Managing Carbon Efficiency and Carbon Equity: What Information Do We Have From Embodied Carbon Emissions?

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ABSTRACT

China has committed to achieving carbon neutrality by 2060, primarily focusing on reducing carbon intensity. Understanding the regional embodied carbon emissions is critical for managing carbon efficiency and carbon equity in this process. Using the input-output and SBM-DEA models, this article first calculates China’s regional embodied carbon emissions. The results reveal substantial carbon transfers between China’s different regions. Therefore, designing reduction pathways solely based on production-based carbon emissions raises fairness concerns. To address this, this article employs the SBM-DEA model to calculate the regional reduction potential and marginal abatement costs using the regional embodied carbon emissions and optimize China’s pathways of regional carbon emission reduction. The new pathways consider consumption-based reduction potential, marginal abatement cost, and reduction equity, and are all in line with China’s carbon reduction target. These schemes are of practical significance for China to develop a more efficient and equitable regional emission reduction plan.

KEYWORDS
Carbon efficiency, Carbon equity, Carbon reduction pathway, Consumption-based carbon emissions, Production-based carbon emissions

INTRODUCTION

China attaches great importance to climate cooperation and actively shoulders the responsibility of emissions reduction. At the 2009 Copenhagen Climate Conference, the government pledged to reduce carbon intensity by 40%-45% by 2020, with non-fossil energy accounting for 16%. In 2015, China reaffirmed its commitment to peak carbon emissions by 2030, with a target of reducing carbon intensity by 60%-65% and increasing the share of non-fossil energy to 20%, as stated in its nationally
determined contributions (NDC) submitted during the Paris Climate Conference. In 2020, China further articulated its goal of striving for a carbon emissions peak before 2030 and carbon neutrality by 2060, with a focus on carbon intensity reduction.

Carbon efficiency and carbon equity serve as crucial allocation criteria for achieving carbon emissions reduction (Jia, Lin, & Liu, 2023; Jia, Wen, & Wang, 2023). Carbon Efficiency refers to the effectiveness and productivity of processes or actions aimed at reducing carbon emissions. It measures how well a particular economic activity, technology, or policy can achieve emission reductions relative to the amount of carbon emissions produced. High carbon efficiency means achieving significant emission reductions with minimal carbon emissions (Lin & Guan, 2023b; Peng, Lu, Gupta, & Wang, 2022). Carbon Equity, on the other hand, pertains to the fairness and just distribution of the burden of reducing carbon emissions among different regions. It ensures that the responsibility for reducing emissions is distributed in a way that considers historical contributions to emissions, economic capacity, and development needs (Jia, 2023; Lin & Zhao, 2023). Carbon equity seeks to address disparities in emissions and their consequences, aiming for a more balanced and equitable approach to regional emission reductions. In this paper, carbon equity carries an additional layer of meaning: it involves setting emission reduction targets based on consumption-based carbon emissions generated by each region’s actual economic development, rather than relying solely on production-based carbon emissions. In practice, governments face the dual challenge of promoting economic development while mitigating the negative economic impact of emissions reduction. Simultaneously, they must ensure the fairness of emission reduction task allocation among regions to alleviate conflicts between economic development and emissions reduction in certain areas. Achieving China’s “peak carbon emissions” and “carbon neutrality” goals necessitates coordinated efforts from all regions, underpinned by scientifically sound carbon reduction pathways and a fair and viable emission reduction target scheme. A program based on embodied carbon emissions might be considered fairer in some respects because it accounts for the carbon emissions associated with the entire supply chain of products. It addresses the concept of “carbon leakage,” where regions with strict emissions reduction targets might see increased imports of carbon-intensive goods, shifting emissions elsewhere.

When formulating regional emission reduction pathways, due consideration must be given to the differences in regional resource endowments, industrial structures, technological levels, and economic development levels. These disparities result in significant variations in carbon emission reduction efficiency, reduction potential, and mitigation costs among regions. From the perspective of resource endowments and industrial structures, the economic growth in China’s eastern coastal regions relies primarily on high-end manufacturing and service sector, with a relatively high degree of industrial structure optimization. This development model tends to be more environmentally friendly and low-carbon. In contrast, the central, western, and northern regions of the country are rich in mineral resources and are dominated by energy and heavy industries in their economic structure. These regions exhibit a higher dependence on energy-intensive sectors, leading to more pronounced conflicts between local economic development and carbon emissions reduction goals (Lin & Wang, 2023). Regarding technological levels, the eastern regions of China also maintain a technological edge over the central and western regions. A notable manifestation of this disparity is the significantly higher energy efficiency and productivity of various factors in the eastern regions (Lin & Guan, 2023b; Lin & Zhou, 2022). Furthermore, the eastern and western regions are at different stages of economic development. The eastern regions embarked on economic development earlier, resulting in higher economic development levels and relatively less pressure to address economic development challenges. In contrast, some of the central and western regions are currently in the early and middle stages of industrialization and need to further enhance their industrial structure while fostering local economic development (Lin & Xie, 2023). These factors have resulted in significant variations in carbon efficiency and emission reduction costs across different regions in China. Hence, the optimization of regional emission reduction pathways should also be tailored to the specific conditions of each region.
In addition to carbon efficiency and abatement costs, carbon equity is also a significant consideration in emission reduction pathway design. The significant differences in China’s regional resource endowments and industrial structures have promoted large-scale interregional carbon emission transfers over the last decades. This leads to a substantial “divergence” between actual carbon emissions from consumption and actual carbon emissions from production (Feng et al., 2020; Mi, Meng, et al., 2017). This “divergence” is likely to result in an unfair distribution of regional emission reduction responsibilities (Jia & Lin, 2022). For instance, based on the calculations in this paper, Inner Mongolia has seen a net outflow of carbon emissions in recent years, accounting for approximately 47% of its actual carbon emissions from production. This is primarily due to Inner Mongolia’s abundant coal resources and thermal power facilities, as the region plays a crucial role in supplying electricity to Beijing, Tianjin, and other areas. Similarly, Hebei Province is the largest producer of steel in China. However, most of the steel produced in Hebei is not used for local development but is shipped to other provinces. Thus, Hebei Province also experiences a significant net outflow of carbon emissions, comprising around 30% of its production-based carbon emissions. In both of these cases, local consumption-based carbon emissions are much lower than local production-based carbon emissions. If we were to formulate regional carbon reduction targets based solely on production-based carbon emissions, it would inevitably fail to fairly assess the relationship between actual carbon emissions and economic contributions across regions. Nevertheless, there is a relative lack of carbon reduction pathway designs based on consumption-based emissions, and interregional carbon emission transfers are seldom considered in the design of emission reduction mechanisms in existing literature.

The existing literature on the design of regional carbon reduction pathways primarily relies on the “ability” principle as the criterion. It pays less attention to differences in interregional emission reduction efficiency (Ni, Wei, & Du, 2015). The allocated emission reduction quotas for each province are often more influenced by local government intentions and negotiation capabilities rather than the actual emission reduction potential and costs of each province. This approach can lead to an outcome where “the faster the emissions reduction, the greater the emissions reduction responsibility” (Qian, Wu, & Ren, 2019), thus reducing the motivation for emissions reductions in various regions. Besides, such an allocation mechanism may result in efficiency losses, exacerbating the conflict between economic development and carbon reduction in certain regions, which is detrimental to achieving China’s overall emission reduction goal. Therefore, developing comprehensive emission reduction pathways that consider the specific circumstances of each province while balancing environmental effectiveness, efficiency, and fairness holds significant practical significance for achieving the “peak carbon emissions” and “carbon neutrality” targets.

Based on the discussion above, this paper aims to address three main questions: Firstly, calculate the carbon transfers among Chinese provinces driven by international and interprovincial trade to clarify the differences between consumption-based and production-based carbon emissions in various regions. Secondly, analyze the differences in carbon reduction potentials and marginal abatement costs between consumption-based and production-based approaches for each region. This will provide references for optimizing provincial emission reduction pathways from different perspectives. Thirdly, design the optimal emission reduction pathways for each province. These pathways aim to maximize efficiency and minimize costs in the emission reduction process while considering both the overall national emission reduction targets and carbon equity between different regions.

In this paper, we first utilize an energy-environment input-output model to calculate the carbon transfer between regions, as well as clarify the divergence between production-based and consumption-based carbon emissions. We find that there is a significant amount of carbon emission transfer among various regions in China. This leads to significant disparities between consumption-based and production-based carbon emissions in some provinces. Furthermore, we employ the SBM model and its dual model to calculate carbon reduction potentials and marginal abatement costs for each province. The results emphasize the differences in costs and potentials between production-based and consumption-based calculations. We find that carbon net-outflow regions often have smaller
consumption-based emission reduction potentials with lower marginal abatement costs, whereas carbon net-inflow often have greater consumption-based emission reduction potentials with higher marginal abatement costs. Finally, based on efficiency and fairness principles, this paper designs three heterogeneous regional emission reduction pathways. In these pathways, we can see both changes in emission reduction responsibility due to reduction potential and marginal abatement costs, as well as the impact of carbon equity on the pathway design.

The marginal contributions of this paper primarily manifest in three aspects:

Firstly, this paper comprehensively calculates carbon emissions, total factor carbon efficiency, and marginal abatement costs for both consumption-based and production-based perspectives across regions in China. And a thorough comparison analysis of the efficiency and abatement costs under these two accounting methods is conducted. Previous literature mostly relied solely on production-based carbon emissions to calculate regional efficiency and abatement costs. This paper provides a new perspective for the relevant analysis.

Secondly, this paper explores the optimal emission reduction pathways based on consumption-based carbon emissions and analyzes the reasons behind the disparities between these pathways and those based on production-based emissions. Existing research has predominantly focused on designing emission reduction pathways according to the production-based carbon emissions. This approach can lead to suboptimal overall emission reduction outcomes and overlook carbon equity. By calculating interprovincial carbon emissions, this paper devises an optimal emission reduction scheme based on consumption-based carbon emissions, which effectively addresses fairness concerns arising from carbon transfers.

Thirdly, this paper provides a clear regional carbon reduction pathways based on considerations of marginal abatement costs and reduction potentials. Many studies have optimized pathways from the perspectives of carbon emission efficiency, marginal abatement costs, or reduction potentials, but very few simultaneously consider these factors, and even fewer provide explicit regional carbon reduction schemes. Such designs often overlook the coordination between carbon reduction and economic development. Through a system of simultaneous equations, this paper constructs regional carbon reduction pathways that consider reduction potentials, abatement costs, emissions, and a nationally unified target. This is of practical reference value for designing China's future emission reduction pathways.

LITERATURE REVIEW

Existing literature on China’s carbon reduction path design has proposed three key optimization approaches: analysis of carbon emission influencing factors, analysis of carbon emission efficiency, and carbon emission allowance mechanisms. Some scholars have proposed reduction plans from the perspective of carbon emission influencing factors using the logarithmic mean Divisia index decomposition method. For instance, F. Wang, Wu, and Yang (2010) decomposed China’s energy consumption and carbon emission growth rate into 11 weighted contributions driven by various factors. The results indicate that per capita GDP growth is the primary driver of China’s carbon emission increase, while improvements in energy efficiency driven by technological advancements are the most crucial factor in reducing carbon emissions. Tu, Zan, and Luo (2012), utilizing the optimized Laspeyres index decomposition method, analyzed the impact of four major factors and confirmed that industrial structure and technological advancements are two significant factors influencing changes in China’s carbon emissions. Therefore, the government should actively promote industrial restructuring and innovation in energy-saving technologies. Yang, Zhu, and Jia (2019) constructed a comprehensive analytical framework combining the index decomposition and production theory decomposition methods. They advocated that governments should drive emissions reductions by investing more in green technologies.
Some scholars have proposed carbon reduction pathways based on Data Envelopment Analysis (DEA) with a focus on carbon emission efficiency. For instance, Liu, Zhu, and Fan (2011) delved into provincial-level analysis using a non-parametric distance function to assess carbon emission efficiency and marginal abatement costs under energy consumption constraints. Their findings revealed significant regional disparities in carbon emission efficiency and abatement costs, with regions having lower carbon intensity often incurring higher abatement costs. Wei, Löschel, and Liu (2013) identified widespread inefficiencies in carbon emissions within the industry, accompanied by substantial variations in shadow prices, suggesting the need for the government to promote flexible carbon trading mechanisms to reduce abatement costs. Furthermore, some studies within the DEA framework have discussed the allocation mechanisms for provincial-level emission reduction targets. For instance, Yu, Lin, Zhang, Jiang, and Peng (2019) and Fang et al. (2019) utilized the zero-sum gain DEA model to allocate carbon emission quotas among Chinese provinces. This mechanism ensures that each province reaches the production frontier, avoiding redundant carbon emission quotas. Yi, Zou, Guo, Wang, and Wei (2011), guided by principles of fairness and development, developed a composite index based on emission reduction capacity, responsibility, and potential. They applied this index to model the regional distribution of carbon intensity, offering a distribution approach of reduction tasks aligned with governmental preferences. Lan et al. (2023) designed an emission reduction pathway based on cost-efficiency considerations, using the marginal abatement costs of the steel industry in fourteen cities in Shandong Province.

Many scholars have also examined the feasibility of China achieving its established carbon peak and carbon intensity reduction targets at both national and sectoral levels. For instance, Mo, Duan, Fan, and Wang (2018) discussed the potential for China to achieve its Nationally Determined Contributions (NDC) emission reduction targets by constructing a comprehensive assessment model and found that it would be possible to achieve the 2030 emission reduction targets with only a minimal 0.87% GDP loss, minimizing abatement costs. Zhu, Wang, Chevallier, Wang, and Wei (2015), utilizing cointegration theory and a differenced moving average autoregressive model, quantitatively analyzed the relationship between China’s economic growth and energy consumption, projecting China’s energy consumption and carbon emission intensity for 2020. Mi, Wei, et al. (2017) employed an input-output optimization model to analyze the relationship between China’s carbon reduction rate and economic growth. Their analysis revealed that if China were to achieve carbon peaking by 2026, it might result in a GDP growth rate decrease to below 4.5% by 2030. However, it would also lead to a 45% reduction in carbon intensity compared to 2015, achieving surplus emissions reduction. Y. Wang, Yang, and Sun (2020) assessed the carbon intensity reduction effect of China’s industrial sector from 2005 to 2017 based on the carbon emission efficiency. The results show that the industrial sector in more than two-thirds of the country’s provinces are able to complete the 2030 emission reduction target ahead of schedule.

METHODOLOGY AND DATA

**SBM-DEA and Input-Output Models**

In this study, the two key variables to be calculated are carbon emission reduction potential and marginal carbon emission reduction cost. To better measure the carbon emission reduction potential of each province, we employ the Slack-based Measure (SBM) model. The SBM efficiency measurement method is a non-radial measure within the DEA efficiency measurement model. It does not assume that all Decision Making Units (DMUs) need to improve proportionally in both inputs and outputs. This makes it more suitable for this study, where not all provinces can or need to adjust their operations similarly. Besides, this model introduces slack variables, which represent the amount by which a DMU can improve its efficiency. This feature provides insights into both the underutilization of inputs and the overproduction of outputs, allowing decision-makers to focus on specific areas of improvement.

Based on the above analysis, the SBM model set in this paper is as follows:
\[ \phi^* = \min \frac{1 - \frac{1}{m} \sum_{i=1}^{m} s_i^{\ell}}{1 + \frac{1}{s_1 + s_2} \left( \sum_{i=1}^{s_1} s_i^{g\ell} + \sum_{i=1}^{s_2} s_i^{b\ell} \right)} \]  

\[ s.t. x_0 = X_{\to} + s_0^- \]

\[ y_{0}^g = Y_{\to}^g - s_0^g \]

\[ y_{0}^b = Y_{\to}^b + s_0^b \]

\[ s_0^- \geq 0, s_0^g \geq 0, s_0^b \geq 0, \rightarrow 0 \]

where subscript 0 represents the DMU that is currently being estimated, subscript \( i \) denotes the \( i \)th input, and \( i \in \{1, 2, \ldots, m\} \); The subscript \( r_1 \) indicates the \( r_1 \)st expected output, where \( r_1 \in \{1, 2, \ldots, s_1\} \); The subscript \( r_2 \) indicates the \( r_2 \)st expected output, where \( r_2 \in \{1, 2, \ldots, s_2\} \); \( x_{\to}, y_{\to}^g \) and \( y_{\to}^b \) are the inputs, expected outputs and unexpected outputs of the DMUs, respectively.

\( x_0, y_0^g \), and \( y_0^b \) are the matrices that make up these inputs and outputs. \( X_{\to}, Y_{\to}^g \) and \( Y_{\to}^b \) are the production frontiers. \( s_0^-, s_0^g \), and \( s_0^b \) are the vectors of slack variables (potential improvement space) comprising the full set of DMUs to be estimated. Finally, with the estimated slack variables, we can obtain the efficiency of the unexpected output. In this paper, the non-consensual output is only CO2, so we can define the carbon reduction potential in the SBM model as:

\[ CE = \frac{s_{10}^b}{y_{10}^b} \]  

The SBM model can evaluate how efficiently DMUs convert inputs into outputs. Its dual model, on the other hand, focuses on the shadow prices or dual values associated with inputs and outputs. These shadow prices represent the marginal rates of substitution between inputs and outputs and can provide valuable insights into the economic interpretation of DEA results. In this paper, we use the dual model of SBM to calculate the marginal cost of carbon emissions reduction. The specific formulation is as follows:

\[ \theta^* = \max \theta \]

\[ s.t. \quad \theta + \mu^g y_0^g - \mu^b y_0^b = 1; \]

\[ \mu^g y_0^g - \mu^b y_0^b \leq 0; \]

\[ v \geq \frac{1}{m} \left[ \frac{1}{x_0} \right]; \]

\[ \mu^g \geq \frac{\theta}{s_1 + s_2} \left[ \frac{1}{y_0^g} \right]; \]

\[ \mu^b \geq \frac{\theta}{s_1 + s_2} \left[ \frac{1}{y_0^b} \right]; \]
where \( v \) and \( \mu^h \) are the shadow prices of these expected inputs and unexpected outputs, and \( \mu^g \) is the marginal dummy return per unit of output. \( \left[1 / x_0 \right] \) is the row vector of \( \left(1 / x_{i0} \ldots 1 / x_{m0}\right) \).

In the model of this paper, the unexpected output is only carbon dioxide emission, and the consensual output is only real GDP, so \( \mu^h = sp^{co2} \) and \( \mu^g = sp^{GDP} \). \( sp^{co2} \) and \( sp^{GDP} \) are the parameters of the shadow price of carbon emission and GDP, respectively, and by setting the shadow price of GDP to 1, we can get the shadow price of carbon emission, i.e. the marginal abatement cost of carbon emission reduction:

\[
\text{Shadow Price of CO2} = \frac{sp^{co2}}{sp^{GDP}}
\]

(4)

This paper considers two types of carbon emissions measurement. The first type is the commonly used production-based carbon emissions calculation, where carbon emissions are accounted for based on the actual location of emissions. The second type is consumption-based carbon emissions, which are also known as embodied carbon emissions and refer to the total carbon emissions associated with the production and transportation of goods and services consumed in a specific region or by a particular entity. Unlike production-based emissions, which account for emissions generated within the boundaries of a specific location or country, consumption-based emissions consider the carbon footprint of all the products and services consumed, regardless of where they were produced. For the former, this paper calculates the carbon dioxide emissions of the entire energy commodity using the method outlined by the Intergovernmental Panel on Climate Change (IPCC). The calculation is detailed in the following formula:

\[
CO_{2}^{i} = \sum_{j} E_{i,f} \times CV_{i,f} \times CC_{i,f} \times CO_{i,f} \times \frac{44}{12}
\]

(5)

Where \( CO_{2}^{i} \) represents the total carbon emissions of province \( i \), \( E_{i,f} \) represents the final consumption of fossil energy source \( f \), \( CV_{i,f} \) represents the calorific value of the corresponding fossil energy source, \( CC_{i,f} \) represents the carbon content of the corresponding fossil energy source, and \( CO_{i,f} \) represents the carbon oxidation rate of the corresponding fossil energy source. \( 44/12 \) is the carbon emission conversion factor.

Referring to the method of Zheng et al. (2020), this paper applies the input-output analysis to define the consumption-based carbon emissions resulting from the final demand for commodities, as shown below:

\[
CO^{2} = E(I - A)^{-1} F
\]

(6)

where \( E \) is a \((1 \times n)\) row vector of \( CO2 \) emissions per unit of output for each industry in a given province; \( I \) is an \((n \times n)\) unit matrix, \( A \) is an \((n \times n)\) direct consumption matrix, and \( F \) is an \((n \times 1)\) column vector of final consumption for each industry in a given province. \( CO2^{e} \) on the left side of the equation is the consumption-based carbon emissions for a given province.

Based on the input-output data, we can further calculate the embodied carbon emissions driven by interprovincial trade, also known as interprovincial carbon transfer.
\[ PC' = E(I - A)^{-1}(IM^p - EX^p) \]  

(7)

Here, \( IM^p \) and \( EX^p \) are (n×1) column vectors, representing the interprovincial imports and exports of various industrial outputs in a specific province. \( (IM^p - EX^p) \) represents the net interprovincial imports of goods. Similarly, through a similar approach, we can calculate carbon transfer driven by international trade. The carbon transfers driven by interprovincial and international trade collectively constitute the total carbon transfer for a region.

**Optimization of Emission Reduction Pathways**

This section aims to set a more scientific and reasonable carbon emission reduction program based on the national carbon intensity reduction target for 2030. Specifically, it is necessary to consider the different marginal abatement costs, abatement potentials, and carbon emission accounting methods of each province, so as to construct heterogeneous provincial abatement pathways under different focus. Firstly, we need to normalize the emission reduction potential and abatement cost obtained from the SBM model.

\[ E_{i,c} = \text{mean}\left(\frac{\max CE_{i,c} - CE_{i,c}}{\max CE_{i,c} - \min CE_{i,c}}\right) - \frac{CE_{i,c} - \min CE_{i,c}}{\max CE_{i,c} - \min CE_{i,c}} \]  

(8)

\[ C_{i,c} = \text{mean}\left(\frac{MAC_{i,c} - \min MAC_{i,c}}{\max MAC_{i,c} - \min MAC_{i,c}}\right) - \frac{MAC_{i,c} - \min MAC_{i,c}}{\max MAC_{i,c} - \min MAC_{i,c}} \]  

(9)

Here, the subscripts \( i \) and \( c \) represent provinces and carbon accounting methods (production-based carbon emissions, consumption-based carbon emissions), respectively. \( E_{i,c} \) and \( C_{i,c} \) denote the normalized carbon reduction potential and marginal abatement cost for province \( i \) under carbon accounting method \( c \), where \(-1 \leq E_{i,c} \leq 1 \) and \(-1 \leq C_{i,c} \leq 1\). \( CE_{i,c} \) and \( MAC_{i,c} \) represent the carbon reduction potential and marginal abatement cost for province \( i \).

It’s important to note that negative values of \( E_{i,c} \) or \( C_{i,c} \) indicate that the reduction potential is below the mean or the marginal abatement cost is above the mean. Generally, lower reduction potential and higher cost suggest lower economic efficiency in carbon reduction. Therefore, to minimize overall abatement costs, lower-than-baseline reduction targets should be set for a province when \( E_{i,c} \) and \( C_{i,c} \) is negative. Conversely, when \( E_{i,c} \) and \( C_{i,c} \) is positive, the reduction task should be appropriately increased.

Next, we calculate the allocation indicator \( A_{i,r,c} \) for province \( i \) under different prioritization principles:

\[ A_{i,r,c} = w_r^E E_{i,c} + w_r^C C_{i,c} \]  

(10)

Here, \( w_r^E \) and \( w_r^C \) represent the weights associated with \( E_{i,c} \) and \( C_{i,c} \), respectively, with the constraint that \( w_r^E + w_r^C = 1 \). The subscript \( r \) denotes the prioritization principle for emission reduction pathway design. This paper assumes that the importance of emission reduction potential and cost have the same degree of importance, in which case \( w_r^E = w_r^C = 0.5 \). We refer to this setting as an emission reduction scheme based on the “balance” principle. Recognizing that in reality, different
priorities may be assigned during actual emission reduction efforts, this paper considers two additional scenarios for robustness analysis: the potential-first principle and the cost-first principle. Under the potential-first principle, \( w^p_r = 0.7 \), and under the cost-first principle, \( w^c_r = 0.3 \).

\[
G_{i,r,c} = T + \frac{A_{i,r,c} - \min_i A_{i,r,c}}{\max_i A_{i,r,c} - \min_i A_{i,r,c}} \vartheta_{r,c} T
\]  

(11)

Where \( T \) represents China’s annual average emission reduction target for the year 2030. In 2015, China submitted its Intended Nationally Determined Contributions (INDC) to the United Nations, committing to reduce carbon intensity by 60%-65% compared to 2005 levels by 2030. In 2021, the State Council of China released the “Notice on the Action Plan for Carbon Peaking Before 2030,” which further increased the target to 65%. Combining the emission reduction goals achieved in 2020, this paper calculates that in order for China to achieve its 2030 emission reduction target, the annual carbon intensity reduction rate should not be less than 1.41%. Therefore, referring to the method of (F. Wang, Sun, Reiner, & Wu, 2020), we set 1.41% as the baseline for carbon intensity reduction in each region. \( \vartheta_{r,c} \) represents the normalized dispersion of emission reduction tasks \( A_{i,r,c} \), and can be measured using standard deviation:

\[
\vartheta_{r,c} = \sqrt{\frac{1}{n} \sum_i (A_{i,r,c} - \bar{A}_{i,r,c})^2}
\]  

(12)

The magnitude of \( \vartheta_{r,c} \) determines the variation in emission reduction targets among different provinces due to differences in emission reduction costs and potential. Additionally, considering that different provinces have varying carbon emissions, the direct summation of \( G_{i,r,c} \) cannot equal the average intensity reduction target \( T \) for China. Therefore, it is necessary to introduce a drift term \( \tau_{r,c} T \) to the emission reduction targets, along with the following constraints:

\[
T = \sum_i w^\text{carbon}_{i,c} G_{i,r,c}
\]  

(13)

Where \( w^\text{carbon}_{i,c} \) represents the proportion of carbon emissions from province \( i \) under carbon accounting method \( c \) to the total carbon emissions.

In most cases, we cannot directly calculate the emission reduction targets \( G_{i,r,c} \) because the value of \( \tau_{r,c} T \) cannot be determined directly. Instead, it is calculated based on the constraints of equation (13). Therefore, to solve for \( G_{i,r,c} \), we need to simultaneously consider equations (11), (12), and (13). The above equations consist of \( i \times r \times c + 2 \times r \times c \) equalities and three groups of unknowns. And the three groups contain \( i \times r \times c \) “\( G_{i,r,c} \)”, \( r \times c \) “\( \vartheta_{r,c} \)”, \( r \times c \) “\( \tau_{r,c} \)”. Thus, the system of equations has a unique solution. We employed the General Algebraic Modeling System (GAMS) with the Mixed Complementary Problem (MCP) solver to identify this solution, resulting in the comprehensive optimization path for provincial emissions reduction \( G_{i,r,c} \).

The advantage of this path design is that it simultaneously considers emission reduction potential and cost (reflected in \( A_{i,r,c} \)), and can be adjusted based on different emphases. It also combines both...
overall and individual targets (reflected in the drift term $\tau_{rc}$). Additionally, it takes into account the impact of different carbon accounting principles (reflected in the subscript c). Therefore, the optimized emission reduction path proposed in this paper considers both the economic efficiency of emissions reduction and carbon equity among regions.

Data
The SBM model requires provincial data on input factors, expected output, and unexpected output.

Expected output (Regional Gross Domestic Product, GDP): The total output in this paper is based on the regional Gross Domestic Product at constant prices. Using the year 2000 as the base year, we deflate the nominal GDP of each region annually with the respective regional GDP deflators. The data source is the National Bureau of Statistics.

Unexpected output (Production-based carbon emissions): This paper calculates the carbon emissions of each region based on the consumption of 17 types of fossil fuels. The calculation involves parameters such as the heat value, carbon content, and carbon oxidation rate of these 17 fossil fuels. The heat value data for various energy sources is referenced from the “China Energy Statistical Yearbook,” while the carbon content is derived from the IPCC 2006 data.

Capital input: This paper uses the capital stock of each region for the current year as its capital input. The specific calculation steps are as follows: Using the year 2000 as the base year, we first deflate the total nominal fixed asset investment of each region for the current year based on the price index of fixed asset investment. This gives us the constant-price total fixed asset investment for each region. Then, we calculate the capital stock for each region annually using the perpetual inventory method.

Energy input: For the energy input factor in this paper, we use the total energy consumption in each region for the corresponding year, measured in 10,000 tons standard coal equivalent. We collect data on the annual consumption of 17 types of fossil energy sources in each provinces. These consumption figures are converted into standard coal equivalent units using conversion factors published in the China Energy Statistical Yearbook.

Labor input: The labor input factor in this paper is represented by the total employed population in each region.

The data sources for the input factors mentioned above include the China Energy Statistical Yearbook, provincial statistical yearbooks, and the National Bureau of Statistics.

This paper calculates consumption-based carbon emissions as well as trade-driven embodied carbon emissions using multi-provincial input-output tables from the CEADs database. As of now, CEADs publishes China’s multi-regional input-output data from 2012, 2015, and 2017. Therefore, in the process of calculating consumption-based carbon emissions, we primarily relied on data from the input-output tables for these three years. Additionally, due to the absence of energy data for Tibet, Taiwan, Hong Kong, and Macao, these regions were excluded from the analysis.

EMPIRICAL RESULTS
Carbon Emission Transfer Between Provinces
Following the method outlined in Section 3.2.2, this paper calculates the carbon transfer caused by inter-provincial and international trade. Figure 1 displays the net carbon emissions outflow for each province driven by domestic inter-provincial trade, while Figure 2 shows the net carbon emissions outflow for provinces driven by international trade. Figure 3 illustrates each province’s total net carbon emissions outflow, which is the sum of the previous two. A positive value in the total net carbon emissions outflow indicates that the province is a net carbon emissions outflow region for that year. In contrast, a negative value indicates that the province is a net carbon emissions inflow region.

From the data in Figure 1, it can be observed that while there are variations in the net carbon emissions outflow direction for individual provinces across different years, the overall carbon emissions
transfer trend remains consistent across these three years for most provinces. Looking at the overall flow pattern, there is a distinct “from west to east, from north to south” trend in China’s inter-provincial carbon emissions transfer: eastern coastal provinces such as Guangdong, Shanghai, Zhejiang, Tianjin, and Jiangsu are major net carbon emissions inflow regions, whereas central and western provinces, including Inner Mongolia, Guizhou, Shanxi, Henan, Shaanxi, Ningxia, and Xinjiang, are major net carbon emissions outflow regions.

The trend of carbon emission transfer in various regions has distinctive features. In the following two sections, we will analyze in detail the trends and features of carbon transfers in different regions.

**Developed Eastern Regions**

Developed eastern regions, like Guangdong, Zhejiang, Shanghai, and Jiangsu, primarily experience a net inflow of carbon emissions. In these provinces, Guangdong exhibits the highest net inflow, with an average annual net inflow of carbon emissions reaching 62 million tons. This accounts for 12.4% of its total production-based carbon emissions. Two main factors contribute to this phenomenon:

Firstly, Guangdong is the province with the highest volume of energy imports in China, importing a significant amount of electricity annually from southwestern China. In the years 2012, 2015, and 2017, Guangdong Province’s electricity imports amounted to 9.83 billion kilowatt-hours, 14.26 billion kilowatt-hours, and 30.6 billion kilowatt-hours, respectively, accounting for 21.3%, 26.9%, and 51.4% of Guangdong Province’s total electricity consumption for each respective year. Electricity

Figure 1. Net carbon emissions outflow driven by inter-provincial trade

Figure 2. Net carbon emissions outflow driven by international trade
imports have become the primary driver of carbon emissions inflow in Guangdong. While the volume of electricity imports increases each year, the rapid development of green power generation in southwestern China has led to a yearly decline in Guangdong’s carbon emissions inflow driven by electricity imports (Jia, 2023; Jia, Wen, et al., 2023). Over the three years, the carbon emissions inflow driven by electricity imports in Guangdong was 120 million tons, 71 million tons, and 47 million tons, accounting for 73.85%, 82.41%, and 67.48% of the total carbon emissions inflow for each respective year. This decreasing trend in carbon emission inflows driven by electricity imports also reflects the development of green power in southwestern China (Qiao & Lin, 2023).

Secondly, Guangdong boasts a relatively high level of industrial structure optimization. The tertiary industry’s value-added output accounts for a significant proportion of the regional GDP, ranking among the top in the nation. In contrast, the secondary industry’s value-added output as a proportion of the regional GDP is relatively low. Additionally, most of Guangdong’s industrial enterprises operate in high-value-added segments of the industrial chain, such as automobile manufacturing, general and special-purpose equipment manufacturing, electronic equipment manufacturing, electrical machinery and equipment manufacturing, etc. This aspect has led to a lower dependence on energy-intensive sectors for Guangdong’s economic development. However, to support the development of local high-end industries, Guangdong relies heavily on the import of industrial raw materials and energy from other provinces. This dependence is also reflected in the import of metal and non-metal mineral products in Guangdong. Over the three years, the net carbon emissions inflow driven by the import of metal and non-metal mineral products accounted for approximately 17.2%, 27.9%, and 24.2% of Guangdong’s total carbon emissions inflow, making it the second-largest driver of carbon emissions inflow in the province.

The situation in provinces like Shanghai, Jiangsu, and Zhejiang is similar to Guangdong. On one hand, these provinces are all major energy importers in China. In the three years, the proportion of carbon emissions inflow driven by electricity imports in these three provinces averaged 52.8%, 83.8%, and 75.5%, respectively. Electricity imports are the primary driving factor for carbon emissions inflow in these provinces. On the other hand, these provinces were among the earliest to develop economically in China. They have a relatively high degree of industrial structure optimization, with most of their industrial sectors concentrated in high value-added segments. Consequently, their economic development relies less on local energy-intensive industries and more on interprovincial trade for carbon-intensive industrial materials and energy resources. This regional industrial division allows developed eastern provinces to gain high industrial value-added while experiencing lower emission reduction pressure on the production side.
Undeveloped Central and Western Regions

In contrast to the eastern regions, the central and western provinces, including Inner Mongolia, Shanxi, Xinjiang, Shaanxi, and Guizhou, are major carbon net-outflow regions. These provinces serve as primary energy producers and exporters in China. Between 2012, 2015, and 2017, the electricity exports of these five provinces account for 44.0%, 40.1%, and 31.2%, respectively, of the total dispatched electricity in China, making the Northwest Power Grid becoming the largest power exporter in China. Over these three years, the average annual carbon emissions outflow driven by electricity exports from these five provinces reached 230 million tons, 120 million tons, 65 million tons, 22 million tons, and 35 million tons, respectively, representing 79.6%, 68.5%, 52.0%, 27.7%, and 62.8% of their respective average total carbon emissions outflows. Additionally, these regions possess abundant oil and gas resources, further contributing to carbon emissions outflow. For instance, in Shaanxi, the export of coal and coke products alone drives over 26 million tons of carbon emissions outflow annually, approximately 40% of its total emissions outflow.

The net outflows of carbon emissions are also significant in three eastern provinces: Hebei, Shandong, and Fujian. Hebei is the province with the highest steel production in China, providing approximately one-quarter of the national steel output annually. However, most of the steel produced in Hebei is supplied to other provinces. In 2012, 2015, and 2017, carbon outflows driven by metal smelting and rolling product exports in Hebei were 183 million tons, 187 million tons, and 133 million tons, respectively. These figures accounted for 67.6%, 78.7%, and 87.3% of Hebei’s total carbon emissions outflows in those respective years. This concentration of iron industry has made Hebei one of the highest carbon emissions outflow regions in the country, imposing significant pressure on its carbon reduction efforts. Shandong’s carbon emissions outflow is primarily driven by electricity, metal smelting and rolling products, petroleum, and coke exports, accounting for 47.3%, 20.1%, and 6.5% (three-year average) of the province’s total carbon emissions outflow. Fujian province has witnessed rapid growth in electricity exports in recent years, totaling 44.4 billion, 33.9 billion, and 75 billion kilowatt-hours in 2012, 2015, and 2017, respectively. The average annual carbon emissions outflow driven by this electricity export exceeds 27 million tons, which has been a key factor in transforming Fujian from a carbon emissions net inflow region to a net outflow region.

In summary, the central and western provinces rely more on low-end and carbon-intensive industries to fuel their economic development. This development approach places them in a situation where they can only access lower industrial value-added, while having to bear a greater burden of carbon reduction on the production side. This inevitably accentuates the contradiction between economic development and carbon reduction in these regions, further widening the economic development gap between regions and creating a vicious cycle of “the poor getting poorer.” Hence, there is a need to balance this situation by clarifying carbon reduction responsibilities on the consumption side.

Port Area Specificity

In the eastern region, Tianjin has the smallest net carbon inflow, which is basically due to the fact that Tianjin plays more of a “transit station” role. As an important port city, Tianjin needs to undertake the task of transporting a large number of imported goods and raw materials to various provinces in China every year. This inter-provincial transfer of products makes Tianjin a net exporter of carbon emissions in inter-provincial trade, and at the same time, it also offsets most of the net inflow of carbon emissions driven by international trade, so that Tianjin’s actual net inflow becomes very small. The situation in Shanghai is also similar to that of Tianjin, and although the net carbon outflow driven by inter-provincial trade and the net carbon inflow driven by international trade were both large in Shanghai in 2017, the total net outflow in Shanghai was not really large after the two canceled each other out.
Regional Emission Reduction Potential and Marginal Abatement Costs

Based on the research methodology and data described in Section 3.1, this paper calculates the carbon emission reduction potential and marginal carbon abatement costs (measured using the shadow price of carbon emissions) for both production and consumption sides of each province. Figure 4 illustrates the average emission reduction potential and average abatement cost for different regions across China, considering both production and consumption sides.

Region-Specific Emission Reduction Potential

As shown in Figure 4, both Beijing and Shanghai have a zero emission reduction potential on both the production and consumption sides. This suggests that these two regions are situated at the efficient production frontier. Being the national economic and administrative centers, Beijing and Shanghai exhibit highest levels of industrial structural optimization, management proficiency, and technological advancement, which result in their relatively low emission reduction potentials and higher marginal abatement costs.

Nationally, 11 regions have a smaller emission reduction potential on the production side compared to the consumption side. This includes most of the eastern coastal provinces and some central and western provinces. We also observed that the magnitude of the difference in emission reduction potential between the production and consumption sides is primarily influenced by the scale of net emission outflows in the provinces. Provinces with more significant net emission outflows tend to have greater differences in emission reduction potential between the production and consumption sides. For example, provinces like Zhejiang, Guangdong, Hainan, Jiangsu, and Chongqing are the leading net importers of carbon emissions. The differences between their production- and consumption-based carbon emissions are often significant. And the gaps between their production-based emission reduction potential and consumption-side emission reduction potential are also significant. For Zhejiang, Guangdong, Hainan, Jiangsu, and Chongqing, on the one hand, these regions are net inflows of carbon emissions, and their consumption-side carbon emissions tend to be higher than production-side carbon emissions; on the other hand, after taking into account the net inflow of carbon emissions, the distance between the consumption-side emissions of these regions and the effective frontier of the consumption-side is greater than that of their production-side emissions, and therefore the emission reduction potential of the production-side of these regions is basically lower than that of their consumption-side emission reduction potential, and there is a large gap between the two.

Figure 4. Average emission reduction potential and carbon emission shadow prices
There are 17 provinces where the production-based emission reduction potential is lower than the consumption-based potential. These provinces encompass nearly all central and western provinces, such as Inner Mongolia, Shaanxi, Shanxi, Xinjiang, Guizhou, and Hubei, along with a few eastern provinces like Shandong, Hebei, and Tianjin. These regions are net carbon emission exporters, with consumption-based emissions lower than production-based emissions. As a result, the consumption-based emission reduction potential in these provinces is generally lower than the production-based emission reduction potential. In particular, several provinces with leading net carbon emissions inflow, such as Inner Mongolia, Gansu, Hebei, and Shandong, exhibit a considerable difference between their production-side and consumer-side emission reduction potentials.

In contrast, regions like Fujian, Guangxi, Jiangxi, Anhui, and Hunan, while also being net carbon emission exporters with small net emission outflows. Consequently, the gaps between their consumption-based emission reduction potential and production-based emission reduction potential are also smaller than other provinces with larger carbon outflows.

**Regional Carbon Emission Shadow Prices**

As shown in Figure.4, the shadow prices of carbon emissions on the consumption side are higher than those on the production side in 28 provinces. An important reason for this is that the average consumption-side carbon emissions calculated in this study for 2012, 2015, and 2017 were lower than the production-side carbon emissions, at around 1.2 billion tons. This is equivalent to the net carbon emissions export amount driven by international trade estimated by other literature (Huang & Zou, 2020; Lin & Guan, 2023a). This implies that as a trade surplus country, China's overall consumption-based carbon emissions are lower than its overall production-based carbon emissions. Consequently, the consumption-based shadow price of carbon emissions is slightly higher than that for production.

Overall, due to variations in the industrial structure and their positions within industrial supply chains, the eastern regions have become major recipients of industrial raw materials, energy, and carbon emissions inflows, while the central and western regions have become the primary suppliers of these resources. Allocating carbon reduction tasks solely based on production-based carbon emissions may overlook consumption-based emission responsibility and lead to unfairness. Therefore, it is necessary to optimize the emission reduction pathways from both consumption perspectives to balance the inequality resulting from this carbon leakage. The regional disparities in marginal abatement reduction costs and reduction potentials also provide opportunities for optimizing emission reduction strategies.

**Optimization of Emission Reduction Pathways**

After gaining insights into regional reduction potentials and marginal abatement costs, we further explore how to optimize provincial carbon reduction pathways to balance overall emission reduction efficiency and carbon equity. Using the design scheme from Section 3.3, we first derive production-based optimal emission reduction pathways for each province by solving a planning model. Like most existing literature, these optimal pathways are designed based on the production-based emission. We compare these optimal pathways with the national baseline emission reduction target (1.41%) to analyze the differences.

**Production-Based Emission Reduction Pathway**

Utilizing the path design scheme from Section 3.3, we initially calculate the optimal emission reduction pathways for each province based on production-based carbon emissions and compare them with the national average reduction path, as shown in Figure 5. Overall, provinces like Beijing, Shanghai, Tianjin, Guangdong, and Fujian all have reduction pathways below the national baseline reduction target. These provinces are predominantly developed areas characterized by a higher degree of industrial structure optimization, economic development, and energy utilization efficiency. And they also tend to have the lower emission reduction potential and the higher marginal abatement costs compared to other regions. Therefore, to maximize the overall emission reduction efficiency and
minimize the overall emission reduction cost, the emission reduction tasks in these regions should be less stringent than other provinces.

In contrast, provinces like Ningxia, Xinjiang, Qinghai, Guizhou, Shanxi, and Inner Mongolia have optimal reduction pathways above the national baseline target. This indicates that these provinces need to undertake stricter emission reduction constraints. These provinces are mostly less developed central and western regions and are major producers of energy and carbon-intensive industrial products. This implies that emission reduction has a relatively minor negative impact on the local economy (low shadow prices) and more significant room for emission reduction (low overall carbon efficiency). Imposing stricter emission reduction constraints on these provinces can reduce overall efficiency losses and emission reduction costs.

**Equity Consideration: The Difference Between Two Emission Reduction Pathways**

As mentioned earlier, designing emission reduction paths solely based on production-based carbon emissions can lead to fairness issues. Therefore, based on consumption-based carbon emissions, efficiency, and abatement cost, we re-optimize the emission reduction pathways. Figure 6 illustrates the comparison of the differences between these two optimal emission reduction pathways and the national baseline reduction magnitude.

As mentioned, designing emission reduction paths based solely on production-based carbon emissions can lead to fairness issues. Therefore, based on consumption-based carbon emissions, efficiency, and abatement cost, we re-optimize the emission reduction pathways. Figure 6 illustrates the comparison of the differences between these two optimal emission reduction pathways and the national baseline reduction magnitude.

Comparing these two optimal emission reduction pathways, we find that 16 provinces have optimal consumption-based emission reduction magnitudes higher than their production-based counterparts. These provinces include all the developed eastern provinces, such as Beijing, Shanghai, Guangdong, Zhejiang, Jiangsu, and Fujian, as well as some central and western provinces like Hubei, Jiangxi, Chongqing, and Sichuan. These regions have a significant annual net carbon emission inflow, which means they do not need to bear many emission reduction responsibilities on the production side. Hence, for these regions, stricter optimal emission reduction pathways on the consumption side than on the production side reflect the fairness in carbon reduction responsibility allocation.

However, being a carbon net importer does not necessarily translate to higher consumption-based carbon reduction responsibilities. For example, provinces like Jiangxi and Guangxi, despite being carbon net exporters, have higher consumption-based emission reduction magnitudes compared to
their production-based counterparts. This also implies that the carbon transfers in these regions are likely to be inefficient. Even when accounting for trade-induced hidden carbon emissions, the emission reduction potentials and marginal abatement costs in these net outflow regions still exhibit higher deviations from the national averages on the consumption side compared to the production side.

A similar example is Henan. Henan’s consumption-based carbon reduction potential and marginal abatement costs remain virtually unchanged after accounting for its net carbon outflow, even though it is one of the largest net carbon outflow regions. This indicates that Henan’s carbon emissions export might be relatively inefficient. Henan has a significant outflow of non-metallic mineral products and metal smelting and rolling products. However, these local industries do not operate with high production efficiency. They consist of a large number of small and medium-sized enterprises with excess capacity. Therefore, even considering the substantial net carbon outflow, Henan’s carbon efficiency and marginal abatement costs do not experience a significant improvement. The slight difference between the consumption- and production-based reduction pathways can be considered a mechanism to penalize “inefficient” carbon exports, enabling net exporting regions to control their “ineffective” carbon emissions exports. This also illustrates the efficiency consideration of our design.

Out of the 30 provinces, 14 provinces, the majority of which are located in the central and western regions, have a lower optimal emission reduction magnitude on the consumption side compared to the production side, such as Inner Mongolia, Shaanxi, Shanxi, Qinghai, Ningxia, Xinjiang, and Guizhou. These provinces are major energy and carbon emission outflow areas. Thus, after considering their carbon emissions outflow, their emission reduction potential decreases, and their marginal abatement costs increase. As a result, the optimal emission reduction targets on the consumption side are lower than those on the production side for these provinces. This design offers less emission reduction pressure and more room for economic development in western regions, helping to alleviate the regional imbalances and reflecting the principle of carbon equity.

Optimal Emission Reduction Pathways Under Different Principles

In practical scenarios, governments may also design emission reduction pathways based on various priority principles. Therefore, in addition to the scheme designed based on the “balance” principle, we also calculate the emission reduction pathways based on the potential-first principle and the cost-first principle for reference, as mentioned in section 3.3. As shown in Figures 7 and 8, these two pathways do not significantly differ from the one designed based on the “balance” principle.
CONCLUSIONS AND POLICY IMPLICATIONS

Regional industrial specialization has driven extensive interprovincial trade and carbon emission transfers between different regions in China, resulting in significant disparities between regional production-based and consumption-based carbon emissions. Using an energy-environment input-output model, this study calculates and analyzes the scale and trends of interprovincial carbon transfers in China. We find that the economically developed provinces in the eastern regions act as major net carbon emission importers, while the less developed central and western regions predominantly serve as net carbon emission exporters. Among the various driving factors behind these carbon emission transfers, interprovincial trade in the electricity, metals, and mineral products industries is the most significant.

Furthermore, the disparity between production-based and consumption-based carbon emissions has also resulted in variations in the provinces’ emission reduction potentials and marginal abatement costs. In particular, existing regional emission reduction pathway designs based on production-
based emissions have several shortcomings. This regional division of industry has placed more stringent emission reduction constraints on the less developed central and western regions, which are not conducive to coordinated economic development and overlook the consumption-based emission responsibility. Consequently, this paper proposes a regional carbon reduction pathway design considering embodied carbon emissions. Specifically, by employing the SBM model and its dual model, we calculate the carbon reduction potentials and marginal carbon abatement costs for consumption-based emissions in each province. We optimize regional emission reduction pathways by utilizing the differences in efficiency and cost as benchmarks. This scheme offers the potential to enhance the overall efficiency and cost-effectiveness of carbon reduction efforts in China. Compared to traditional designs, this approach also better embodies the concept of carbon equity.

Combining the conclusions of this paper yields a series of policy insights:

Emission reduction pathway designs based on production-side emissions are likely to lead to unfair allocation of emission reduction tasks, reduce overall emission reduction efficiency, and increase overall abatement costs. Therefore, when governments design regional emission reduction pathways, they should consider the differences between production-side and consumption-side emissions while considering reduction potentials and costs. This will enhance overall emission reduction efficiency.

A reasonable method for assigning carbon emission responsibilities is crucial for addressing emission reduction equity and improving the feasibility of carbon reduction policies. Therefore, when setting carbon emission targets, differences in regional carbon emission efficiency and reduction potential should be considered, and attention should be paid to the issues of unequal responsibilities arising from carbon transfers. Internal carbon transfer adjustment taxes or heterogeneous carbon emission rights allocation methods can be employed to avoid efficiency and fairness losses when necessary.

This paper finds that interregional electricity dispatch and trade in energy-intensive industrial products are the main drivers of China’s inter-provincial carbon emission transfers. The central and western regions have a comparative advantage in developing these high-energy-consuming industries. Therefore, their emission reduction efforts should prioritize clean and efficient utilization of fossil energy rather than industrial structure adjustments. Increased investment in and utilization of clean energy sources, such as wind and solar power, is also a good approach. This will ensure the rationality of regional specialization and the synergistic development of regional economies.

To enhance emission reduction equity and policy feasibility, it is crucial to set carbon emission targets that consider variations in regional carbon emission efficiency and reduction potential. To mitigate unequal responsibilities resulting from carbon transfers, governments can explore methods such as internal carbon transfer adjustment taxes or diverse carbon emission rights allocation strategies when necessary. These measures can help maintain both efficiency and fairness in emission reduction policies.

Declaration of Interest Statement

None

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ENDNOTES

1 Note that governments are using the percentage decrease in carbon intensity to measure the progress of emission reductions, so here the reduction potential is also expressed as a percentage.

2 The fossil energy sources in carbon emissions calculations include coal, crude oil, natural gas, peat, shale oil, shale gas, oil sands, liquefied petroleum gas (LPG), gasoline.

3 The total inflow and outflow mentioned here are distinct concepts from net inflow and net outflow. Total inflow/ outflow refers to the overall amount of carbon emissions that have entered (or exited) a province in a given year. Net inflow (or outflow), on the other hand, is the difference between the inflow and outflow (or outflow and inflow). The use of total inflow in this context is to clarify the key factors driving the carbon transfer.

4 According to data published in China Statistical Yearbook: In 2017, the added value of the tertiary industry in Guangdong Province accounted for about 53.6% of the GDP, ranking seventh in the country; the added value of the secondary industry accounted for about 43.4% of the GDP, ranking sixteenth in the country.

5 One of the five major power grids in China. These five grids are: North China Grid, East China Grid, South China Grid, Southwest China Grid, and Northwest China Grid. These five grids cover all regions within China to meet the demand for power supply and distribution.
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