling. However, copper consumption and economic growth in Germany and Japan display periodic decoupling and recoupling phenomena.

Currently, China's copper consumption remains in the pre-peak climbing stage (see Fig. 3). With the exception of 1985–1990, a negative decoupling relationship between copper consumption and economic growth is observed in Fig. 3. The decoupling elasticity of copper consumption exceeds 1.5 and exhibits a gradual downward trend, indicating a negative decoupling state of growth. This suggests that China's economic growth heavily relies on metal resources, but resource utilization is improving. As copper consumption is still in the growth phase and has not yet reached its peak, it can be inferred that China's consumption of metal minerals will continue to grow at a certain rate in the future as it strives to become a strong manufacturing and quality-focused country. The "dual carbon" goal will impose mandatory constraints on high energy-consuming industries like non-ferrous metals, altering the timeline and decoupling trajectory for China's peak copper consumption. The utilization of technology and industrialization of existing minerals, such as "urban mines," will also highlight technological and economic benefits. Studying the internal drivers of copper consumption enables us to better comprehend the relationship between copper consumption and economic growth, as well as the connection between changes in industrial structure and improvements in resource utilization efficiency.

Analysis of LMDI Decomposition Results

Analysis of the Total Consumption and Consumption Structure of Copper in China

As a bulk non-ferrous metal, copper plays a significant role in various industries such as electrical, light industrial, mechanical manufacturing, construction, and defense. Its consumption is closely linked to the industrialization process of a country. Over the years, China's total consumption of copper has exhibited consistent growth since the establishment of the People's Republic of China. From 2007 to 2010, there was a rapid growth period for copper consumption, with

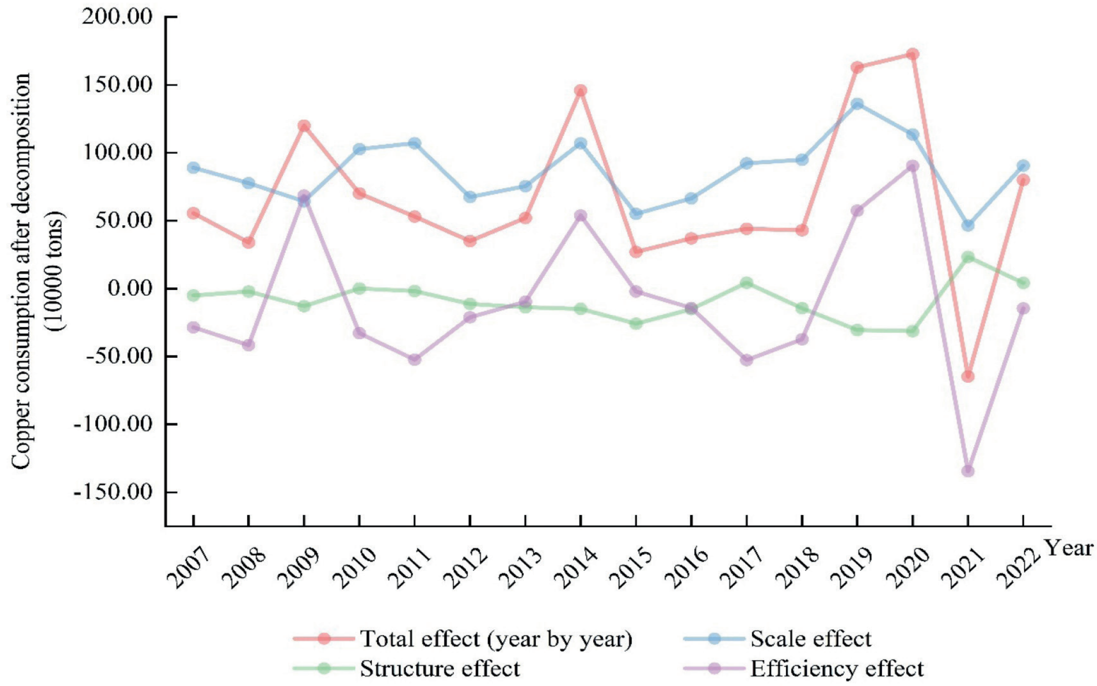

Fig. 4. Decomposition results of the annual effects of copper consumption in China from 2007.

a peak growth rate of 25.93% in 2010. However, since 2012, the growth rate has gradually slowed down.

In terms of industry structure, the power sector and air conditioning and refrigeration industries are the major subsectors driving copper consumption in China. The power sector has consistently accounted for over 40% of copper consumption since 2006, and this proportion is projected to reach 52% by 2018 due to increased investment in power grid construction and production in industries like air conditioning. Additionally, the transportation, electronics, and construction industries contribute to copper consumption but to a lesser extent; hence, they have been merged into the "other" category. Similarly, the power, air conditioning, refrigeration, and electronics industries have been grouped under the "industrial" category.

Decomposition of Factors Influencing Changes in Copper Metal Consumption in China

To analyze the factors driving China's copper consumption from 2007 to 2018, the LMDI model was utilized, taking 2006 as the base period. This paper calculates the annual and cumulative effects of GDP per capita, industrial structure, and resource consumption intensity. Fig. 4 depicts the cumulative effect decomposition plot and the contribution of each factor. The results indicate that, with 2006 as the base period, the cumulative effect of China's copper consumption in 2017 was negative for structural and efficiency factors but positive for scale factors. This implies that changes in industrial structure and resource consumption intensity have somewhat hindered the growth of copper consumption, while the increase in GDP per capita has had a positive impact. In terms of contribution, the cumulative effect of GDP per capita remains the largest during the middle and later stages of industrialization, with the scale effect contributing 134.31% to the cumulative increase in copper consumption in 2017. On the other hand, the cumulative contributions of industrial structure and resource consumption intensity were negative, contributing -14.62% and 19.69%, respectively, to the cumulative increase in copper consumption.

The main driving force behind the growth of copper consumption in the middle and later stages of China's industrialization is the increase in GDP per capita. This paper computes that the scale effect consistently demonstrates positive values in both annual and cumulative impacts, signifying a robust correlation between rising GDP per capita and increased copper consumption. The contribution of the scale effect is also significant, emphasizing the substantial influence of GDP per capita on copper consumption. This conclusion is further supported by Figs. 4 and 5. The annual scale effect factor accounted for 90.50% of the total change in copper consumption in 2022, while the cumulative scale effect factor from 2007 to 2022 contributed to 129.84% of the total change in copper consumption, making it the primary explanatory factor for the increase in copper consumption.

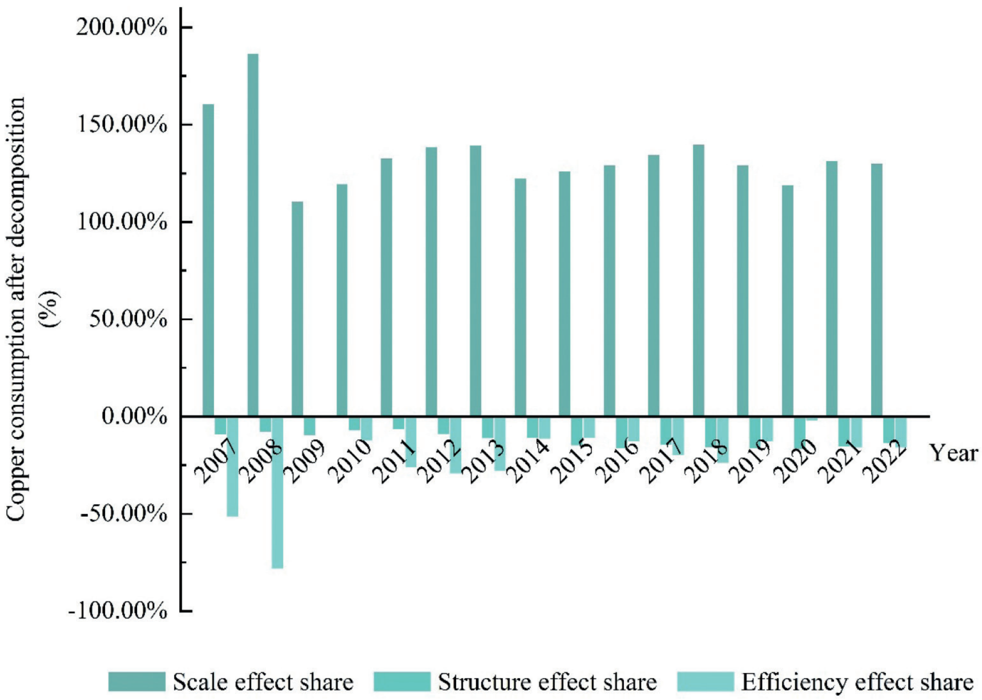

Fig. 5. Decomposition results of the cumulative effects share of copper consumption in China from 2007 to 2022.

Overall, the industrial structure effect and consumption intensity effect have consistently shown negative values during this phase, indicating that these factors have primarily suppressed the growth of copper consumption. Fig. 5 presents the cumulative effect values for each factor, revealing that the efficiency effect had a greater inhibitory effect on copper consumption from 2007 to 2014, while the structural effect had a stronger impact from 2014 to 2017. The regulatory impact of the efficiency effect has significantly intensified from 2018 to 2022. The negative regulatory influence of the structural effect suggests that changes in industrial structure have impeded the increase in copper consumption in China. Conversely, the inverse regulatory effect of the efficiency effect indicates that technological innovation has led to a decrease in copper consumption. The declining proportion of industrial GDP in China from 2006 has had a certain inhibitory effect on the growth of copper consumption. This is attributed to the optimization and upgrading of the industrial structure, the shift in the proportion of the service sector relative to manufacturing, and the development of refined manufacturing, all of which have suppressed copper consumption. In terms of contribution, the annual effect contribution of the industrial structure is relatively low compared to other factors, indicating that changes in industrial structure primarily exert a negative regulatory effect on copper consumption during China's middle and later stages of industrialization. Since 2014, this negative regulatory effect has been increasing year by year.

Robustness Analysis of the Measurement Model

The LMDI decomposition method disaggregates the determinants of copper consumption into three key factors: per capita GDP, industrial structure, and resource consumption intensity. To assess the reliability of the model, a robustness analysis of the LMDI decomposition is necessary. The primary objective of this robustness analysis is to evaluate the credibility and stability of the model's outputs. Regression analysis, a widely accepted method, is employed to assess the impact of different independent variables on the dependent variable, allowing for a comparison between the regression results and the outputs of the LMDI decomposition.

In line with the framework of our measurement model [i.e., Eq. (2)], we applied the STIRPAT model to conduct the regression analysis [38]. This approach allowed us to determine the extent to which changes in these factors affect overall copper consumption.

$$I = aP^{b}A^{c}T^{d}e \tag{14}$$

Taking the natural logarithm of both sides yields,

$$ln\, I = a + b\, ln\, P + c\, ln\, A + d\, ln\, T + ln\, e \tag{15}$$

The random-form STIRPAT model permits the incorporation of additional influencing factors to analyze the elastic relationship between the explanatory variable and the dependent variable. Factor T is further disaggregated

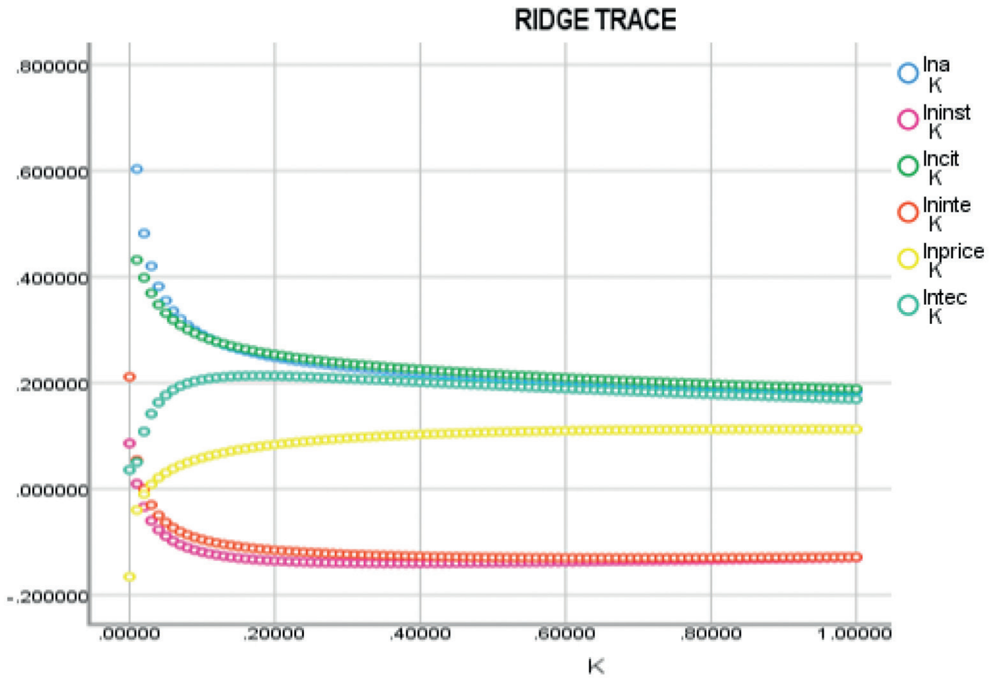

Fig. 6. Ridge trace of copper consumption in China.

in the model with additional control variables incorporated to examine their impact on I, and regression analysis is performed to enhance the model's applicability. In this paper, the model is applied to analyze the influencing factors of copper metal consumption, including economic growth, industrial structure, resource consumption intensity, urbanization, and technological progress. Here, *C* represents the consumption of mineral resources; *A* is the economic growth variable, indicated by per capita *GDP*; *INTR* denotes the industrialization rate, expressed by the proportion of industrial added value to *GDP*; *CIT* signifies the urbanization rate, represented by the proportion of the non-agricultural population; *INTE* measures the consumption intensity of mineral resources, indicated by the amount of mineral resource input per unit of *GDP*; *TEC* reflects technological progress, represented by the proportion of high-tech product exports to manufactured product exports; and *PRICE* refers to the price of mineral resources.

To mitigate the impact of heteroscedasticity, the model is linearly transformed using logarithms, yielding the following model:

$$ln\,C = a + b\,ln\,A + c\,ln\,INST + d\,ln\,CIT + f\,ln\,INTE + g\,ln\,TEC + h\,ln\,PRICE + ln\,e \quad (16)$$

To ensure the effectiveness and accuracy of the model results, mitigate the influence of multicollinearity on regression outcomes, and enhance the stability and reliability of traditional ordinary least squares (OLS) estimation, ridge regression with partial estimation was employed for model fitting. Ridge regression significantly improves the mean square error of traditional least squares estimation, enhances the numerical stability of model estimation at the cost of some information loss, and yields more reliable regression coefficients than OLS. The ridge regression function was used to fit the model, and the ridge regression coefficient demonstrating gradual stability was selected according to the ridge trace plot, as shown in Fig. 6.

As evident from the ridge trace plot, when the ridge parameter (k) ranges from 0 to 1 with a step size of 0.01 and the ridge regression coefficient is set at 0.2, the regression coefficients of each explanatory factor tend to stabilize. The standard ridge regression equation is:

$$ln\,C = 0.2481\,ln\,A - 0.1357\,ln\,INST + 0.2535\,ln\,CIT - 0.1157\,ln\,INTE + 0.2130\,ln\,TEC + 0.0836\,ln\,PRICE \quad (17)$$

With China's gradual integration into the global industrialized economy, copper consumption has increased steadily, with the rapid expansion of economic scale at this stage exhibiting a pronounced "compression" evolution trend. The standard ridge regression results indicate that economic growth is the primary driver of copper consumption growth, with an overall contribution ratio of 0.2481. The regression coefficients for the industrial structure and consumption intensity factors on copper consumption are negative, showing a certain inhibitory effect, though the impact is modest, at -0.1357 and -0.1157, respectively. According to the measurement results, the industrial structure has emerged as a structural factor reducing copper consumption, while the consumption intensity reflects the efficiency of copper resource utilization, which also somewhat restrains the growth of copper consumption.

The research conducted using the modified STIRPAT model not only validates the empirical conclusions drawn from the LMDI factor decomposition but also delves deeper into analyzing the impact levels of factors such as per capita GDP, industrial structure, and consumption intensity on copper consumption.

Conclusions

This paper aimed to study the primary driver for the total consumption and structural changes in metal resources. It is crucial to study the impact of the factors on copper consumption and provide insights for resource conservation targets and the formulation of targeted policies.

This paper has analyzed the relationship between per capita GDP and per capita copper consumption in major countries during the industrialization process. Additionally, by employing the Tapio decoupling model, Kaya identity, and LMDI decomposition model, it has explored the decoupling relationship between copper metal consumption and economic growth and quantitatively examined the influencing factors of copper consumption in China from 2007 to 2022. The main findings are as follows:

Firstly, the correlation between per capita GDP and per capita copper consumption, as well as the intensity of copper consumption relative to per capita GDP in major industrial nations, mirrors a pattern akin to the Kuznets inverted U-shaped curve. The study has quantitatively described the relationship between per capita GDP and per capita copper consumption, as well as the relationship between per capita GDP and copper consumption intensity. It was found that per capita GDP and per capita copper consumption in major developed countries follow a pattern of "slow growth, rapid growth, reaching the peak, and tending to decline," with the United States, the United Kingdom, Japan, and Germany reaching their peaks in sequence. Similarly, copper consumption intensity and per capita GDP in major industrial countries exhibit a Kuznets inverted "U" curve relationship during the industrialization process. Currently, the results of the Tapio decoupling elastic model revealed that the UK and the US demonstrated a strong decoupling state, while Germany and Japan exhibited negative or weak decoupling growth at the present stage. Since China's reform and opening-up, copper consumption has experienced a negative decoupling growth state. China's GDP per capita, per capita copper consumption, and copper consumption intensity are still in the pre-peak climb phase currently.

Furthermore, the LMDI empirical method of Divisia factor decomposition was employed to analyze the driving factors of copper consumption, with the modified STIRPAT model used for validation. The study delved into the driving forces behind copper consumption, revealing the internal factors influencing China's metal growth during the mid-to-late stages of industrialization. By decomposing metal consumption into scale effect, structural effect, and efficiency effect, it assessed the relative strength of each effect in the growth of metal consumption. Due to data limitations, the analysis focused on copper consumption data by subindustry from 2006 to 2022. The findings showed that the main driver of copper consumption during the middle and later stages of industrialization in China was the scale effect, while the structural and efficiency effects exerted negative regulatory effects, indicating that the increase in per capita GDP was the primary driving factor for copper consumption. In recent years, as structural adjustments have accelerated, the inhibitory effect of structural factors on electricity consumption has become more pronounced. The impact of industrial structural changes on copper consumption between 2006 and 2022 has primarily been characterized by negative regulation, with its intensity increasing since 2014. After 2021, the efficiency effect has resulted in significant copper consumption savings, creating a strong inhibitory effect on its growth.

How Does Metal Consumption Decouple? From the evidence from Copper based upon Tapio Theory and the LMDI Model, we can conclude:

(1) Industrialization has been the primary driver for the total consumption and structural changes in metal resources. The large-scale consumption and sustainable utilization of metal resources have been instrumental in achieving "compressed" and "rapid" industrialization. China's industrialization path will face various challenges and opportunities, including an increasingly advanced industrial structure, the rise of the modern industrial revolution, the development of green and intelligent technologies, as well as a transition in the driving forces of economic growth. This will lead to increased consumption of strategic metals like copper. In the future, China's copper consumption will experience a faster decoupling state of "growth linkage, weak decoupling, strong decoupling" after crossing the inflection point of the Kuznets inverted "U" curve.

(2) One key aspect is the industrial structural transition triggered by technological advancements, which serves as the fundamental driving force for metal consumption to peak and move towards decoupling. The implementation of the "dual carbon" goal and the constraints it imposes on metal consumption will have a significant impact on the total amount, intensity, and structure of China's metal consumption. China's commitment to reach the peak of carbon emissions by 2030 and the ongoing supply-side structural reforms will have a reverse effect on high-emission sectors such as steel, non-ferrous metals, building materials, and petrochemicals. This will delay the peak consumption of these metals. The mandatory constraints of the "dual carbon" target on high energy-consuming industries such as non-ferrous metals and the utilization of existing metals like "urban mines" will impact the timeline and decoupling path for China's copper and other base metals to reach their

peak. With its advantage as a latecomer, China is expected to reach the peak consumption intensity and total amount of major basic metal resources at a lower level of per capita GDP, thereby achieving decoupling between economic growth and metal consumption.

The aforementioned conclusions and research findings hold valuable insights for developing countries like China in shaping and executing strategies for the development and utilization of mineral resources. For latecomers like China, it is worth learning from the implementation paths, policy tools, and lessons learned from the decoupling of economic growth and copper resource consumption in industrialized countries.

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Conflict of Interests

The authors declare no conflict of interest.

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