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RESEARCH ARTICLE

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Pathways to achieve the dual targets of carbon neutrality and air quality in Southern China

Abstract Realizing the 2060 carbon neutrality target and air quality goals simultaneously is a common challenge for provinces in China aiming for sustainable development. This study examines the costs and benefits of achieving these dual targets in six southern Chinese provinces. Using a multi-model assessment approach—comprising the economic IMED|CGE model, the environmental GAINS model, and the IMED|HEL health risk assessment model—this study captures the uneven air quality and health burdens associated with inter-regional economic connections. We found that achieving carbon neutrality significantly improves air quality and provides health co-benefits through rapid energy system transformation. However, there is substantial provincial heterogeneity in the pathways chosen to reduce pollution and carbon emissions. As the potential of end-of-pipe control measures diminishes, stricter air quality standards will depend increasingly on profound transformations in energy and economic systems driven by carbon neutrality goals. Carbon reduction policies will reshape trade structures, altering the flow of embodied carbon dioxide (CO_2) and air pollutants. Additionally, provincial carbon quotas significantly influence the health-related net benefits of carbon reduction, as GDP losses are sensitive to the allocation of these quotas. Our study demonstrates the feasibility of simultaneously achieving CO_2 emission reduction and air quality improvement. Policymakers should integrate air quality targets with low-carbon development objectives when creating regional blueprints for green transformation, thereby aligning air pollution and carbon reduction management organically.

Keywords carbon neutrality, air quality, co-benefits, IMED model, GAINS model

1 Introduction

China has experienced a significant increase in greenhouse gas (GHG) emissions and air pollutants over the past few decades, largely due to its rapid economic growth driven by fossil fuels (China Carbon Neutral and Clean Air Synergistic Pathways Annual Report Working Group, 2021). In 2007, China surpassed the United States to become the world’s largest carbon emitter (Liu et al., 2021). Consequently, the country has made substantial

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commitments to reduce carbon emissions. The government has set a target to decrease carbon intensity – measured as tons of CO_2 emissions per unit of Gross Domestic Product (GDP)—by 60%−65% by 2030 compared to 2005 levels. Additionally, in 2020, China announced an ambitious goal of achieving carbon neutrality by 2060. However, achieving these targets is challenging, given the continued reliance on coal in the energy and industrial sectors. To address these challenges, the government has implemented various strategies, including reducing fossil fuel consumption and promoting clean energy sources such as hydropower, wind power, and solar power. Importantly, carbon reduction efforts also have co-benefits for air pollution abatement, as most sources of CO_2 and air pollutants overlap (Dong et al., 2015). The Chinese government has already implemented numerous air pollution control policies that have significantly improved air quality. However, as of 2022, $PM_{2.5}$ concentration in China was still 29 μg/m^3, well above the World Health Organization (WHO)'s air quality guidelines of 5 μg/m^3 (World Health Organization, 2021). This persistent air pollution has profound adverse health effects (Stanaway et al., 2018; Murray et al., 2020; Zhang et al., 2023) and imposes significant social costs. Therefore, more ambitious actions are necessary to address air quality urgently.

Studies on evaluating the benefits of achieving deep decarbonization and air pollution alleviation have been conducted in the United States (Tong et al., 2020; Shindell et al., 2021), China (Yang et al., 2016; Zhang et al., 2021) and worldwide (Markandya et al., 2018). However, many of these studies have focused on a cost-benefit analysis at the regional level, disregarding regional differences (Xie et al., 2018; Tang et al., 2022). Notably, most studies treat regions as isolated systems, neglecting economic links to neighboring domestic regions or international markets. Consequently, local carbon and air pollution mitigation efforts are assumed to have limited spillover effects on other regions through economic linkages. This approach disregards inter-provincial and international commodity trade, along with the corresponding embodied CO_2 and pollutant emissions. As a result, it fails to explore how mitigation policies will reshape regional economic structures and trade patterns. Moreover, given that air quality improvement is a regional issue and health exposure varies significantly by region, it is essential to conduct sub-national level investigations rather than relying solely on nationwide analyses.

By selecting six provinces in Southern China as the subjects of this study, the aim is to uncover the complex regional relationship between carbon, air quality, and health. This will be done by addressing the following inquiries: (1) Which sectors hold critical control in reducing CO_2 and air pollutants in order to achieve carbon neutrality and improve air quality? (2) What are the co-benefits of carbon neutrality in terms of air quality improvement, and do they vary across regions? (3) How do trade and environmental linkages between provinces change under the influence of carbon-neutral policies? (4) Can the public health co-benefits offset the costs associated with reducing carbon emissions, and what are the differences and similarities across different regions?

The six provinces under investigation include Guangdong, Guangxi, Hunan, Hainan, Jiangxi, and Fujian. These provinces are closely linked economically, with many of them having export-oriented economies. However, there are significant variations in economic structure and environmental pressure among these provinces, making it crucial to explore the impacts of regional heterogeneity on cost-benefit analysis. For example, there are notable differences in the economic development, population density, and energy structure of these provinces. Guangdong and Hainan have a higher share of the service sector compared to the national average, while Hunan and Jiangxi are relatively more focused on inland trade and have fewer exports. Considering these disparities, exploring the synergistic control of carbon and air pollutant emissions in these provinces could provide valuable insights for other regions in China and developing countries in different stages of development.

Notably, the Pearl River Delta (PRD) located in Guangdong Province serves as the economic core of Southern China and was previously recognized as a successful area in preventing and controlling air pollution (Jiang et al., 2015; Liang et al., 2019; Lu et al., 2019). However, it still faces significant pressure to reduce carbon emissions and improve air quality. In 2021, for instance, the CO_2 emissions from these six provinces accounted for 16.1% of China's total CO_2 emissions, and the current annual $PM_{2.5}$ concentration in all provinces exceeds the guidelines set by the World Health Organization (World Health Organization, 2021) (Fig. 1). In response, the Chinese government issued the Outline of the Plan for the Development of the Guangdong–Hong Kong–Macao Greater Bay Area (China's State Council, 2019), which emphasizes that the Greater Bay Area should actively pursue green governance and take the lead in promoting a low-carbon transformation by 2035. Against this backdrop, finding effective strategies to reduce CO_2 emissions and improve air quality will provide scientific evidence for other regions, both domestically and internationally, to learn from in their efforts to combat climate change and air pollution.

To address the questions raised above, an integrated assessment framework is proposed, consisting of the IMED|CGE (Integrated Model of Energy, Environment, and Economy for Sustainable Development | Computable General Equilibrium) model, Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, and IMED|HEL (Integrated Model of Energy, Environment, and Economy for Sustainable Development | Health) model. This framework aims to investigate the impacts of

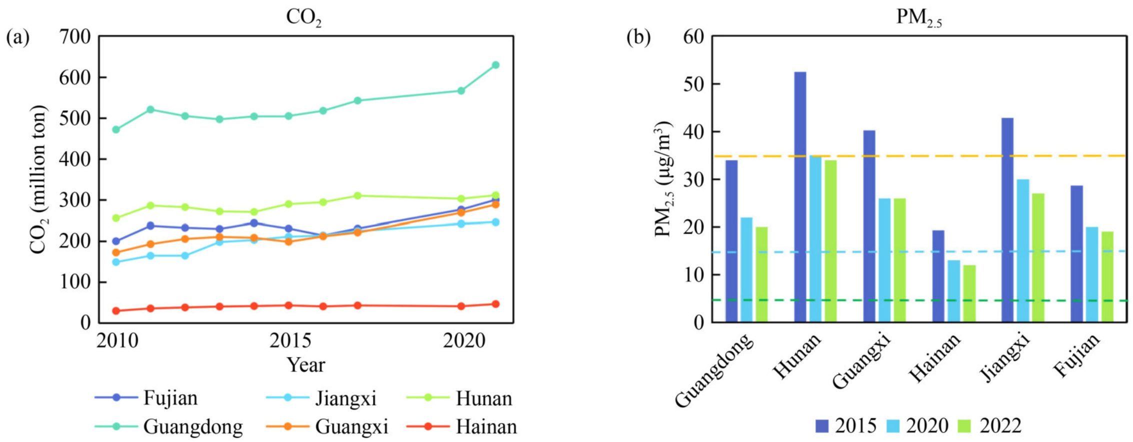

Fig. 1 CO_2 emissions (a) and ambient $PM_{2.5}$ concentrations (b) in Southern China. The yellow horizontal line indicates China's Class 2 limit values of the current National Ambient Air Quality Standard (NAAQS II) for annual $PM_{2.5}$ concentration (35 μg/m^3), and the blue one indicates China's Class 1 limit values of the current NAAQS (15 μg/m^3) and the green one for WHO's air quality fourth interim target (5 μg/m^3).

climate mitigation and air pollution abatement on energy, environment, health, and economy.

This study is innovative for two reasons. First, in terms of the modeling approach, a 31-region CGE model representing the 31 provinces/regions of China is used, allowing for climate policy shocks to be simultaneously applied to different provinces while ensuring comparability of results across provinces and sectors. The 31-region CGE model also accurately depicts the economic linkages among regions. Moreover, this study establishes a scale-matched and efficient data transfer interface between models, connecting the macro-energy economic model (IMED|CGE), the air pollution assessment model (GAINS), and the population health impact assessment model (IMED|HEL) through the hard-link method. This approach eliminates connection barriers between different models, improves the accuracy of the simulation of air pollutants driven by economic activities, and dynamically assesses the transmission process of the multiple effects of climate policy along the entire chain. Secondly, in terms of policy insights, this study explores the regional heterogeneity and effects across regions and sectors under climate policy shocks. It also examines the potential for air pollution improvement and identifies critical abatement sectors.

2 Methodology

2.1 Overview of the integrated modeling framework

This study establishes an integrated assessment framework consisting of the IMED|CGE model, GAINS model, and IMED|HEL model (Fig. 2). This approach has been employed in our previous studies (Xie et al., 2016; Xie et al., 2018; Xie et al., 2019; Xie et al., 2020).This framework consists of four modules, each corresponding to a specific step. It allows for the analysis of the economic and environmental impacts of carbon emission reduction policies from a forward-looking and sector-wide perspective.

In the first step, the IMED|CGE model is used to investigate socioeconomic status, energy consumption, and CO_2 emissions from the base year of 2017 to the target year of 2050, in one-year increments.

The second step applies the GAINS model to estimate air pollutant emissions and $PM_{2.5}$ concentrations in five-year increments. The energy consumption data from the CGE model is passed to the GAINS model, creating a hard link between the two models to maintain consistency in activity levels. The sectoral mapping rules are provided in Supplementary Material Table S3. As the sectoral and fuel categorization in GAINS is more detailed than in CGE, the total consumption levels of the broader sectoral and fuel categories are kept consistent during the transfer of parameters. The structure of the subdivided sectors and fuels remains consistent with the original parent scenarios in GAINS.

The third step utilizes the IMED|HEL model to evaluate the health-related economic effects of $PM_{2.5}$ pollution, including the value of statistical life (VSL) associated with mortalities.

In the final step, a cost-benefit analysis is conducted. The benefits consist of the population health benefits calculated by the IMED|HEL model, in terms of the VSL losses avoided by the policy scenario compared to the baseline scenario. The cost is the loss of GDP evaluated by the IMED|CGE model for the carbon neutrality scenario compared to the Business-as-Usual (BaU) scenario. The net benefit is calculated by subtracting the GDP loss from the health benefits.

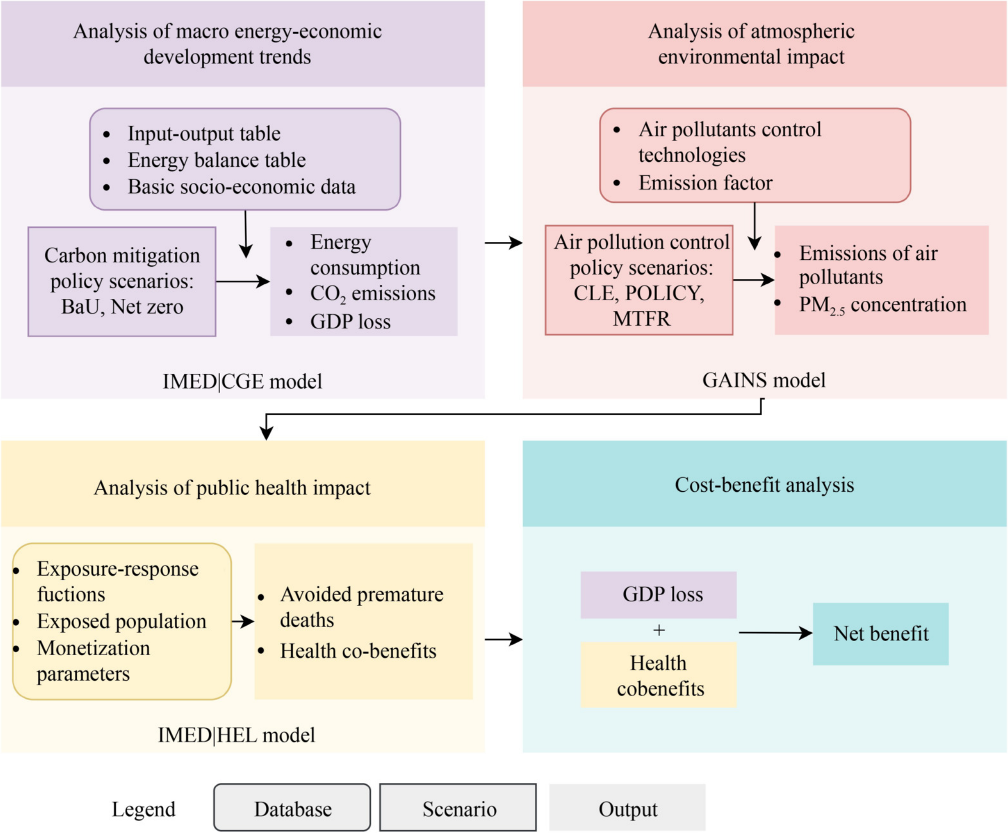

Fig. 2 Integrated modeling framework.

2.2 The IMED|CGE model

The IMED|CGE model is a comprehensive model developed by the Laboratory of Energy & Environmental Economics and Policy (LEEEP) at Peking University. It depicts the relationship between economic development, energy demand, greenhouse gas emissions, and air pollutant emissions. The model utilizes input-output tables as the basis for social and economic data and combines them with the energy balance table and data obtained from industry statistical yearbooks to establish the base year data (National Bureau of Statistics of China, 2018). The model is programmed in GAMS/MPSGE and solved using the PATH algorithm. It dynamically simulates the economic trends, changes in industrial structure, energy consumption, and carbon emission trends of each region on a yearly basis, from the base year to the future target year. More information about the model can be found in Section 1 of the supporting information and on the website of PKU. The online version of the IMED|CGE model can be accessed at the website of imedmodel. The model comprises a production block, a market block with domestic and international transactions, and government and household income and expenditure blocks (Supplementary Material Figure S1). For this study, we developed a recursive-dynamic Computable General Equilibrium (CGE) model that includes 24 aggregated economic sectors representing 31 province/regions in China's mainland. The sectoral classification can be found in Supplementary Material Table S1. Using this model, we simulated the future industry-level energy consumption, carbon emission pathways, and relevant socioeconomic trends from the base year 2017 to the target year 2050, with annual increments. Innovatively, this study made adjustments to the parameter of energy efficiency improvement by sector and energy type, which builds upon our previous research (Liu et al., 2022). Many CGE modeling studies simplify the improvement of autonomous energy efficiency (AEEI) by using a constant value. However, by doing so, the AEEI parameter fails to accurately capture the energy transition rate. To address this, we adjusted the direct input coefficients in the Input-Output table for the power generation and end-use sectors, thus simulating energy efficiency improvements in a more appropriate manner. Additionally, we indirectly reflected the increase in the share of non-fossil energy generation by increasing capital investment and reducing fossil energy inputs in the power generation sector. Details of these adjustments can be found in Supplementary Material Table S2.

2.3 The GAINS model

The GAINS model, developed by the International Institute of Applied Systems Analysis (IIASA), is a comprehensive assessment system that evaluates the interactions and effectiveness of different atmospheric management policies. This model simulates the flow of pollutants from their sources to their various effects and estimates the costs and impacts of policy interventions. It considers activities such as power generation, industry, transportation, etc., and incorporates air pollution controls for different pollutants from different source sectors at 5-year intervals.

For this study, we utilized the GAINS-China version and its optimization module, which was solved using GAMS. Our focus was on Southern China to assess the air pollutant emissions and $PM_{2.5}$ concentrations. We combined activity data results modeled by IMED|CGE and end-of-pipe technology mix projections under different air pollution control scenarios in the GAINS model to estimate pollutant emissions and $PM_{2.5}$ concentrations for each scenario. More information about the calculation principles of the model can be found in Supplementary Material Section 2.

2.4 The IMED|HEL model

The IMED|HEL model is a health impact assessment model that evaluates the impact of $PM_{2.5}$ exposure on mortality rates and the associated economic cost. Developed using the GAMS software, the IMED|HEL model is regularly updated, and comprehensive information about it can be found online at the website of PKU. This model has been widely used to analyze the health effects of climate change mitigation and air pollution control policies at various scales (Xie et al., 2019; Xie et al., 2020). Its input data incorporates air pollutant concentration levels, the exposed population, and the most recent exposure-response functions (ERFs) derived from epidemiological studies (Pope III et al., 2002; Burnett et al., 2018).

Within this study, the IMED|HEL model applies the nonlinear GEMM function (Burnett et al., 2018) to assess the relative risk of $PM_{2.5}$-related mortality and calculate the total excess mortality for each province under each scenario. Furthermore, the model's monetization module evaluates the economic losses associated with the disease burden, and the avoided economic losses under carbon mitigation scenarios are compared against the costs of carbon mitigation.

2.5 Scenario setting and data

In this study, a total of eight scenarios were established across two dimensions to explore the potential for reducing air pollutants, improving air quality, and the economic costs of achieving carbon neutrality.

In relation to climate policy, two scenarios have been developed to simulate the effects of implementing low-carbon policies: the BaU with no carbon emission constraint and the carbon neutrality scenario (Net zero) in the IMED|CGE model. The BaU scenario assumes that China will achieve its Nationally Determined Contributions (NDCs) pledges, with carbon emissions peaking around 2030. The Net zero scenario aims to achieve carbon neutrality by 2060 and assumes a faster rate of electricity substitution and a higher level of technological progress compared to the BaU scenario. It is estimated that total carbon sinks and negative emissions will reach 3.0 billion tons in China by 2060 under the carbon neutrality scenario (Xu et al., 2016; Cai et al., 2021).

Subsequently, national carbon emission quotas are allocated to each province using the following methods. Consistent per capita emissions are considered one of the dominant international allocation approaches based on the principle of equity (Lin et al., 2018). We assume that per capita carbon emissions in each province will converge to around 1.6 tons per capita in 2060 and then multiply this by each province's population to determine the total emissions for each region under the Net zero scenario in 2060. After interpolation, the annual carbon emissions serve as the emission limit in the IMED|CGE model. The results allocated through the single principle allocation method are more representative.

To analyze the effect of different allocation principles on the results, two additional carbon-neutral scenarios have been established based on the convergence of carbon emission intensity and a consistent rate of carbon emission decline, denoted as Net Zero_CO_2Intensty and Net Zero_SameRate, respectively. Critical indicators for uncertainty analyses and discussions are presented in Section 4. In the Net Zero_CO_2Intensty scenario, each province's carbon emissions per unit of GDP are assumed to converge by 2060. In the Net Zero_SameRate scenario, the carbon emission reduction rate of each province is assumed to remain consistent. The specific calculation formula and key data are provided in the S.I.

In terms of end-of-pipe control of air pollutants, this study considers different levels of control efforts to explore the potential for improving air quality (Table 1). Three different degrees of air pollution controls are applied, including controls following current legislation trend (CLE), achieving specific regional $PM_{2.5}$ concentration targets with the least control cost (Table 2), and the maximum technically feasible reduction (MTFR).

According to the 14th Five-Year Plan for Ecological and Environmental Protection, there is a target to reduce $PM_{2.5}$ concentration in cities above the prefecture level by 10% compared to 2020 by 2025. Additionally, in the Beautiful China Strategy, the government has a longer-term vision to achieve a $PM_{2.5}$ concentration of 25 $\mu g/m^3$ by 2035. Therefore, air quality objectives for the 2025 policy scenario have been set. In the absence of longer-term quantitative emission reduction targets in government policy documents, an extrapolation has been done from 2035 to 2050, with a 10% reduction every five years.

Table 1 Scenario setting in this study

Air pollution control	Climate target	
	BaU	Net zero
CLE	BaU_CLE	Net zero_CLE
POLICY	BaU_POLICY	Net zero_POLICY
MTFR	BaU_MTFR	Net zero_MTFR

Table 2 $PM_{2.5}$ concentration target in the POLICY scenario (μg/m^3)

Province	2025	2035	2050
Fujian	16.2	13.1	9.6
Guangdong	19.8	16.0	11.7
Guangxi	23.4	19.0	13.8
Hainan	11.7	9.5	6.9
Hunan	31.5	25.5	18.6
Jiangxi	27	21.9	15.9

3 Results

The results presented in Sections 3.1 and 3.2 do not involve air pollutant emissions, so there is no distinction between different levels of end-of-pipe control efforts. The results for the BaU and Net zero scenarios are reported.

3.1 Trends of main social-economic, energy, and environmental indicators

As depicted in Fig. 3, under the BaU scenario without any CO_2 cap limitations, the per capita GDP in all six provinces will increase over time. By 2050, the per capita GDP will be 3.9, 4.4, 4.0, 3.9, 3.5, and 6.0 times higher than the levels in 2017 for Guangdong, Jiangxi, Hunan, Fujian, Guangxi, and Hainan, respectively. With economic development, the demand for primary fossil energy in these six provinces will also increase by 25.2%, 21.6%, 15.4%, 27.3%, 41.8%, and 46.5% in 2030 compared to 2017. Carbon emissions will follow similar trends, increasing by 24.4%, 22.2%, 21.1%, 28.4%, 36.4%, and 20.6%, respectively. Specifically, Guangdong has the highest carbon emissions, followed by Hunan, Fujian, Guangxi, Jiangxi, and Hainan. However, as the energy structure transforms, the demand for fossil fuels and carbon emissions will gradually decline from 2030 to 2050. Furthermore, electricity consumption will increase by 1.4, 1.8, 1.5, 1.9, 2.2, and 0.9 times by 2050 compared with 2017 in Guangxi, Fujian, Guangdong, Hunan, Jiangxi, and Hainan, respectively. All six provinces have experienced a continuous decline in carbon emissions intensity from 2017 to 2050 under the BaU scenario, with reductions ranging from 56.4% to 76.2%. The results indicate that under the BaU scenario, primary fossil energy consumption and carbon emissions in all six provinces will continue to rise due to rapid economic growth by 2030. Under the Net Zero scenario, there will be further reductions in fossil fuel demands, CO_2 emissions, and carbon intensity in all six regions compared to the BaU scenario. Specifically, in 2050, carbon emissions are projected to decrease by 26.6%, 40.2%, 24.4%, 21.8%, 17.9%, and 9.8% in Guangxi, Fujian, Guangdong, Hunan, Jiangxi, and Hainan, respectively. Demands for fossil fuel are expected to decrease by 20.7%, 39.3%, 31.5%, and 23.0% in each region except Hainan, while increasing by 8.1%. It is important to note that Hainan's increased fossil energy consumption is mainly natural gas

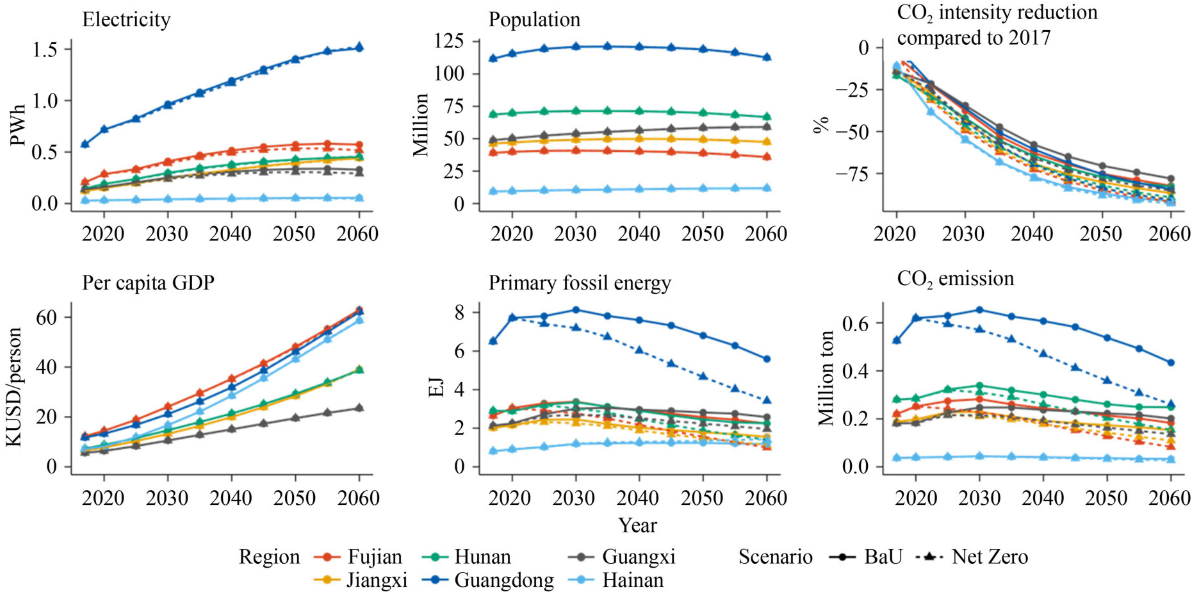

Fig. 3 Changing trends of energy, environment, and economy in Southern China.

(Fig. 4b), which has a smaller carbon emission factor than coal, resulting in lower carbon emissions for Hainan. The share of electricity in total final energy consumption is projected to increase by 5.7%, 10.5%, 8.0%, 5.6%, 5.4%, and 0.8%. Carbon intensity is expected to decrease by 7.9%, 9.9%, 8.2%, 5.0%, 3.5%, and 1.3% in each region in 2050, compared to the BaU scenario. The provincial carbon quota allocation method has limited impacts on the indicator of GDP per capita, as the pressure to reduce carbon emissions is relatively small in most regions. Specifically, GDP per capita is projected to decrease by 0.6%, 0.1%, and 0.2% in Fujian, Hunan, and Jiangxi, respectively, while increasing by 0.2% and 0.1% in Guangdong and Hainan. GDP per capita in Guangxi will remain unchanged.

3.2 Final energy demand and CO_2 emissions

Regarding final energy demand and CO_2 emissions, under the BaU scenario, the trend shows a continuous increase in Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Hainan. By 2050, the demands are projected to be 99.5%, 76.5%, 56.9%, 82.0%, 59.4%, and 69.1% higher compared to 2017. Under the Net Zero scenario, energy consumption in all six regions exhibits a trend of initial growth followed by a decline. The achievement of the carbon neutrality goal will significantly transform the energy structure in Southern China, as depicted in Fig. 4. Primary fossil fuel consumption is projected to peak in 2040, 2050, 2035, 2045, 2035, and 2035 for the provinces of Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Hainan, respectively, under the Net Zero scenario. Furthermore, total final energy demand is expected to decrease by 22.6%, 11.3%, 16.8%, 17.7%, 21.5%, and 15.8% in Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Hainan, respectively, in 2050, in comparison to the BaU scenario. The proportion of coal is anticipated to decrease by 4.5%, 2.0%, 7.6%, 2.6%, 5.5%, and 0.2% in 2050 under the Net Zero scenario, relative to the BaU scenario for each respective province.

The impact of carbon emission constraints on electricity consumption, as per the carbon neutrality target, is relatively complex. On the one hand, higher energy costs and enhanced energy efficiency result in a reduction in electricity demand. On the other hand, elevated fossil energy prices and subsequent increases in electricity prices contribute to a decrease in electricity consumption. However, the overall effect of scale outweighs that of substitution, leading to a decline in electricity demand. Nevertheless, the share of electricity consumption in final energy consumption has seen an increase. For the period of 2050, it is projected to rise by 10.5%, 5.4%, 5.6%, 8.0%, 5.7%, and 2.5% for Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Hainan, respectively, in comparison to the BaU scenario.

Under the BaU scenario, CO_2 emissions are expected to reach their peak around the year 2030. Specifically, in 2030, CO_2 emissions in Fujian, Jiangxi, Hunan,

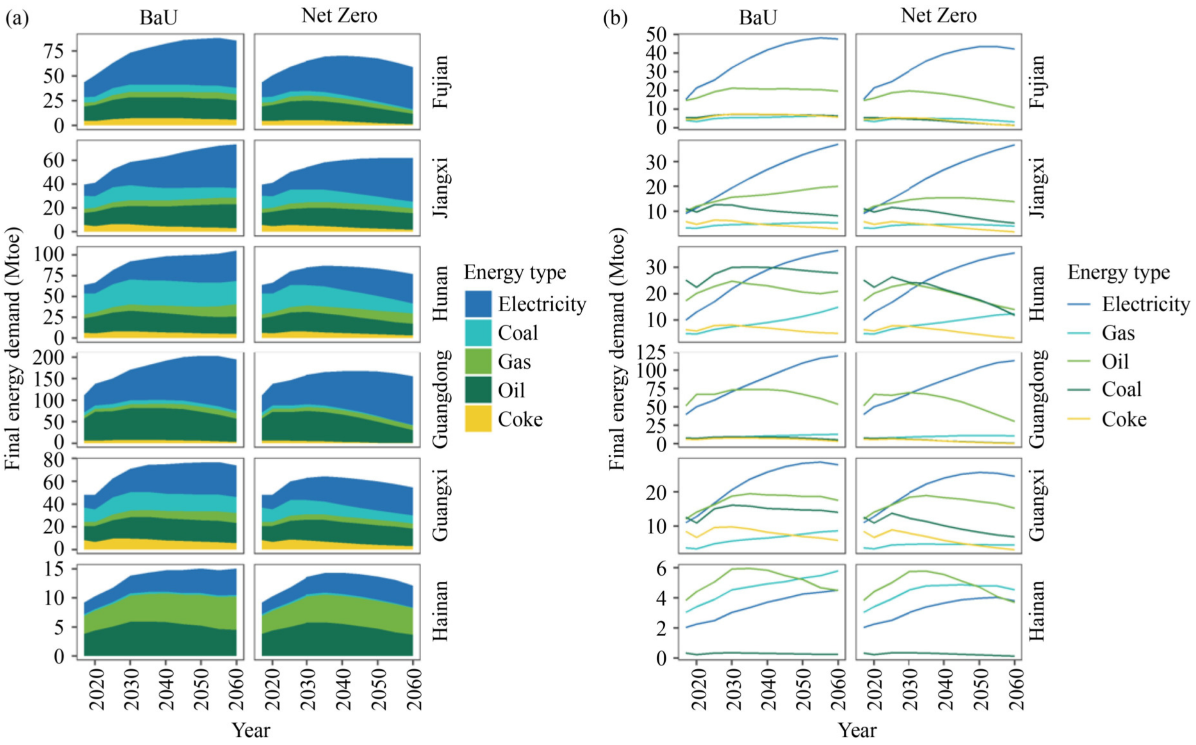

Fig. 4 Final energy demand under different scenarios of each province (Mtoe: Million tons of oil equivalent).

Guangdong, Guangxi, and Hainan are projected to increase by approximately 28.4%, 22.2%, 21.1%, 24.4%, 36.4%, and 20.6%, respectively, compared to levels in 2017. Subsequently, from 2030 to 2050, CO_2 emissions are predicted to show a declining trend. By 2050, CO_2 emissions in Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Hainan are estimated to be reduced by 24.4%, 24.5%, 23.1%, 17.8%, 10.0%, and 18.2%, respectively, in comparison to the levels in 2030 (Fig. 5(a)). Power generation is identified as the largest contributor to CO_2 emissions.

To achieve the target of carbon neutrality, significant cuts in carbon emissions are necessary. By 2050, the absolute emission reductions in Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Hainan will need to reach 85.5, 31.0, 57.0, 179.8, 59.3, and 3.6 million tons, respectively (Fig. 5(b)). Additionally, CO_2 emissions are expected to peak around 2025 in all the six regions. The plan to reach the carbon peak in all six provinces will be completed ahead of the scheduled time in 2030. Furthermore, the sectors that make the most significant contributions to carbon emission reductions will vary from province to province due to differences in industrial structure by 2050. In Fujian, Jiangxi, and Guangxi, the

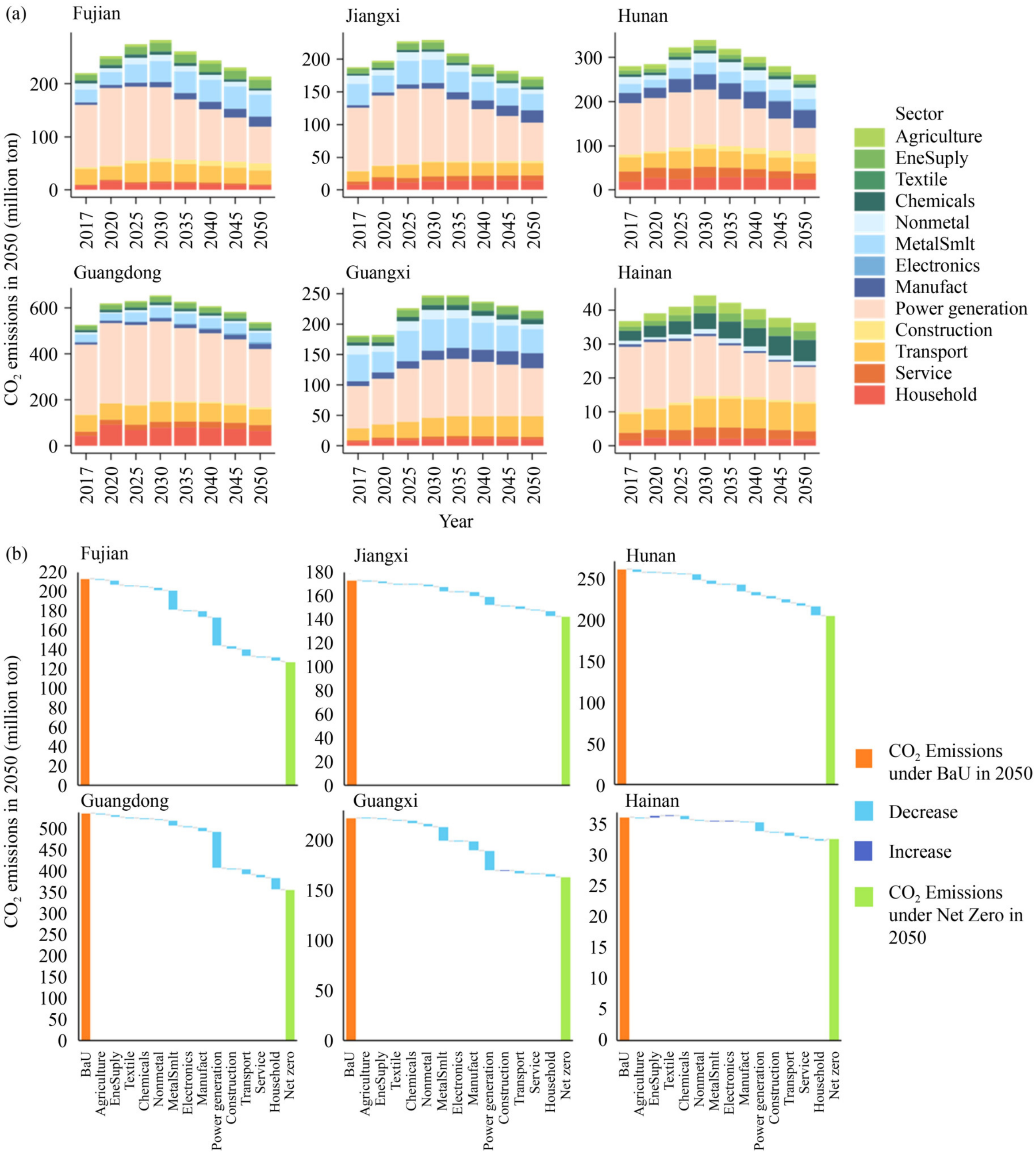

Fig. 5 CO_2 emissions by sector in BaU from 2017 to 2050 (a) and CO_2 emission changes in Net zero compared with BaU in 2050 (b).

priority sectors are electricity and metal smelting, while in Hunan, it is residential and manufacturing, and in Hainan, it is electricity and transport.

3.3 Air pollutant emissions and $PM_{2.5}$ concentration

Regarding air pollutant emissions and $PM_{2.5}$ concentration, under the CLE (Figs. 6(a)–6(b)), air pollutant emissions can be effectively controlled and will not increase drastically. Under the carbon neutral scenario (Net zero_CLE), there will be a decreasing trend in air pollutant emissions. However, this decrease is insufficient to achieve the air quality control objectives in most provinces. Cutting air pollutant emissions significantly is necessary to reach the air quality targets. Figures 6(c) and 6(d) display the reductions in air pollutant emissions in the POLICY scenarios compared to the CLE scenarios. The POLICY scenario is set based on achieving specific air quality goals in a given year, and the emission difference between the CLE and POLICY can be understood as the additional reduction required to meet each region's air quality goal. Areas shown in light red indicate that the concentration targets are below MTFR, meaning that these provinces will be unable to achieve the POLICY targets even with the maximum practicable control measures. On the other hand, the gray area signifies that the concentration target is higher than the CLE, implying that the POLICY target can be achieved by maintaining control measures at the current level.

In the BaU scenario, continuous strengthening of end-of-pipe control for air pollutants is necessary to achieve the air quality goal (BaU_POLICY). For example, in Guangxi, SO_2 needs to be reduced by 338.1 and 465.8 kilotonnes in 2035 and 2050, respectively, resulting in a decrease of 37.5% and 56.9% compared to BaU_CLE. NO_x needs to be reduced by 31.1 and 170.4 kilotonnes, corresponding to a decrease of −6.0% and −33.4% compared to BaU_CLE. In Guangdong and Fujian, air quality targets cannot be achieved even with the maximum feasible control measures by 2050. In the Net zero scenario, as the energy transition progresses, the co-benefits of reducing air pollutant emissions are significant. Moreover, the additional emission reductions required to meet the air quality objectives are substantially lower compared to the BaU scenario. By 2035, regions such as Fujian, Guangxi, Hainan, and Hunan can even achieve their air quality goals without implementing additional air pollutant reduction measures.

In 2050, let's take Hunan as an example. To achieve a $PM_{2.5}$ concentration of 13.8 μg/m^3, the reductions in SO_2, NO_x, primary $PM_{2.5}$, NH_3, and VOC emissions would need to be 252.2, 218.2, 212.9, 421.3, and 72.6 kilotonnes, respectively, compared to the BaU_CLE scenario. However, in the Net zero scenario, compared to the Net zero_CLE scenario, only minimal reductions of 0, 4.1, 44.1, 0.9, and 1.5 kilotonnes would be necessary.

The priority sectors for emission reductions vary significantly depending on the pollutant. For primary $PM_{2.5}$, the main control sectors are power generation and metal smelting. The agriculture sector plays a major role in reducing NH_3 emissions, accounting for over 91% of the total reduction. The transport sector is the key sector for controlling NO_x emissions. As for SO_2 emissions, power generation and non-metal sectors are the main control sectors. It is important to note that the priority pollution control sectors may change under different climate scenarios and timeframes. For example, in the Net zero scenario, the power generation sector abatement potential for primary $PM_{2.5}$ and SO_2 in Guangxi is significantly reduced, and the priority sectors shift to metal smelting and non-metals, respectively. In Jiangxi, the power generation sector is the controlling sector for primary $PM_{2.5}$ in 2025, but by 2050, it will be metal smelting.

Without additional climate action, all six regions would not be able to achieve their air quality goals by 2050 under the BaU_CLE scenario, even with the maximum feasible control measures (BaU_MTFR) in Fujian and Guangdong (Fig. 7). In the BaU_MTFR scenario, the $PM_{2.5}$ concentrations in Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Hainan in 2050 would be 10.9, 14.9, 17.7, 12.9, 11.8, and 5.9 μg/m^3, respectively. This indicates the limited potential of end-of-pipe controls in improving air quality. Furthermore, with the current level of CLE in the BaU scenario, there is a risk of worsened pollution in Guangdong, with $PM_{2.5}$ concentrations possibly reaching 22 μg/m^3 in 2025. Under the target of achieving carbon neutrality, significant improvements can be made in air quality. The provinces of Fujian, Guangxi, Hainan, and Hunan can reach their air quality objectives by 2035 using the current level of end-of-pipe control (Net zero_CLE). In comparison to the BaU_CLE scenario in 2050, $PM_{2.5}$ concentrations in Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Hainan could be reduced by the following amounts: 6.6, 7.9, 10.5, 9.7, 9.9, and 4.4 μg/m^3, respectively.

However, in the 2050 Net zero_MTFR scenario, Fujian is unable to achieve its air quality goal of 9.6 μg/m^3. At the maximum feasible end-of-pipe control level (Net zero_MTFR), Fujian can only reach 10.3μg/m^3. This indicates the need to increase energy transformation efforts and reduce the use of fossil fuels.

3.4 Inter-regional economic and environmental linkages

The implementation of differentiated regional carbon emission reduction policies will lead to changes in relative product prices across various sectors, as fossil fuel prices will increase to varying degrees. This, in turn, will affect trade patterns (refer to Fig. 8). In the BaU scenario for 2050, the provinces of Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Hainan have net export values of 89.2, 66.8, −23.0, 1121.4, −192.5, and −61.2 billion

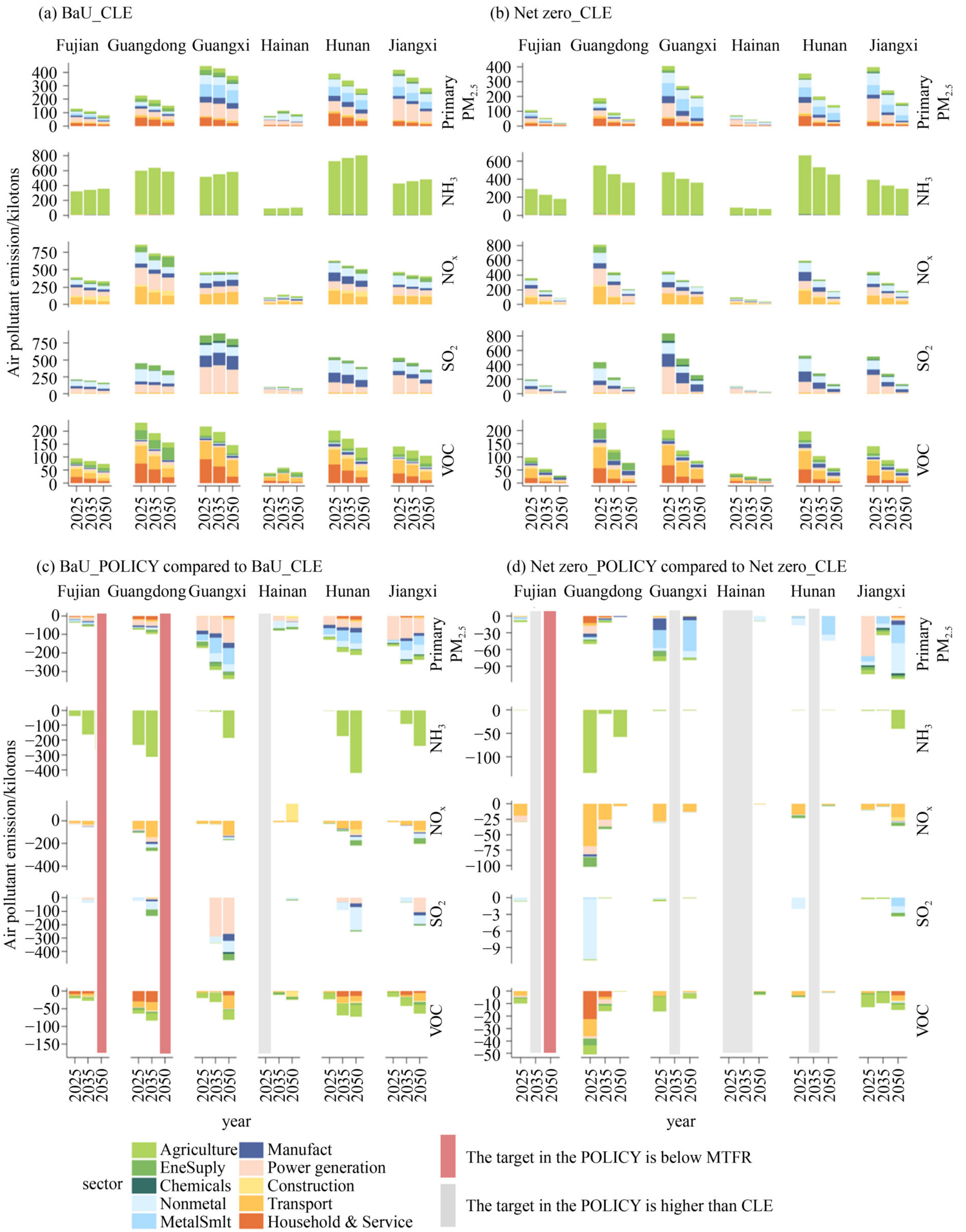

Fig. 6 Air pollutant emissions in the BaU_CLE (a) and Net zero_CLE scenario (b), and air pollutant emission reductions in the BaU_POLICY compared to the BaU_CLE (c) and Net zero_POLICY compared to the Net zero_CLE (d) in 2025, 2035 and 2050.

USD, respectively. Additionally, the net inter-provincial outflows are −40.8, −31.6, 71.7, −1083.1, and 112.8 billion USD, respectively. On the other hand, in the Net zero scenario, the changes in the value of net exports for these provinces are as follows: −8.4%, 12.6%, 23.4%, −40.5%, −16.8%, and −1.0%. The changes in net inter-provincial outflows are 7.1%, 48.1%, 1.0%, −54.6%, −18.0%, and 2.4%, respectively.

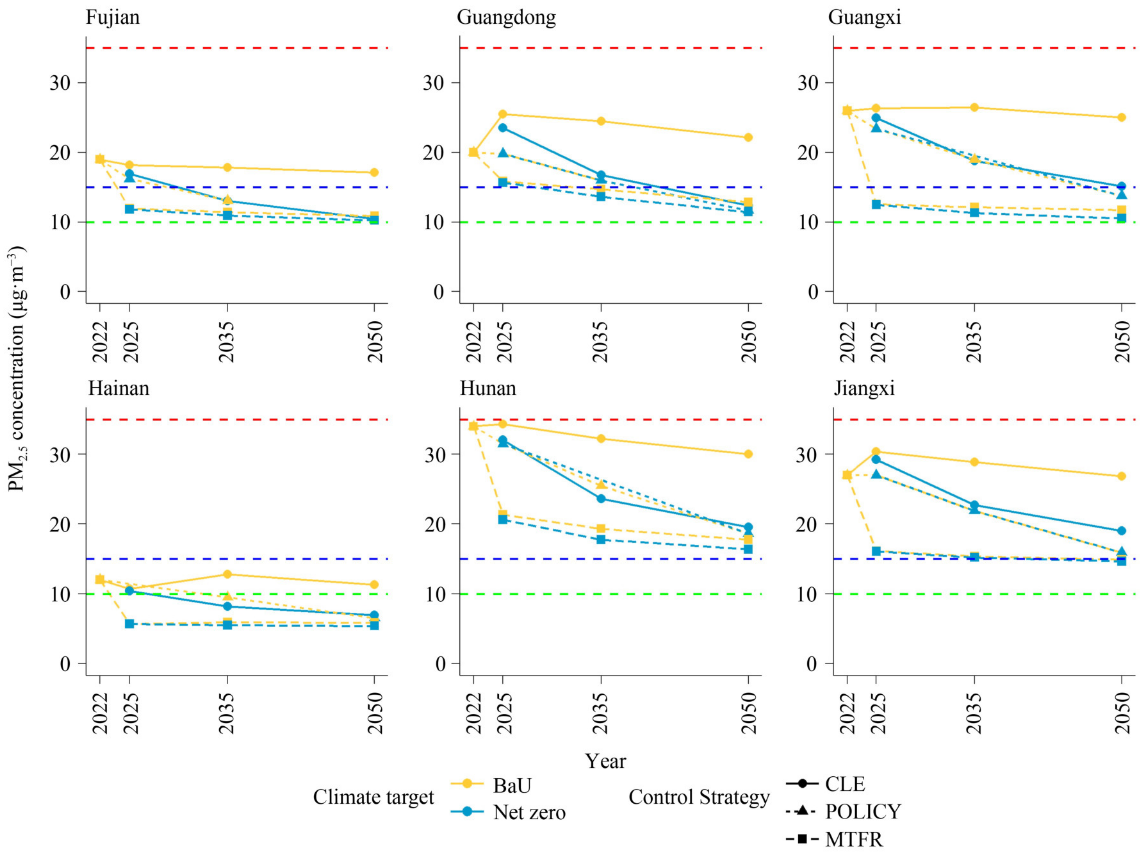

Fig. 7 Population-weighted PM$_{2.5}$ concentrations under different scenarios.

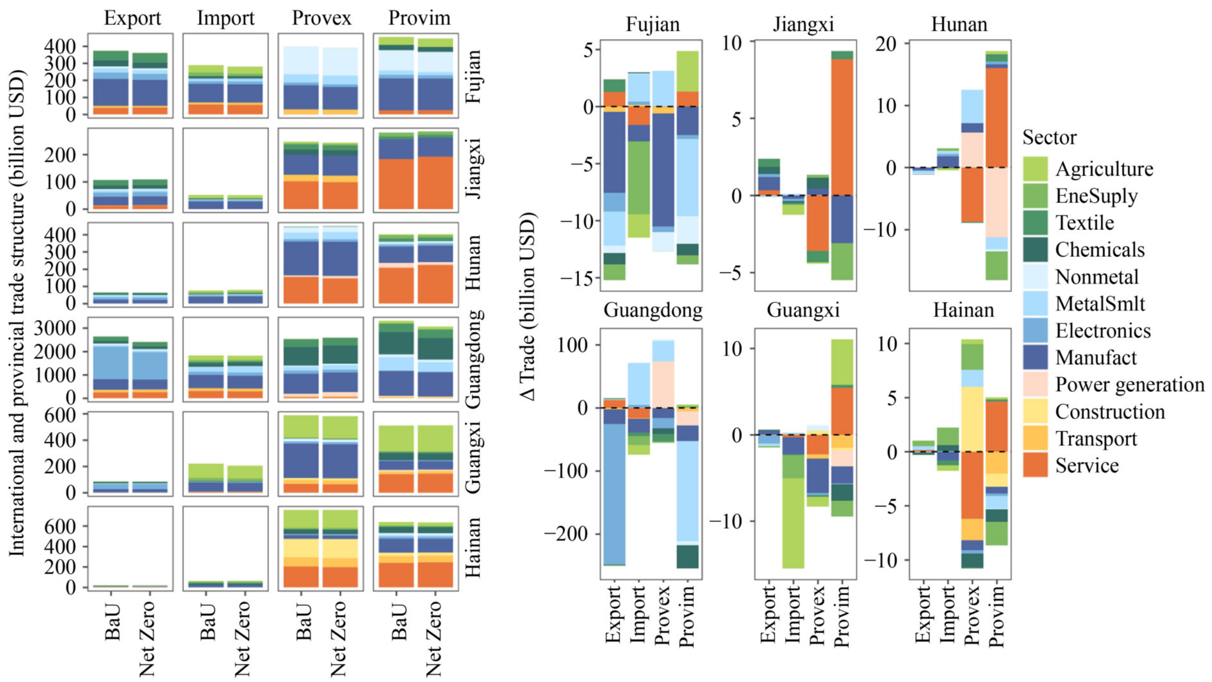

Fig. 8 International and provincial export and import structure (a) and GDP composition change in Net zero compared with BaU (b) in 2050. The "Proex" represents inter-provincial outflow, and the "Proim" represents inter-provincial inflow.

Trade activities not only involve the exchange of commodities but also result in the transfer of CO_2 and air pollutants. Specifically, under the BaU scenario in 2050, there is a greater inflow than outflow in the inter-provincial trade of Guangdong Province. This inflow is primarily composed of carbon-intensive industries such as chemicals and metal smelting, which transfer pollutants to provinces that produce primary products at the expense of their economic returns. However, in the Net zero scenario, Guangdong Province will reduce its economic losses by reducing the inflow of chemical products and increasing the outflow of clean electricity. This will also mitigate the transfer of embodied CO_2 and air pollution. Jiangxi Province, on the other hand, will have a net inflow of services in inter-provincial trade in 2050 but will keep CO_2 and air pollution within the province through net outflows of manufacturing products. Under the Net zero scenario, inter-provincial outflows of Jiangxi Province are further increased in the services sector, thereby increasing inter-provincial outflows overall.

On the contrary, in 2050, under the BaU scenario, Hunan Province experiences smaller inflows in inter-provincial trade compared to outflows. The net outflows primarily originate from carbon-intensive industries such as machinery, metal smelting, and paper making, while the cleaner services sector sees inflows. Under the Net Zero scenario, Hunan increases inter-provincial outflows of low value-added products like metal smelting, electricity, and machinery, and experiences inter-provincial inflows of higher value-added products such as services.

3.5 Cost-benefit analysis

Figure 9 illustrates the health benefits and costs associated with the low carbon transition for different regions in each scenario in 2050. Benefits are measured as avoided Statistical VSL loss in comparison to the BaU_CLE scenario. The cost refers to the loss of GDP in the carbon neutrality scenario compared to the BaU scenario. The data indicates that the net benefits are highest in the MTFR scenario, followed by the POLICY scenario, and lastly, the CLE scenario. However, further discussion on the implementation costs of these control strategies is required in future studies.

Climate policies do not uniformly impact all regions negatively, and a moderate carbon reduction pressure can actually promote the development of low-carbon industries. In 2050, Fujian, Jiangxi, Guangxi, and Hunan will experience a decrease in GDP of 10.8, 3.0, 0.5, and 1.3 billion USD (0.6%, 0.2%, 0.04%, and 0.1%), respectively, compared to the BaU scenario. In contrast, Guangdong and Hainan will see an increase in GDP of 13.1 and 0.6 million USD (0.2% and 0.1%) respectively. Supplementary Material Fig. S8 indicates that the decline in

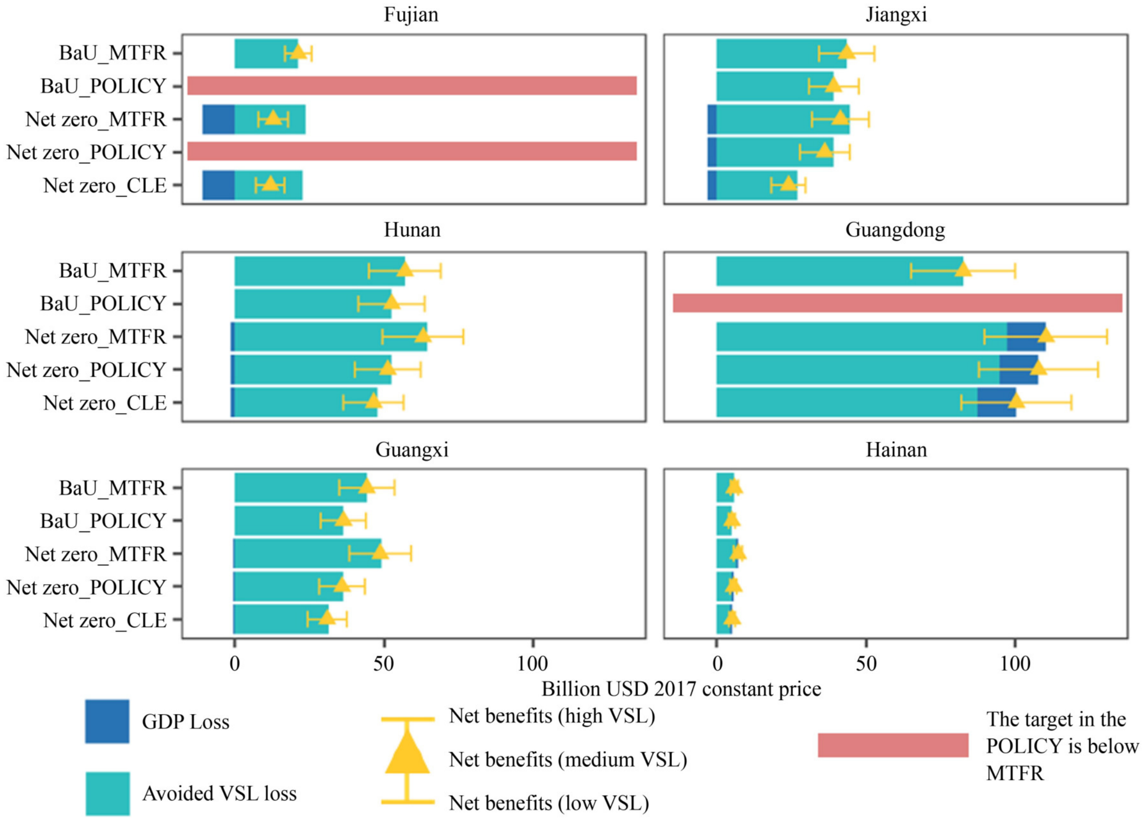

Fig. 9 A cost-benefit analysis by region and scenario compared to the BaU_CLE scenario in 2050.

exports and inter-provincial transfers in the machinery sector in Fujian Province is the primary factor contributing to the decrease in GDP. Conversely, the increase in inter-provincial transfers from the power sector and metal smelting in Guangdong Province, as well as the decrease in inter-provincial transfers from the metal smelting and chemical industry, are the primary reasons for the GDP increase.

The health benefits associated with various regions can offset the costs of carbon reduction by 2050. The net benefits vary greatly across different regions. In 2050, Guangdong exhibits the highest net benefits of 94.7 and 107.8 billion USD under the BaU_POLICY and Net zero_POLICY scenarios, respectively, compared to BaU_CLE. Meanwhile, Jiangxi, Hunan, and Guangxi experience moderate increases in health benefits of 36.2, 51.1, and 35.8 billion USD, respectively, in 2050 under the Net zero_POLICY scenario compared to BaU_CLE. Conversely, Fujian and Hainan demonstrate smaller net benefits of 11.8 and 5.7 billion USD in 2050, respectively. The differences in net benefits can be attributed to variations in each region's energy mix, population size, and initial environmental quality. For instance, Guangdong and Hunan exhibit significant health benefits during the low-carbon transition due to their larger populations and poorer initial environmental quality. In contrast, Hainan experiences fewer health benefits due to its smaller population, better environmental quality, and cleaner energy mix. Based on these variations, it is crucial to tailor low-carbon transition targets and incentive subsidies to promote environmental improvements in each region.

4 Discussion and policy implications

This study employs an integrated assessment framework to evaluate cost-effective methods for achieving carbon neutrality and air quality targets. Our findings indicate that without further climate mitigation policies and strengthened end-of-pipe control measures (BaU_CLE), CO_2 emissions in these six provinces will be roughly the same as in 2017, with little improvement in $PM_{2.5}$ concentration. Conversely, when carbon neutrality goals are achieved, even without strengthened end-of-pipe control measures, $PM_{2.5}$ can further decrease by 4.4−10.5μg/m^3 (29.3% to 43.9%) in 2050 under the Net Zero_CLE scenario compared to BaU_CLE. Additionally, the co-benefits of public health could reach 5.1−94.7 billion USD, with Jiangxi and Hunan provinces gaining net benefits. The selection of pathways to reduce air pollutants and carbon emissions exhibits significant inter-provincial heterogeneity.

4.1 Policy implications

Our results demonstrate that a low-carbon transition toward achieving carbon neutrality can also lead to a reduction in air pollutant emissions. The sectors prioritized for decreasing air pollutant emissions show significant variation across different scenarios. For example, in the Net zero scenario, the emission reduction potential of Guangxi's power generation sector is significantly reduced, with the priority sectors for $PM_{2.5}$ and SO_2 shifting toward metal smelting and non-metal sectors, respectively.

The long-term effectiveness of implementing additional pollution control measures under the net-zero scenario is limited due to the necessity of a cleaner energy system. In the net-zero scenario, the strictest end-of-pipe control measures result in a decrease in $PM_{2.5}$ concentration ranging from 2.3% to 30.3% compared to the CLE in various regions. In contrast, in the BaU scenario, the decrease is as high as 36.5% to 53.1%. Furthermore, implementing measures to enhance end-of-pipe control measures will increase control costs. Therefore, balancing low-carbon transitions and end-of-pipe controls is necessary over time.

Different regions experience significant disparities in economic benefits from air pollution abatement and carbon emission reductions. For instance, in Fujian, the health benefits are outweighed by GDP losses, whereas in Hunan and Jiangxi, the opposite is true. Therefore, it is crucial to tailor air pollution abatement and carbon emission reduction targets to local conditions or facilitate inter-provincial transfers to mitigate inequalities.

Additionally, regional joint prevention and control have emerged as key mechanisms for improving air quality in China in recent years. To assess the impact of cooperation and transboundary effects, we constructed a scenario where only Guangdong achieves carbon neutrality while other regions lack carbon emission restrictions. The resulting simulations indicate that, compared to a scenario where all six regions achieve carbon neutrality targets, $PM_{2.5}$ concentrations in Guangdong would decrease by less than 0.1 μg/m^3 in 2035 and 2050 under the CLE. Considering the range of uncertainties in the simulation, these results suggest that the transboundary impact is not significant. This may be due to the relatively low severity of $PM_{2.5}$ pollution in Southern China. Cooperation and transboundary effects may have a more substantial influence in heavily polluted areas of China, such as the Beijing–Tianjin–Hebei region.

4.2 Uncertainty analysis

To explore the impact of different carbon emission constraints on GDP losses, two additional carbon-neutral scenarios have been established based on the convergence of carbon emission intensity and a consistent rate of carbon emission decline, denoted as Net Zero_CO_2 Intensty and Net Zero_SameRate, respectively (Fig.10a). In the Net Zero_CO_2 Intensty scenario, it is assumed that each province's carbon emissions per unit of GDP will converge by 2060, with allowed carbon emissions for each province in 2060 calculated based on the 2060 GDP simulated by the model. In the Net Zero_SameRate scenario, it is assumed that each province's carbon emission reduction rate will remain consistent, and the specific calculation formula is provided in the Supplementary Material.

The lower the carbon quota, the greater the loss in GDP will be (Fig. 10b). The carbon quotas of the provinces of Fujian, Guangdong, and Hainan are the highest among the three carbon-neutral scenarios due to their lower carbon intensity in the base year. Consequently, these provinces experience the smallest GDP loss and even a potential increase in GDP. Conversely, under the equal rate of carbon emission reduction scenario, all six provinces face the least favorable conditions, with the lowest carbon quotas and the most significant GDP loss.

Taking Guangdong province as an example, under the carbon intensity convergence scenario (Net Zero_CO_2 Intensity), the shadow price of carbon in 2050 is 81.8 USD/ton, resulting in a 0.5% increase in GDP. This increase is mainly attributed to higher inter-provincial transfers out of electricity and metal smelting, as well as reduced inter-provincial transfers in the electricity and chemical industry. In contrast, under the same rate reduction scenario (Net Zero_SameRate), the shadow price of carbon in Guangdong province increases to 299.3 USD/ton, causing a 0.1% decrease in GDP.

These findings highlight the significant impact of provincial carbon allowance allocation on the net benefits of carbon emission reduction. While the health benefits are substantial, the net benefits are sensitive to GDP loss, which is heavily influenced by how carbon allowances are allocated. For instance, Hainan's net benefits shift from positive to negative under the same rate of abatement

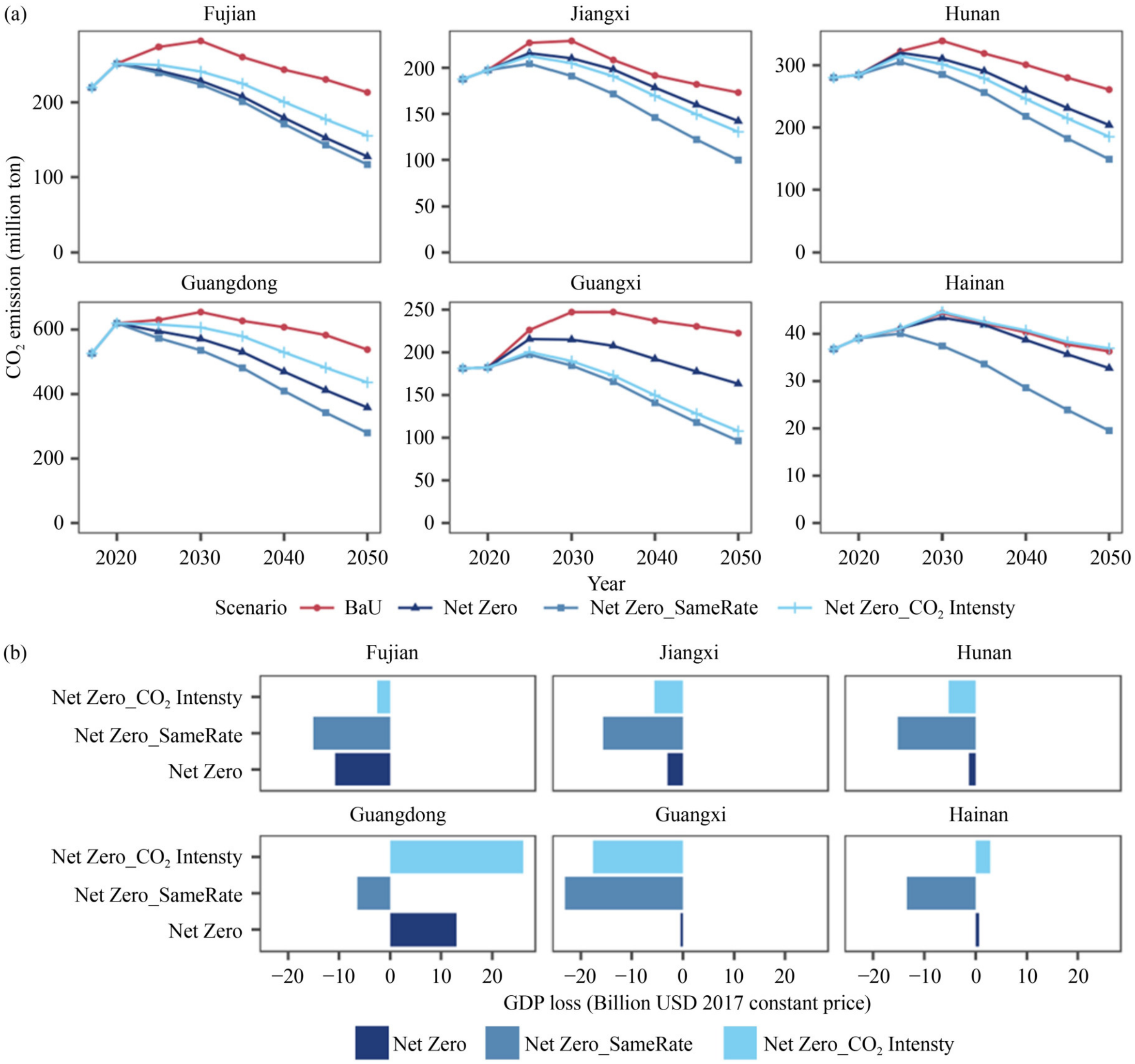

Fig. 10 CO_2 emissions from 2017 to 2050 (a) and GDP loss under different Net zero scenarios compared to BaU in 2050 (b).

scenario (Net Zero_SameRate).

4.3 Comparison with other studies

Many existing studies have quantified the air quality improvement co-benefits of carbon emission reduction, but fewer studies have analyzed the synergistic control pathways to achieve realistic regional air quality objectives. This study, however, examines both objectives simultaneously and sets air quality goals that are consistent with reality. Surprisingly, even with maximum end-of-pipe control efforts under the carbon neutrality goal, the air quality goal in Fujian Province remains unachievable. This situation highlights the need to strengthen energy transition efforts in order to attain the air quality goal. Policymakers should, therefore, consider setting carbon emission reduction and air quality goals in an integrated manner and prioritize the implementation of synergistic measures.

Existing studies have failed to consider the heterogeneity among provinces and the impact of different provincial carbon neutrality pathways on the results. Furthermore, these studies mostly indicate that carbon reduction targets negatively impact the economy, although health benefits can partially or fully offset the costs of reducing emissions. In a study conducted by Wu et al. (2022), it was found that the synergistic benefits of population health in the Beijing–Tianjin–Hebei region cannot outweigh the costs of the carbon reduction policy under the 1.5-degree scenario in 2030. In this case, Beijing experienced a loss of GDP amounting to 12 billion USD, which far exceeded the health benefits of 1.57 billion USD due to the high cost of carbon emission reduction. Zhang et al. (2021) noted that under the 1.5-degree scenario, the population health benefits resulting from the carbon reduction in Sichuan Province fully covered the costs, resulting in net benefits of 9 billion and 22 billion USD in 2025 and 2035, respectively. This study suggests that while there may be uncertainty in health impact assessments, it does not decisively influence the qualitative results. Fan et al. (2024) discovered that by 2035, promoting the electrification path would impact Anhui Province’s GDP by 1.4%–4.5%, while the GDP loss associated with developing the renewable energy path would only be 1.1%–1.4%. Tang et al. (2022) found that, compared to the REF scenario, China would generate net benefits of 393 billion and 3017 billion USD (2017 USD value) in 2050 under SSP1-RCP2.6 and SSP5-RCP2.6, respectively. These figures are equivalent to 0.45% and 2.77% of China’s GDP in 2050 and are sufficient to offset the direct costs of carbon reduction.

However, this study indicates that moderate carbon emission reduction pressure could also promote the development of low-carbon industries and have a positive impact on the economy. Guangdong Province, for example, experienced increased GDP and substantial health benefits through the vigorous development of non-fossil energy generation and increased inter-provincial electricity transfer under the Net zero scenario. This achievement demonstrates that planning for transformation and developing low-carbon industries in advance is necessary to minimize economic losses. Additionally, it is crucial to adopt tailored policies based on different carbon neutrality pathways, as a one-size-fits-all approach is not suitable for all regions. In the future, conducting more parameter uncertainty analyses will be essential for exploring key influencing factors that impact the cost and benefits of emission reduction.

5 Conclusions

The main conclusions of this study are as follows: (1) The critical sectors for carbon reduction vary in each province due to differences in industry and energy structure. In Fujian, Jiangxi, and Guangxi, power generation and metal smelting are critical sectors, while in Hunan, they are household and manufacturing industries. In Hainan, they are power generation and transportation. (2) The extent to which carbon neutrality contributes to achieving air quality goals differs across regions. By achieving carbon neutrality goals, Fujian, Guangxi, Hainan, and Hunan can meet their air quality goals by 2035 under the CLE, leading to significant co-benefits in reducing pollution and carbon emissions. Compared to the BaU_CLE scenario in 2050, $PM_{2.5}$ concentrations in Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Hainan could be reduced by 6.6, 7.9, 10.5, 9.7, 9.9, and 4.4 $\mu g/m^3$, respectively, even under the Net zero_CLE scenario. However, in Fujian, under the Net Zero_MTFR scenario in 2050, it is not possible to achieve air quality goals, and there is limited control space at the end-of-pipe control. (3) Carbon reduction policies will reshape the trade structure and alter the flow of embodied CO_2 and air pollutants. Under the Net zero scenario, Guangdong Province can decrease economic losses and pollution transfer to other provinces by adjusting its inter-provincial trade. Hunan, Jiangxi, and other provinces at the middle and lower ends of the industrial chain can increase inter-provincial transfers of energy-intensive industries, which will also increase the pressure to reduce emissions. (4) An outward-oriented economy is more resilient to climate policy shocks and can mitigate its negative impact on the economy by increasing exports or outflow of low-carbon products to international or other provinces’ markets. Furthermore, provincial carbon quotas significantly affect the cost-effectiveness ratio of carbon reduction. Net benefits are more sensitive to GDP losses, while GDP losses are sensitive to the allocation of carbon quotas in each province. The health benefits of all regions can offset the cost of carbon reduction by 2050 under the allocation principle of per capita carbon emissions converging (Net zero). However, under the same rate of abatement scenario (Net Zero_SameRate), Hainan's net benefits will shift from positive to negative. Additionally, implementing the low-carbon transition and air pollutant end-of-pipe controls will have significantly unequal economic impacts across regions. Guangdong has the highest net benefits of 107.8 billion USD in 2050 under the Net zero_POLICY scenario compared to BaU_CLE. Jiangxi, Hunan, and Guangxi have moderately higher health benefits of 36.2, 51.1, and 35.8 billion USD in 2050, respectively. Fujian and Hainan have smaller net benefits of 11.8 and 5.7 billion USD, respectively. This implies that setting low-carbon transition targets and air pollutant end-of-pipe control measures cannot be a one-size-fits-all approach. It requires either locally tailored measures that consider local economic benefits or economic compensation measures between locations.

In summary, the achievement of carbon neutrality necessitates a rapid overhaul of the energy system and has the potential to yield significant enhancements in air quality, along with corresponding public health benefits. However, it is important to note that the potential for emission reduction through end-of-pipe control measures aimed at further ameliorating air quality is limited. This limited potential makes it more challenging to meet stringent air quality standards, thereby necessitating a more profound transformation of energy and economic systems. Our study demonstrates that it is indeed feasible to simultaneously realize the objectives of CO_2 emission reduction and the improvement of air quality in Southern China. Moreover, the pursuit of carbon neutrality goals can result in lower costs for air pollution control and substantial health advantages. Hence, it is crucial for policymakers to integrate air quality objectives with the objectives of low-carbon development while devising regional plans for green transformation, thereby ensuring a harmonized approach to air pollution and carbon reduction management.

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Competing Interests The authors declare that they have no competing interests.

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