

Impact of Energy Mix Transition in China's Power Sector on the Domestic and Global Economy and CO₂ Emissions

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Abstract

China was committed to the dual carbon targets of peaking emissions by 2030 and achieving net-zero emissions by 2060. Past studies have mostly analyzed the impacts on power generation, while paying little attention to carbon leakage to other domestic industries and to countries and regions outside China. This study estimates the amount of carbon leakage with an international computable general equilibrium model. We found that China's switch from coal power to renewable energy and efficiency improvements in coal power will raise domestic electricity prices and lower coal prices, leading to carbon leakage to other industries within China. Production in energy-intensive sectors increases in most countries and regions except China, but GDP declines in half of them. As a result, the switch can trigger sectoral carbon leakage in most sectors except the power sector, international carbon leakage in some countries, and may reduce global GDP. To prevent carbon leakage and reduce the economic burden, all industries and countries must advance decarbonization.

Keywords

CGE analysis, GTAP-E-Power model, China, Coal power, Renewable energy, Energy structure transition, Carbon leakage

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1. Introduction

Under its Nationally Determined Contribution (NDC) outlined in the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), China has committed to peaking CO₂ emissions by 2030 and achieving carbon neutrality by 2060 (Dual carbon goals). Although the power generation sector is the largest CO₂ emitter in most countries, its share is particularly high in China. As discussed in the next section, this is largely due to the dominance of coal power in China's power generation sector. Therefore, decarbonizing this sector is crucial to meeting their CO₂ reduction targets.

The fundamental approaches to decarbonizing the power generation sector would involve two main strategies: transitioning from coal power generation to renewable energy generation and improving the efficiency of coal power generation. It is important to evaluate the economic viability and environmental efficiency of these strategies, while it is not straightforward to determine which decarbonization pathway is most economically and environmentally efficient because each power generation technology has different input structure, considering the broader economic impacts—such as inter-industry linkages, labor market dynamics, and international trade.

There have been a lot of analyses using energy system models and integrated assessment models regarding China's achievement of its Dual carbon goals. For example, studies using energy system models include those by Franke et al. (2021), Cai et al. (2022), Zhang et al. (2022), Wang et al. (2023) and Zhang, Q. et al. (2024). Studies using integrated assessment models include those by Shao et al. (2022), Ma et al. (2023), and Pan et al. (2023). These studies analyze macroeconomic indicators such as GDP, but there is little analysis of the impact on other industries or other countries through economic linkages.

Some analyses have used computable general equilibrium (CGE) models, which can take into account broader and more complex economic interdependencies. Examples of research using CGE models include Cao et al. (2021), Lu et al. (2022), Zhang, L. et al. (2024), Jiang et al. (2024), Zhou et al. (2024), Feng et al. (2024), and Gao et al. (2024). However, as Feng et al. (2024) points out, there are few studies that comprehensively examine the impact on industries outside the power generation sector and labor markets in the context of China's Dual carbon goals. Furthermore, as far as we know, there are no studies that address the impact of changes in China's electricity mix on other countries or carbon leakage.

Therefore, to address these research gaps, this study examines based on CGE model how the decarbonization in China's power sector affects CO₂ emissions in other domestic sectors (domestic carbon leakage) and in countries and regions outside China (transboundary carbon leakage), considering the impact on the labor market.

This paper is structured as follows. Section 2 presents an overview of the energy structure transition of China's power generation sector. Section 3 details the analytical model, followed by Section 4 which describes the simulation analysis based on this model. Section 5 interprets the simulation outcomes from the perspective of environmental economics. Section 6 discusses the

realistic relevance of the simulation scenarios in this study. Finally, Section 7 offers a summary of the findings, highlighting the study's limitations and outlining areas for future research.

2. Transition in China's Power Generation Sector

At the December 2020 Climate Ambition Summit, which marked the fifth anniversary of the Paris Agreement, Chinese President Xi Jinping pledged to increase the installed capacity of solar and wind power generation to over 1,200 Gigawatt (GW) by 2030. However, this target was achieved well ahead of schedule, with total installed capacity reaching 1,410 GW by the end of 2024—a testament to China's rapid introduction of renewable energy. The shares of coal, wind, and solar power in China's power sector in terms of power generation were 77.0%, 1.1%, and 0.0%, respectively, in 2010, shifting to 61.3%, 9.3%, and 6.1%, respectively, in 2023 and such figures reflect a significant transition toward renewable energy sources over the past decade or so (IEA, 2025).

Although China's share of coal power generation has declined, the absolute volume of coal power has continued to grow—rising from 3.24 million gigawatt-hour (GWh) in 2010 to 5.85 million GWh in 2023, reflecting a 80.8% increase. Although Western countries have generally seen a decline in capacity since 2012, China has experienced consistent and substantial expansion. Consequently, a complete phase-out of coal power generation, as pursued by European nations, is unlikely to be a realistic option for China in near future.

Figure 1 illustrates China's coal power generation, categorized by plant age and technology type. Coal power plants are classified according to the temperature and pressure of the steam within the boiler, ranked in descending order of energy conversion efficiency as ultra-supercritical, supercritical, and subcritical¹. Although the typical operational lifespan of a coal power plant is approximately 40 years, most plants older than 20 years are subcritical, and among those aged 10–19 years, roughly half are subcritical. This suggests that a substantial portion of China's coal power plants continue to operate with relatively low energy efficiency.

The Chinese government recognizes this issue well, and in June 2024, the National Development and Reform Commission (NDRC) and the National Energy Administration (NER) jointly released the Action Plan for the Low-Carbon Transition and Construction of Coal Power Generation (2024–2027). The plan promotes improving efficiency through retrofitting existing coal power plants and constructing new high-efficiency facilities in a unified manner. These actions are designed to support China's objectives of reaching peak carbon emissions targets and achieving carbon neutrality.

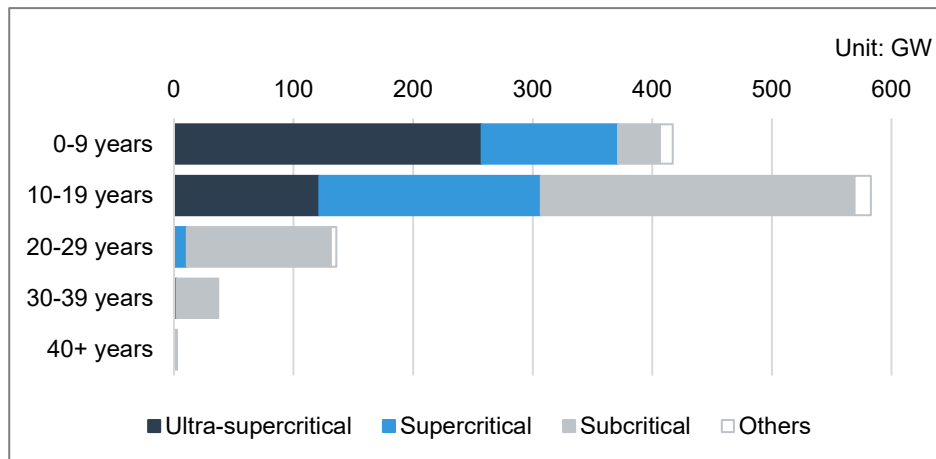


Figure 1 Coal Power Plant Capacity in China by Age and Type (GW)

Note: “Others” includes IGCC (Integrated Coal Gasification Combined Cycle), CFB (Circulating Fluidized Bed) and unknown.

Source: prepared by authors based on Global Energy Monitor (2025)

3. Model

3.1 Features of the GTAP and GTAP-E Models

In this study, we employ the GTAP-E-Power (GTAP-EP) model (Peters, 2016), an international CGE model. This model is derived from the Global Trade Analysis Project (GTAP) and GTAP-E (Energy-Environmental Version of GTAP) models, both developed by the GTAP at Purdue University².

The GTAP model is built upon equilibrium in goods markets, equilibrium in production factor markets, and the zero pure profit condition. As a global model, it incorporates distinctive sectors—a global bank and global transportation—to adjust for international capital flows and trade. The global bank acts as an intermediary sector, balancing global savings and investment by pooling savings from individual countries/regions and investing them in a way that equalizes the rate of change in expected returns on investment. Meanwhile, the global transportation sector is the sole provider of transportation services for international trade, sourcing transport inputs from individual countries/regions and providing international transport services in exchange. This structural framework allows the model to analyze the impacts of structural and efficiency changes in international transportation.

The GTAP model’s production function assumes substitutability among production factors such as labor and capital, and intermediate inputs are represented using fixed coefficients in the Leontief form. This includes energy goods like oil and electricity, which are also treated as intermediate inputs with fixed proportions. However, this specification does not consider the suppression of energy demand due to changes in energy prices, such as those resulting from a carbon tax. To address this limitation, the GTAP-E model was developed. In the GTAP-E framework, energy is incorporated as part of the production factors, enabling adjustments in energy consumption in response to relative price changes.

Figure 2 illustrates the production structure of the GTAP-E model, which is also adopted in the GTAP-EP model. At the top level of the nesting structure, output in each sector is produced through a fixed-coefficient combination of a value-added–energy composite and non-energy intermediate inputs. In the subsequent nesting levels, composite inputs are generated using constant elasticity of substitution (CES) functions. The value-added–energy composite comprises natural resources, land, labor, and a capital–energy composite, with the CES represented by σ_{VAE} in Figure 2. The capital–energy composite, in turn, comprises capital and an energy composite formed through a three-level nesting of gas, oil, petroleum/coal products, coal, and electricity, with the CES denoted by σ_{KE} .

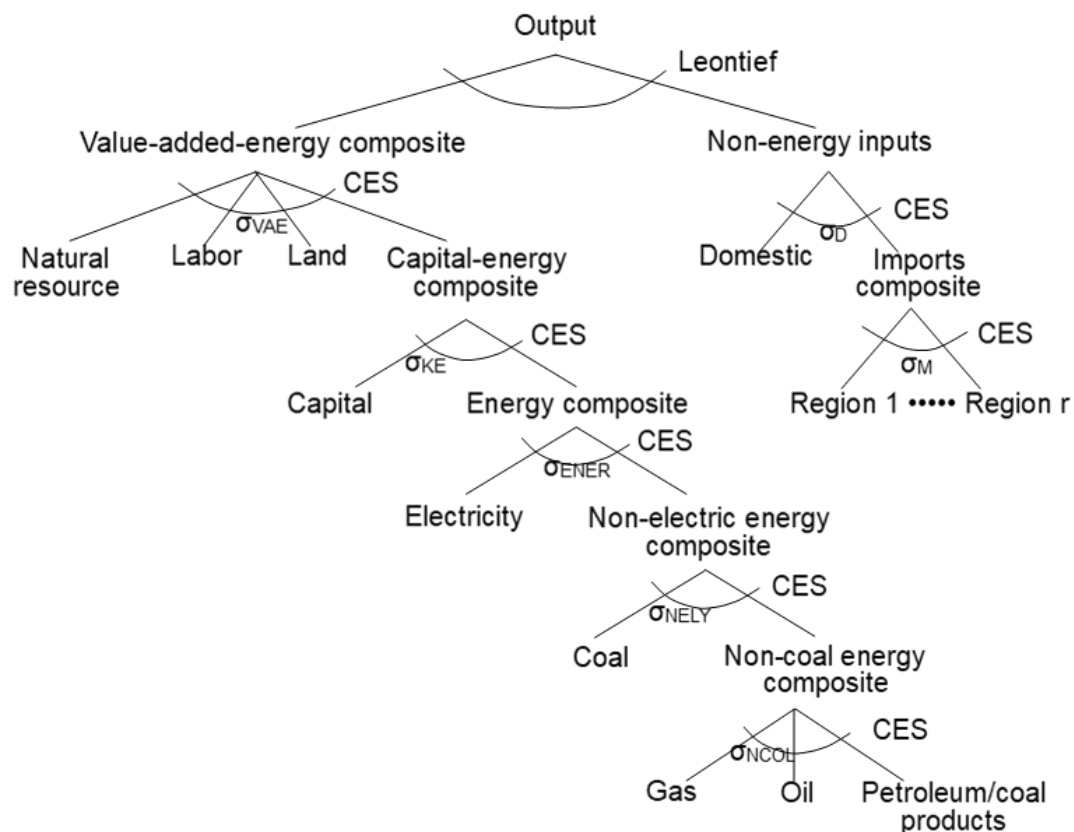


Figure 2 Production Structure of the GTAP-E model

Note: Leontief in the figure indicates that the aggregate is given by a fixed coefficient production function; CES indicates that the aggregate is given by a CES function. In addition, σ represents the elasticity of substitution of the CES function. Although omitted in Figure 2, energy inputs also consist of domestic goods and imports composite.

Source: prepared by the authors based on Burniaux and Truong (2002).

3.2 Features of the GTAP-E-Power Model

The GTAP-E model was developed as an extension of the GTAP model by incorporating capital–energy substitution and linking the economy, energy, and environment (CO₂ emissions). However, in the GTAP-E framework, the power generation sector is treated as a single industry, preventing assumptions such as changes in power source composition or variations in technological progress

across different generation methods. To overcome this limitation, the GTAP-EP model was introduced as an enhancement of GTAP-E, incorporating multiple power generation technologies, as described later, and enabling substitution among them. Due to the nature of electricity demand, generation is categorized into base load, which remains relatively stable throughout the year, and peak load, which fluctuates seasonally and with weather conditions. The power generation sector in the GTAP-EP model is also divided in this way. The base load comprises seven power generation types: nuclear, coal, natural gas, oil, hydro, wind, and others. Meanwhile, the peak load consists of four types: natural gas, oil, hydro, and solar—totaling eleven distinct power generation categories.

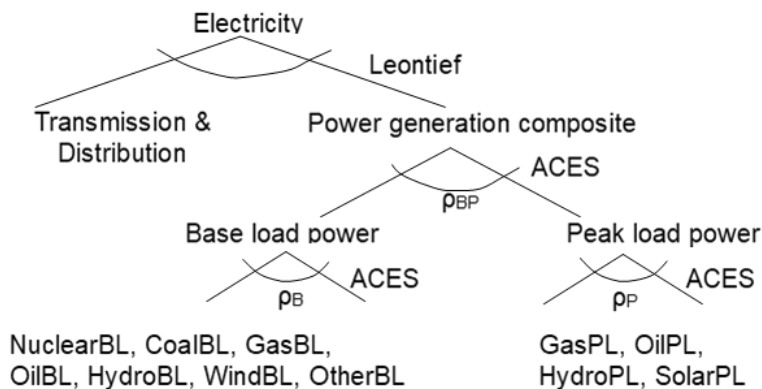


Figure 3 Production Structure of the Power Sector in the GTAP-EP Model

Note: Leontief indicates that the aggregate values are given by the fixed coefficient production function, additive form of the CES (ACES) indicates that the aggregate values are given by the ACES function, and ρ represents the elasticity of substitution of the ACES function.

Source: prepared by the authors based on Peters (2016).

Figure 3 illustrates the substitution relationships within the power generation sector in the GTAP-EP model. At the top-level nest, power is produced through a fixed-coefficient combination of power generation composite and transmission/distribution services. The power generation composite is divided into base load and peak load composites, which consist of seven types of Base Load electricity (BL) and four types of Peak Load electricity (PL), respectively³.

3.3 Changes from the Original Model to the Model Applied in This Study

In the standard GTAP model, production factors such as labor and capital are mobile between industries. Depending on the degree of inter-industry mobility, production factors are classified into three categories: mobile factor, sluggish factor, and fixed factor. The mobile factor can move quickly between industries so that the factor price is uniquely determined in an economy. The sluggish factor can also move between industries, albeit slowly, with factor prices differing between industries. For the mobile and sluggish production factors, total factor endowment is an exogenous variable and factor supply and demand by sector is an endogenous variable. On the other hand, the fixed factor is an industry-specific production factor that does not move between industries, and the factor supply by sector is an exogenous variable.

In the original GTAP-EP model, capital could not be set as a fixed factor, so the authors modified the framework to allow capital to be treated as such. One of methodological contributions in this study is that it has been modified so that capital can be treated as a fixed factor. However, the other production factors remain unchanged from the original model—labor remains a mobile factor, while land and natural resources are considered sluggish factors.

Next, we discuss parameter modifications that are important for interpreting the simulation results. Most of the parameter values were taken from the GTAP 11 Data Base. However, in the revision from ver.10 to ver.11, the elasticity of substitution among inputs in the power generation sectors of NuclearBL, WindBL, HydroBL, HydroPL, and SolarPL was changed to a setting that allows substitution among production factors. The authors questioned this change, because they thought it was not necessarily realistic to assume that the same output could be maintained by substituting labor and energy inputs when capital decreases. Therefore, in the model presented in this paper, the elasticity of substitution among production factors (σ_{VAE}) and the elasticity of substitution between capital and energy (σ_{KE}) are set to zero, in accordance with the previous version 10. Moreover, σ_{VAE} and σ_{KE} were set to zero for coal power generation. Note, however, that if the elasticity of substitution between factors of production is set to zero, the rate of change in the capital stock will be equal to the rate of change in output. In other words, a 10% decrease in the capital stock of coal power generation will result in a 10% decrease in the amount of coal power generation⁴

4. Data and Simulation Scenario

As shown in Section 2, China's coal power plants continue to expand. Given this trend, achieving CO₂ emission reductions necessitates either improving the efficiency of coal power generation or, in the long term, shifting capital investment from coal power generation to renewable energy generation. Accordingly, this study estimates the economic and environmental effects of such low-carbon policies by using data from the GTAP 11 Data Base corresponding to the 2017 economy, integrating it into 22 countries/regions and 20 sectors, and conducting simulations of the 10 scenarios shown in Table 1 based on the following three scenarios (See Appendix 2 and 3)⁵.

Scenario 1: assumes a 10% reduction in the capital stock of coal power generation in China, offset by an equivalent increase in capital for renewable energy power generation.

Scenario 2: maintains constant total power generation and assumes a 10% decrease in the capital stock of coal power generation in China, accompanied by an increase in capital allocated to renewable energy power generation.

Scenario 3: maintains constant total power generation and assumes efficiency improvements in coal power generation in China, enhancing the productivity of all factor input or coal input.

Originally, the GTAP-EP production function handles both base load and peak load for hydropower, but only base load and peak load for wind power and solar power, respectively. Therefore, the scenarios in this study follow this same rule. In order to compare efficiency, the

reduction rate of coal power capital is standardized to 10%. The realistic relevance of the scenario assumptions will be discussed in Section 6.

Table 1 Scenario Settings

Scenario 1: Constant total capital stock in power sector

Scenario	Shock
1WindBL	CoalBL power capital –10%, WindBL power capital +27.80%
1HydroBL	CoalBL power capital –10%, HydroBL power capital +34.64%
1HydroPL	CoalBL power capital –10%, HydroPL power capital +9.43%
1SolarPL	CoalBL power capital –10%, SolarPL power capital +80.67%

Scenario 2: Constant total power output

Scenario	Shock
2WindBL	CoalBL power capital –10%
2HydroBL	CoalBL power capital –10%
2HydroPL	CoalBL power capital –10%
2SolarPL	CoalBL power capital –10%

Scenario 3: Constant total power output

Scenario	Shock
3Output	Improving the production efficiency of all factors in CoalBL power by 10%
3Coal	Improving the production efficiency of coal input in CoalBL power by 10%

Source: prepared by the authors based on the GTAP 11 Data Base.

5. Results

5.1 Domestic Impacts

Table 2 presents the impact of each scenario on China's GDP, energy output and prices, and CO₂ emissions both domestically and globally. In the table, all indicators are shown as percentage deviations from the initial state. Here, "electricity" refers to the composite of power generation, distribution, and transmission shown at the top of Figure 3. The results of the 2SolarPL scenario are shown in Table 2, but please note that the shock in this analysis is so large that the results may not be accurate.

Scenario 1 assumes that capital shifts from coal power to renewable energy while the total amount of capital remains unchanged. In Scenario 1, electricity output declines as capital shifts from coal power generation to renewable energy that tend to have lower generation efficiency than coal power. Although electricity and coal production will decrease, the impact on GDP will be limited but positive. Among Scenario 1 group, solar power, which has the lowest electricity output per unit of capital, experiences the greatest drop in electricity production and the largest increase in electricity prices. The sharp increase in electricity prices drives substitution from electricity to coal in both industry sector and households.

Scenario 2 assumes that total power generation remains constant and capital shifts from coal power to renewable energy. Under this assumption, electricity prices will remain almost unchanged. Therefore, substitution from electricity to coal is largely suppressed. Consequently, the reduction in coal production and prices, as well as the reduction in CO₂ emissions will be greater than in Scenario 1. Even in this simulation, the impact on GDP is limited.

Scenario 3 assumes improvements in total factor productivity and coal productivity in coal power generation. In Scenario 3, the amount of power generated is assumed to remain unchanged,

so there is little change in electricity prices. In Scenario 3, efficiency improvement in China raises China's rate of return on investment and encourage more investment in China. This will lead to increased employment and higher wage rates, resulting in higher incomes. The 3Output scenario, in which the productivity of all inputs improves uniformly, results in larger CO₂ reductions than Scenario 1, and has the largest positive GDP of the scenarios assumed in this study. The 3Coal scenario, which improves the efficiency of coal input, also has large positive effects.

Table 2 Impacts on GDP, Energy sectors, and CO₂ Emissions (%)

Scenario 1: Constant total capital stock in power sector

	GDP	Electricity		Coal		CO ₂	
		Output	Price	Output	Price	China	World
1WindBL	0.03	-5.36	8.62	-4.78	-0.99	-3.65	-1.11
1HydroBL	0.03	-5.33	8.69	-4.78	-0.98	-3.64	-1.11
1HydroPL	0.03	-5.34	8.57	-4.79	-0.99	-3.61	-1.10
1SolarPL	0.02	-5.69	9.25	-4.78	-0.94	-3.58	-1.10

Scenario 2: Constant total power output

	GDP	Electricity		Coal		CO ₂	
		Output	Price	Output	Price	China	World
2WindBL	0.04	0.00	0.30	-4.84	-1.70	-4.16	-1.19
2HydoBL	0.02	0.00	1.74	-4.82	-1.59	-4.06	-1.17
2HydroPL	0.08	0.00	0.14	-4.87	-1.69	-3.86	-1.14
2SolarPL	-1.23	0.00	31.28	-4.38	-0.84	-2.85	-0.95

Scenario 3: Constant total power output

	GDP	Electricity		Coal		CO ₂	
		Output	Price	Output	Price	China	World
3Output	0.24	0.00	0.00	-4.81	-0.73	-3.90	-1.13
3Coal	0.13	0.00	0.20	-4.44	-1.10	-3.67	-1.06

Source: calculated by the authors based on the GTAP 11 Data Base.

Table 3 presents the impact on production by industry. The "Output change of own sector" column shows the percentage change in renewable energy generation for Scenarios 1 and 2, and the percentage change in coal power generation for Scenario 3. For example, in the case of the 1WindBL scenario, it shows that wind power production increased by 27.8%. Due to the production function assumption, the output of each power generation technology is equal to the change in the capital stock of that power generation technology. Therefore, figures of the column "Output change of own sector" are same as change in capital stocks. Because the capital productivity of renewable energy is lower than that of thermal power generation, in this simulation, the value of "change in output of own sector" is quite large.

In Scenario 1, as shown in Table 2, electricity and coal production decreased by approximately 5%. Furthermore, production in energy-intensive industries (Ene_Int) and other manufacturing sectors (O_mfr) also decreased by about 1%. However, the service sector, characterized by a high value-added ratio and large scale, experiences increased production, offsetting the declines in other industries, and leading to overall GDP growth.

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Table 3 Impact on Production by Industry (%)

Scenario 1: Constant total capital stock in power sector

	Output change of own sector	Output change of other sectors				
		Primary	P C	Ene Int	O mfr	Services
1WindBL	27.80	-0.36	0.02	-1.10	-1.02	0.42
1HydroBL	36.64	-0.36	0.02	-1.11	-1.02	0.42
1HydroPL	9.43	-0.36	0.02	-1.10	-1.01	0.42
1SolarPL	80.67	-0.39	0.03	-1.18	-1.08	0.44

Scenario 2: Constant total power output

	Output change of own sector	Output change of other sectors				
		Primary	P C	Ene Int	O mfr	Services
2WindBL	321.37	-0.04	-0.01	-0.10	-0.13	0.10
2HydroBL	414.28	-0.10	-0.00	-0.27	-0.27	0.13
2HydroPL	97.14	-0.05	0.01	-0.13	-0.17	0.14
2SolarPL	8463.52	-0.64	0.08	-1.86	-2.37	-0.26

Scenario 3: Constant total power output

	Output change of coal power	Output change of other sectors				
		Primary	P C	Ene Int	O mfr	Services
3Output	0.11	-0.30	-0.03	-0.67	-0.97	0.58
3Coal	0.03	-0.16	-0.02	-0.37	-0.52	0.32

Source: calculated by the authors based on the GTAP 11 Data Base.

In Scenario 2, with total power output remaining unchanged, the electricity price increase is marginal except for the 2SolarPL scenario. As a result, the decline in production across energy-intensive industries and other manufacturing sectors is less than in Scenario 1. Meanwhile, due to limited substitution toward coal, CO₂ emissions are significantly lower than in Scenario 1.

In the 3Output scenario, despite a limited increase in electricity prices, production in energy-intensive industries and other manufacturing sectors declines. In this scenario, production in the service sector expands, and given its labor-intensive nature, it contributes to an overall wage increase across the economy. Higher wages lead to increased supply costs in the manufacturing sector, leading to reduced exports and lower production.

5.2 Global Economic and Environmental Impact

Figures 4-6 illustrate the impacts of China's decarbonization of its power sector on output in overseas industries, focusing on three scenarios: 1WindowBL, 2WindowBL, and 3Output scenarios. With the exception of the Rest of East Asia, all three scenarios show increases in the production of energy-intensive goods and other manufactured goods, and decreases in the production of services. While these impacts are limited, they are greater in Scenarios 1 and 3 compared to Scenario 2.

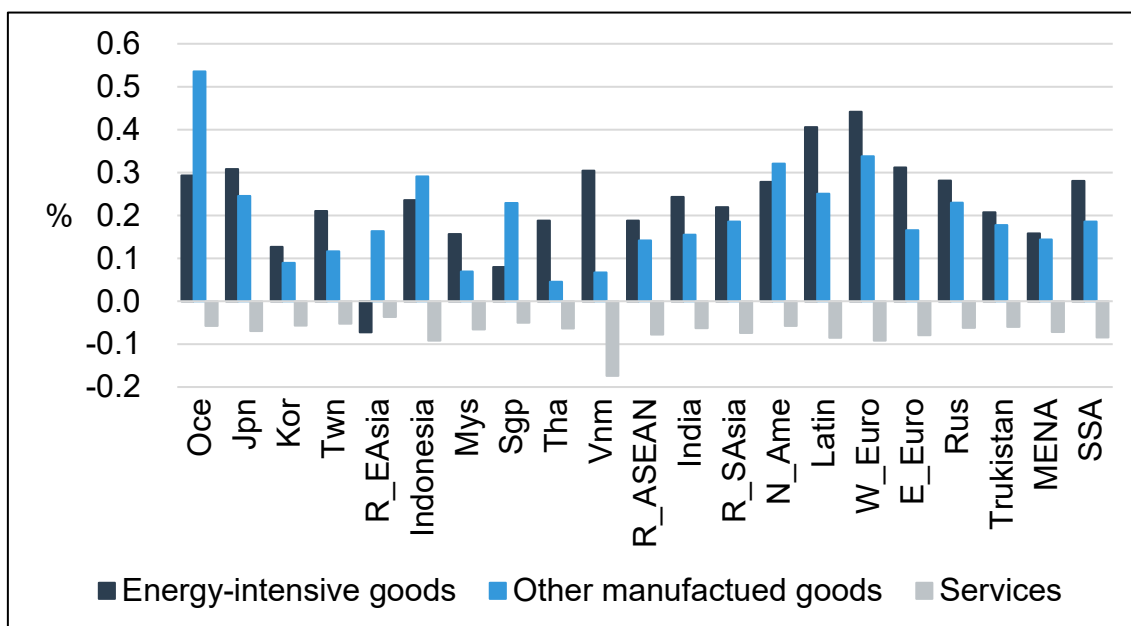


Figure 4 Impact on output in overseas industries under the 1WindBL scenario

Source: prepared by the authors based on the simulation results.

Note: N_Ame represents North America and W_Euro represents Western Europe.

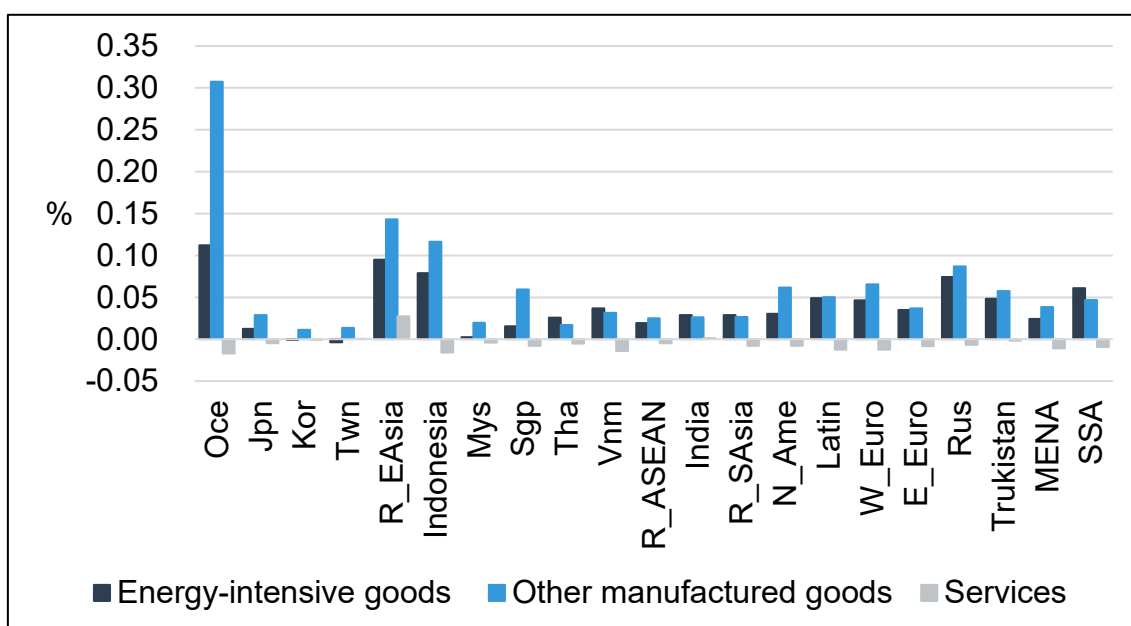


Figure 5 Impact on output in overseas industries under the 2WindBL scenario

Source: prepared by the authors based on the simulation results.

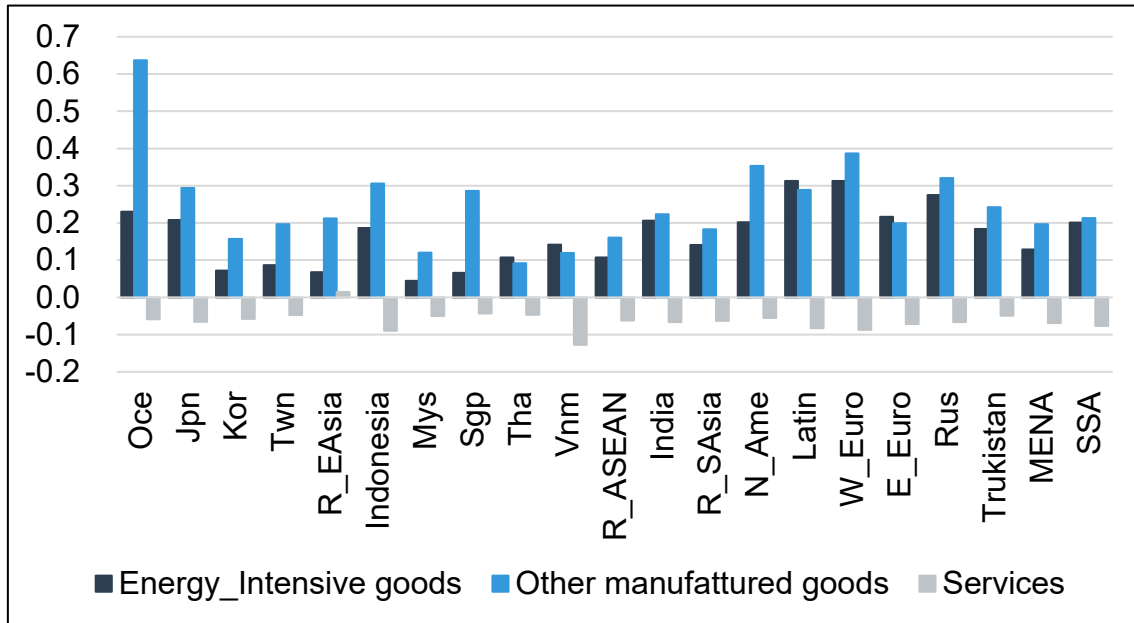


Figure 6 Impact on output in overseas industries under the 3Output scenario

Source: prepared by the authors based on the simulation results.

Figure 7 shows the rate of change in each country's GDP under each scenario. The results of all simulations show that of the 21 countries/regions other than China, GDP is slightly negatively affected in 14 countries/regions in Scenarios 1 and 3, and in 11 countries/regions in Scenario 2.

As mentioned earlier, in Scenario 3, improved efficiency of coal-fired power plants led to increased investment, wages, and incomes in China. Conversely in the most of other countries/regions, investment decreases and the wages and GDP fall⁶.

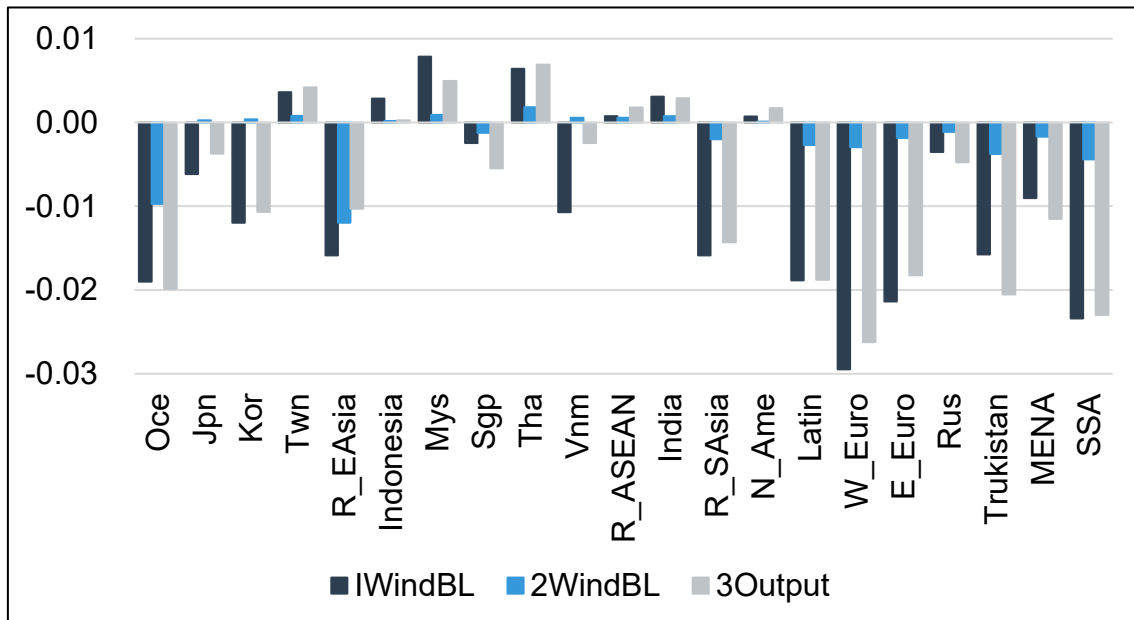


Figure 7 Impact on overseas GDP

Source: prepared by the authors based on the simulation results.

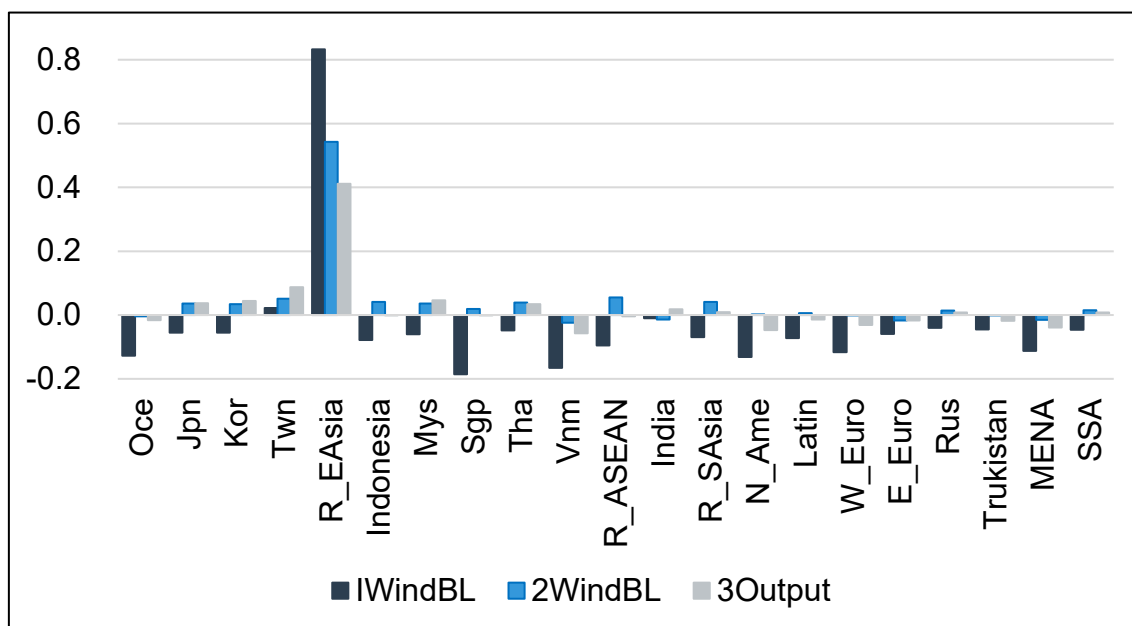


Figure 8 Impact on overseas CO₂ emissions

Source: prepared by the authors based on the simulation results.

Figure 8 shows the rate of change in each country's CO₂ emissions under each scenario. The results of all simulations show that of the 21 countries/regions other than China, CO₂ emissions are slightly negatively affected in 19 countries/regions in the 1WindBL scenario, 7 countries/regions in the 2WindBL scenario, and in 11 countries/regions in the 3Output scenario.

5.3 Carbon Leakage

The Renewable energy shift in China's power sector has various impacts on domestic and international CO₂ emissions. While a shift to renewable energy in the power sector will reduce CO₂ emissions in the power sector, there may be so-called "carbon leakage" where CO₂ emissions increase in other sectors. Changes in CO₂ emissions from each industry depend mainly on changes in output and energy prices. Increases in output increase CO₂ emissions. Rising electricity prices and falling fossil fuel prices due to decarbonization cause energy substitution of fossil fuels for electricity, increasing CO₂ emissions. CO₂ emissions from households increase with increases in GDP, rising electricity prices and falling fossil fuel prices.

In this paper, carbon leakage is defined as follows and examined from the perspective of countries/regions and sectors. From the perspective of countries/regions, global carbon leakage can be seen as the sum of carbon leakage in each country/region.

- Global carbon leakage = Total country-specific carbon leakage
- Country-specific carbon leakage = Changes in CO₂ emissions in a specific country/region.

However, China's country-specific leakage does not include changes in CO₂ emissions from China's electric sector. China's country-specific carbon leakage is so-called domestic carbon leakage, while leakage in countries/regions other than China is known as transboundary carbon leakage.

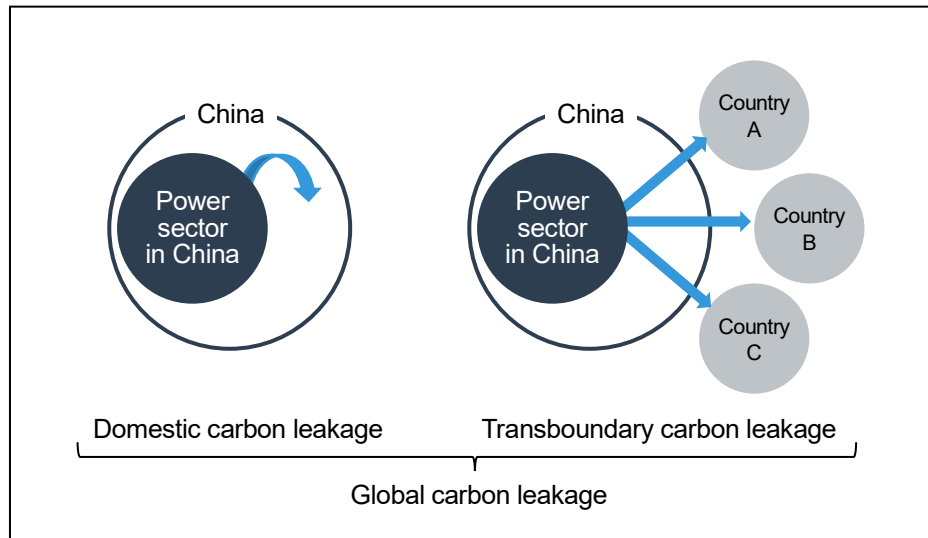


Figure 9 Country-specific carbon leakage

Source: prepared by the authors.

From a sectoral perspective, global carbon leakage can be seen as the sum of carbon leakage by sector.

- Global carbon leakage = Total sector-specific carbon leakage
- Sector-specific carbon leakage = Changes in CO₂ emissions in specific sectors.

However, leakage in the electric sector does not include changes in CO₂ emissions from China's electric sector.

Below, the carbon leakage rate is calculated by dividing each carbon leakage by the reduction in CO₂ emissions in China's electric sector.

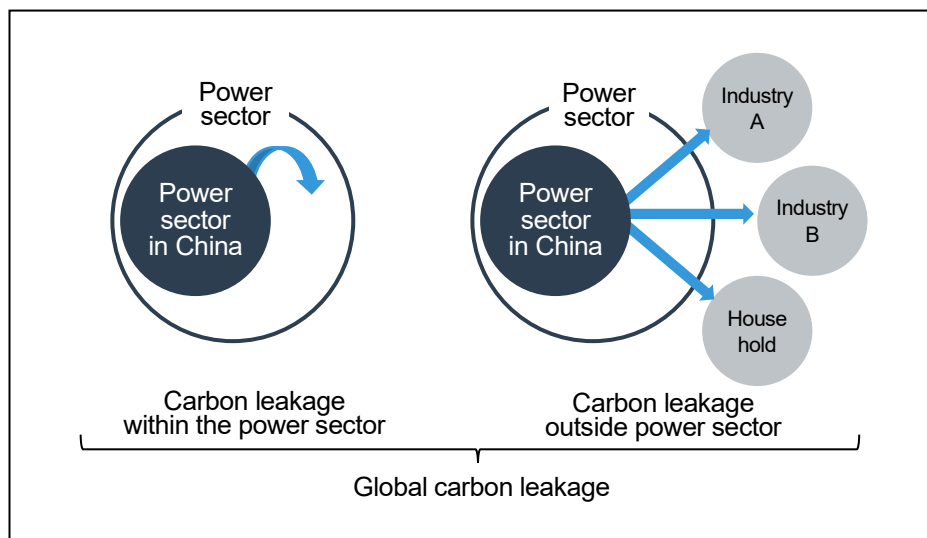


Figure 10 Sector-specific carbon leakage

Source: prepared by the authors.

(a) China domestic carbon leakage

Table 4 shows changes in CO₂ emissions by country and sector. Including scenarios not described in Table 4, CO₂ emissions in China's electricity sector will be reduced by approximately 400 million tons, while CO₂ emissions from China's non-electricity sector and overseas are affected in various ways.

C_leakage in Table 4 represents country-specific carbon leakage. To reiterate, for China, this means domestic carbon leakage, which is largest in the order of 1WinBL, 2WinBL, and 3Output scenarios. Expressed as domestic carbon leakage rates, these are 17.33%, 6.80%, and 4.69%, respectively. The reason leakage is large in the 1WindBL scenario is that, as shown in Table 2, electricity prices will rise in the 1WindBL scenario, causing industry and households (HHs) to shift their energy consumption from electricity to fossil fuel.

(b) Transboundary carbon leakage

The sum of country-specific carbon leakage for countries/regions other than China is total transboundary carbon leakage, and when expressed as a carbon leakage rate, they are -4.86%, 0.13%, and -0.72% in the order of the scenarios. In fact, of all the simulation scenarios, only 2WindBL scenario has transboundary carbon leakage on a global scale. Conversely, in most cases, reverse transboundary carbon leakage (negative leakage) occurs on a global scale. However, transboundary carbon leakage can occur at the individual country/region level, and this occurs in about half of the countries/regions in 2WindBL and 3Output scenarios.

As mentioned earlier, the decarbonization of China's power generation sector leads to increased production of energy-intensive goods and manufactured goods in countries/regions other than China, resulting in increased CO₂ emissions from those sectors. Meanwhile, production in the service sector will decrease in countries/regions other than China, resulting in a decrease in CO₂ emissions from that sector. Furthermore, GDP decreases in many countries, which leads to a decrease in CO₂ emissions from households.

In the 1Wind scenario, changes in CO₂ emissions from energy-intensive industries, other manufacturing sectors, and households in countries/regions other than China are consistent with the changes in production and GDP described above. In the 1WindBL scenario, the effect of reducing CO₂ emissions is dominant in many countries/regions, and carbon leakage occurs only in Taiwan and the Rest of East Asia.

In the 2WindBL scenario, China's electricity supply remains unchanged, so electricity prices remain almost unchanged, the impact on production in countries/regions other than China is mitigated, and GDP tends to increase slightly. In addition, as prices of not only coal but also petroleum and coal products fall, fossil fuel consumption increase⁷. For these reasons, carbon leakage occurs in 14 of the 21 countries/regions in the 2WindBL scenario.

Under the 3Output scenario, in countries/regions other than China wages fall, and energy-intensive goods and other manufacturing production increases, resulting in increased CO₂ emissions. On the other hand, a decline in GDP and a further fall in the prices of coal and petroleum products compared to coal prices reduce CO₂ emissions. In the 3Output scenario, the

former will exceed the latter in 10 of the 21 countries/regions, resulting in carbon leakage.

Table 4 Change in CO₂ Emissions (Million ton)

1WindBL Scenario

	Electricity	Ene Int	O mnf	Services	ROI	HHs	Total	C leakage
Oceania	0.06	0.17	0.02	-0.55	-0.01	-0.28	-0.59	-0.59
China	-416.61	28.92	7.79	18.27	0.63	16.58	-344.41	72.19
Japan	-0.03	0.48	0.03	-0.69	0.01	-0.44	-0.63	-0.63
Korea	0.01	0.11	0.00	-0.34	-0.01	-0.11	-0.33	-0.33
Indonesia	-0.03	0.41	0.07	-0.55	-0.00	-0.29	-0.39	-0.39
India	-0.94	1.73	0.06	-0.76	-0.04	-0.27	-0.23	-0.23
N_Ame	-0.72	0.77	0.05	-4.58	0.12	-3.57	-7.94	-7.94
W_Euro	0.10	0.76	0.05	-2.72	0.06	-1.69	-3.44	-3.44
ROW	-0.35	3.28	-0.01	-6.46	-0.06	-3.11	-6.71	-6.71
World	-418.51	36.62	8.06	1.61	0.70	6.84	-364.68	51.93
S_leakage	-1.90	36.62	8.06	1.61	0.70	6.84	51.93	

2WindBL Scenario

	Electricity	Ene Int	O mnf	Services	ROI	HHs	Total	C leakage
Oceania	0.02	0.11	0.02	-0.12	0.03	-0.08	-0.02	-0.02
China	-421.54	15.51	2.65	5.16	0.72	4.57	-392.92	28.62
Japan	0.06	0.21	0.05	0.04	0.01	0.04	0.41	0.41
Korea	0.02	0.08	0.01	0.05	0.00	0.05	0.21	0.21
Indonesia	-0.01	0.30	0.08	-0.10	0.01	-0.07	0.21	0.21
India	-1.29	0.68	0.08	0.11	0.01	0.09	-0.31	-0.31
N_Ame	-0.01	0.22	0.11	-0.20	0.07	-0.07	0.12	0.12
W_Euro	-0.13	0.17	0.05	-0.14	0.02	-0.01	-0.04	-0.04
ROW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
World	-422.88	17.27	3.06	4.80	0.87	4.52	-392.36	29.18
S_leakage	-1.34	17.27	3.06	4.80	0.87	4.52	29.18	

3Output Scenario

	Electricity	Ene Int	O mnf	Services	ROI	HHs	Total	C leakage
Oceania	0.06	0.17	0.03	-0.25	0.04	-0.13	-0.08	-0.08
China	-386.43	-2.35	0.37	12.68	-0.63	8.02	-368.34	18.10
Japan	0.17	0.48	0.09	-0.25	0.04	-0.11	0.42	0.42
Korea	0.08	0.11	0.03	-0.02	0.01	0.05	0.26	0.26
Indonesia	-0.02	0.35	0.09	-0.31	0.02	-0.14	-0.00	-0.00
India	-0.80	1.59	0.12	-0.44	0.02	-0.09	0.40	0.40
N_Ame	-0.21	0.75	0.28	-2.37	0.33	-1.62	-2.85	-2.85
W_Euro	0.18	0.67	0.22	-1.38	0.14	-0.77	-0.93	-0.93
ROW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
World	-386.96	1.78	1.24	7.67	-0.03	5.20	-371.11	15.33
S_leakage	-0.53	1.78	1.24	7.67	-0.03	5.20	15.33	

Note 1: C_leakage represents leakage by country, and S_leakage represents leakage by sector.

Note 2: ROI represents rest of industry and ROW represents rest of world.

(c) Sector-specific carbon leakage

In all three scenarios, sector-specific carbon leakage is negative in only the electricity sector, while they are positive in the energy-intensive industries, other manufacturing sectors, service sector, and household sector. Although not shown in Table 4, the primary sector is also positive. In other words, even if CO₂ emissions are reduced in the electricity sector, carbon leakage occur

in other sectors. It is interesting to note that while carbon leakage from Chinese domestic industries sometimes has a dominant impact, it is not always the case.

(d) Global carbon leakage

The sum of C_Leakage or S_leakage in Table 4 is global carbon leakage. The leakage rates are 12.46%, 6.92%, and 3.97% for the respective scenarios, which means that the loss is not that significant. Conversely, of the CO₂ emissions reduced in China's power generation sector, 87.54%, 93.08%, and 96.03%, respectively, remain as global CO₂ reductions, which would be considered an "A" in terms of university grades. One reason global carbon leakage is not so significant is that the GDP of countries/regions other than China will decrease, resulting in a decrease in CO₂ emissions.

6. Discussion

In this section, we discuss the realistic relevance of the scenario assumptions for actual changes in China's power generation capacity and technological advances. However, coal power generation also has increased since 2017, so a direct comparison is not possible. Consider the following ratio of renewable energy power generation capacity to coal power generation capacity.

Let K_t^C be the installed capacity of coal power generation at time t , and K_t^R be the installed capacity of renewable energy power generation. If the ratio of installed capacity of renewable energy power generation to installed capacity of coal power generation at time t is represented by α_t , then it is defined as follows:

$$\alpha_t = \frac{K_t^R}{K_t^C}$$

The ratio of α at time t to α at the base point (time 0) can be expressed as follows, so if we know the rate of change in power generation capacity for each energy source, we can also find the change in the ratio between renewable energy power generation capacity and coal power generation capacity.

$$\frac{\alpha_t}{\alpha_0} = \frac{K_t^R}{K_0^R} \cdot \frac{K_0^C}{K_t^C} = \frac{K_t^R}{K_0^R} \cdot \frac{K_0^C}{K_t^C}$$

The actual ratios of installed capacity in 2024 to 2017 are 1.23 for coal power, 3.17 for wind power, 1.27 for hydropower, and 6.79 for solar power. Therefore, over the same period, α increased by 1.03 times for hydropower, 5.53 times for solar power, and 2.58 times for wind power from 2017 to 2024⁸.

For Scenario 1, the rates of change in installed capacity between the ex-ante and ex-post simulations are shown in Table 1. Expressed as a multiple, these are 0.90 for coal power, 1.28 for wind power, 1.35 for hydropower BL, 1.09 for hydropower PL, and 1.81 for solar power. Therefore, α increases by 1.42 times for wind power, 1.50 times for hydropower (BL), 1.22 times for hydropower (PL), and 2.01 times for solar power compared to the base year. The simulated α base year ratios for Scenario 1 are 55.0% for wind, 144.9% for hydropower (BL), 117.8% for hydropower (PL), and 36.3% for solar compared to the actual ratios. Simulation 1's assumptions for wind and solar power are more conservative than actual changes, but the direction is the same.

In Scenario 2, the rates of change in renewable energy generation capacity are shown in Table 3. Expressed as a multiple, they are 0.90 for coal, 4.21 for wind, 5.14 for hydro BL, 1.97 for hydro PL, and 85.64 for solar. Therefore, the simulated α increases 4.68 times for wind power, 5.71 times for hydropower BL, 2.19 times for hydropower PL, and 95.15 times for solar power, compared to the base year. The simulated α base year ratios for Scenario 2 are 181.2% for wind power, 553.5% for hydropower BL, 212.2% for hydropower PL, and 1,722.1% for solar power to the actual ratios. Leaving solar power out of the question, Scenario 2 assumes that renewable energy will expand more than the actual changes. In terms of ratio, not volume, the reality is probably somewhere between Scenario 1 and Scenario 2.

Regarding technological progress, according to the NDRC, coal consumption in the power sector averaged 305.5 grams per kilowatt-hour (kWh) in 2020, down 17.4% from 370 grams per kWh in 2005. The NDRC economic planning agency has stated that by 2025, coal power plants will need to adjust their consumption to an average of 300 grams of standard coal per kWh (Reuters, 2021). This target represents an 18.9% reduction from 2005 usage. Scenario 3 of this study assumes a 10% reduction from 2017, which is considered a realistic assumption.

7. Conclusion

7.1 Summary of This Study

This study employed CGE analysis to assess the economic and environmental impacts of transitioning from coal power to renewable energy and improving coal power efficiency within China's power generation sector. The main conclusions can be summarized as follows:

We found that decarbonization in China's power generation sector would lead to lower coal prices and higher electricity prices, which would induce a shift from electricity to fossil fuels in industries and households outside the power generation sector, resulting in domestic carbon leakage. This suggests that implementing complementary measures such as a carbon tax is essential.

Our study demonstrated that, while maintaining constant total power output, a reduction in capital for coal power generation necessitates a substantial increase in capital for renewable energy power generation. Accordingly, assuming the current economic conditions where electricity demand has not declined, the study concludes that, in the short term, improving the efficiency of coal power generation presents a more realistic approach.

In all scenarios, China will see a decline in production in the coal and energy-intensive sectors and an increase in production in the service sector, which has a higher added value rate. The shift to an industrial structure with a higher added value rate will result in a slight increase in China's GDP. This suggests that promoting a shift toward a service-oriented economy plays a crucial role in reducing the economic burden of achieving the dual coal target.

Additionally, analysis of international carbon leakage underscores the global economy's reliance on China—both as a major export destination for coal and a production base for energy-intensive goods. China's decarbonization will lead to a decrease in global coal production, and will also lead to increased production in energy-intensive sectors and decreased production in

service sector in countries/regions other than China. As a result, GDP decreases slightly in half of the countries/regions other than China. In total, transboundary reverse carbon leakage occurs in most scenarios. However, at the individual country level, transboundary carbon leakage occurs in half of the countries/regions in Scenarios 2 and 3. Furthermore, the analysis of carbon leakage by sector shows that as China's power sector advances decarbonization, simply shifting energy-intensive industries from China to other countries will have a counterproductive effect on sectors other than the electricity sector. Therefore, while urging China to decarbonize, its trade partners must also commit to decarbonizing their own economic structures to ensure a globally effective transition.

7.2 Limitations of This Study and Future Issues

Finally, this study examines its limitations and outlines directions for future research. By utilizing the GTAP-EP model, which differentiates power generation technologies, the study compared the economic and environmental impacts of transitioning from coal power to renewable energy and enhancing coal power efficiency—enabled by treating capital as an exogenous factor. In Scenario 1 and Scenario 2, capital was reallocated from coal power generation to renewable energy power generation by reducing coal power capital. However, in practice, this transition is not straightforward. Replacing coal power with renewable power demands large amounts of land and may lead to environmental degradation. Additionally, while Scenario 3 assumes efficiency improvements, it does not account for the time and financial costs associated with developing new technologies or retrofitting coal power generation units. In the future, such times and costs should be considered.

Furthermore, while this study focuses on improving boiler energy efficiency as a means of decarbonizing coal power generation, future approaches could include biomass co-firing, ammonia co-firing, and the implementation of CCUS technologies. Establishing evaluation methods for the integration of these new decarbonization technologies will be a critical area for future research.

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- ¹ The energy conversion efficiency for each type is approximately 44%–46%, 37%–40%, and 33%–37%, respectively.
- ² See Hertel (ed.) (1997) for the standard GTAP model, Burniaux and Truong (2002) and McDougall and Golub (2009) for the GTAP-E model, and Peters (2016) for the GTAP-EP model.
- ³ In the GTAP model, most variables are expressed as rates of change. Within the power generation sector, total power output should match the sum of power produced by each power generation technology, but this requirement is not fulfilled under standard CES aggregation. Although this is a technical constraint, the GTAP-EP model is specifically adjusted to ensure that total power sector output equals the sum of its components in physical units (GWh).
- ⁴ The GTAP model uses a common database and parameters, so parameter sensitivity testing is considered less necessary in standard GTAP usage. However, when running a simulation using the default parameters of the GTAP 11 Database, a 10% reduction in coal power generation capital only reduces its generation by 1.9% (Scenario 1WindBL case, described below). Since the purpose of this study is to analyze the impact of decarbonization of coal power generation, we have adopted some parameters that mimic the settings of version 10 to prevent such substitutions. (see Appendix 1 for parameter values).
- ⁵ See the Appendix 2 and 3 at the end of this paper for more information on region integration and sector integration.
- ⁶ The rates of change in the wage for unskilled labor are 0.85%, 0.18%, and 1.26% for China, and –0.16%, –0.05%, and –0.21% for the average of countries/regions other than China, in the order of 1WindBL, 2WindBL, and 3Output scenarios. The rates of change in the wage for skilled labor are 1.33%, 0.32%, and 1.84% for China, and –0.21%, –0.05%, and –5.55% for the average of countries/regions other than China.
- ⁷ The rates of change in international prices for coal and petroleum products are 0.21%, –0.05%, and –0.15% for the 1WindBL, 2WindBL, and 3Output scenarios, respectively.
- ⁸ The authors calculated the ratios based on data from the Global Energy Monitor (GEM) (2025) for coal power generation capacity and International Renewable Energy Agency (IRENA) (2025) for renewable energy power generation capacity.

Appendix

Appendix 1 Parameter

Sector	σ_{VAE}	σ_{KE}	Sector	σ_{VAE}	σ_{KE}
Primary	0.25	0.50	HydroBL	0.00	0.00
Coal	3.79	0.00	OilBL	0.00	0.50
Oil	0.38	0.00	OtherBL	1.26	0.50
Gas	0.00	0.00	GasPL	1.26	0.50
P_C	1.00	0.00	HydroPL	0.00	0.00
TnD	1.26	0.50	OilPL	1.26	0.50
NuclearBL	0.00	0.00	SolarPL	0.00	0.00
CoalBL	0.00	0.00	Ene_Int	1.17	0.50
GasBL	1.26	0.50	Oth_mfr	1.23	0.50
WindBL	0.00	0.00	Services	1.26	0.50

Source: prepared by the authors based on the GTAP 10 and 11 Data Base.

Note: The parameters for nuclear, wind, hydro, and solar are the same as in Version 10. We followed the same pattern for coal power. σ_{KE} is the same for all countries/regions, but σ_{VAE} for the Primary, Coal, Oil, Gas, Ene_Int, and Oth_mnf sectors differ. The values of σ_{VAE} in the table are for China.

Appendix 2 Region Aggregation

No	Aggregated Countries / Regions	Original Countries / Regions
1	Oceania	Australia; New Zealand; Rest of Oceania.
2	China	China; China, Hong Kong SAR.
3	Japan	Japan.
4	Korea	Republic of Korea.
5	Taiwan	Taiwan Province of China.
6	Rest of East Asia	Mongolia; Rest of East Asia.
7	Indonesia	Indonesia.
8	Malay	Malaysia.
9	Singapore	Singapore.
10	Thai	Thailand.
11	Vietnam	Viet Nam.
12	Rest of ASEAN	Brunei Darussalam; Cambodia; Lao People's Democratic Republic; Philippines; Rest of Southeast Asia.
13	India	India.
14	Rest of South Asia	Afghanistan; Bangladesh; Nepal; Pakistan; Sri Lanka; Rest of South Asia.
15	North America	Canada; United States of America; Mexico; Rest of North America.
16	Latin America	Argentina; Bolivia; Brazil; Chile; Colombia; Ecuador; Paraguay; Peru; Uruguay; Venezuela; Rest of South America; Costa Rica; Guatemala; Honduras; Nicaragua; Panama; El Salvador; Rest of Central America; Dominican Republic; Haiti; Jamaica; Puerto Rico; Trinidad and Tobago; Caribbean.
17	West Europe	Austria; Belgium; Denmark; Estonia; Finland; France; Germany; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Portugal; Spain; Sweden; United Kingdom of Great Britain; Switzerland; Norway; Rest of EFTA.
18	East Europe	Bulgaria; Croatia; Cyprus; Czechia; Greece; Hungary; Poland; Romania; Slovakia; Slovenia; Albania; Serbia; Belarus; Ukraine; Rest of Eastern Europe; Rest of Europe.
19	Russia	Russian Federation.
20	Turkistan	Kazakhstan; Kyrgyzstan; Tajikistan; Uzbekistan; Rest of Former Soviet Union.
21	Middle East and North Africa	Armenia; Azerbaijan; Georgia; Bahrain; Iran (Islamic Republic of); Iraq; Israel; Jordan; Kuwait; Lebanon; Oman; Palestine; Qatar; Saudi Arabia; Syrian Arab Republic; Turkiye; United Arab Emirates; Rest of Western Asia; Algeria; Egypt; Morocco; Tunisia; Rest of North Africa.
22	Sub-Sahara Africa	Benin; Burkina Faso; Cameroon; Cote d'Ivoire; Ghana; Guinea; Mali; Niger; Nigeria; Senegal; Togo; Rest of Western Africa; Central African Republic; Chad; Congo; Democratic Republic of the Congo; Equatorial Guinea; Gabon; South-Central Africa; Comoros; Ethiopia; Kenya; Madagascar; Malawi; Mauritius; Mozambique; Rwanda; Sudan; United Republic of Tanzania; Uganda; Zambia; Zimbabwe; Rest of Eastern Africa; Botswana; Eswatini; Namibia; South Africa; Rest of Southern African Customs Union; Rest of the World.

Source: prepared by the authors based on the GTAP 11 Data Base.

Appendix 3 Sector Aggregation

No	Aggregated Sectors	Original Industrial Sectors
1	Primary	Paddy rice; Wheat; Cereal grains nec; Vegetables, fruit, nuts; Oil seeds; Sugar cane, sugar beet; Plant-based fibers; Crops nec; Bovine cattle, sheep and goats; Animal products nec; Raw milk; Wool, silk-worm cocoons; Forestry; Fishing.
2	Coal	Coal mining
3	Oil	Crude oil mining
4	Gas	Gas; Gas manufacture, distribution.
5	P_C	Petroleum, coal products.
6	TnD	Electricity transmission and distribution
7	NuclearBL	Nuclear power.
8	CoalBL	Coal power base load.
9	GasBL	Gas power base load.
10	WindBL	Wind power base load
11	HydroBL	Hydro power base load.
12	OilBL	Oil power base load.
13	OtherBL	Other base load.
14	GasPL	Gas power peak load.
15	HydroPL	Hydro power peak load.
16	OilPL	Oil power peak load.
17	SolarPL	Solar power peak load
18	Ene_Int	Minerals nec; Chemical products; Basic pharmaceutical products; Rubber and plastic products; Mineral products nec; Ferrous metals; Metals nec.
19	Oth_mfr	Bovine meat products; Meat products nec; Vegetable oils and fats; Dairy products; Processed rice; Sugar; Food products nec; Beverages and tobacco products; Textiles; Wearing apparel; Leather products; Wood products; Paper products, publishing; Metal products; Computer, electronic and optic; Electrical equipment; Machinery and equipment nec; Motor vehicles and parts; Transport equipment nec; Manufactures nec.
20	Services	Water; Construction; Trade; Accommodation, Food and services; Transport nec; Water transport; Air transport; Warehousing and support activity; Communication; Financial services nec; Insurance; Real estate activities; Business services nec; Recreational and other services; Public Administration and defense; Education; Human health and social work activities; Dwellings.

Source: prepared by the authors based on the GTAP 11 Data Base.