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YSSP Report
Young Scientists Summer Program

Cost-optimized pathways to achieve the carbon neutrality and PM2.5 air quality targets in Southern China

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Program: Energy, Climate, and Environment (ECE) program
June 2021 - Sep. 2021

This report represents the work completed by the author during the IIASA Young Scientists Summer Program (YSSP) with approval from the YSSP supervisor.

It was finished by Xiaorui Liu and has not been altered or revised since.

This research was funded by IIASA and its National Member Organizations in Africa, the Americas, Asia, and Europe.

目录

Abstract

China’s newly proposed carbon neutrality target in September 2020 requires deep decarbonization with an interim goal of peak carbon emissions approximately by the year 2030. At the same time, although significant results have been achieved in recent years in the prevention and control of air pollution, the air quality situation remains serious, with $PM_{2.5}$ concentrations as high as 34ug/m^3 in 2020 even under the impact of the COVID-19. How to achieve carbon neutrality and air quality goals simultaneously in a cost-effective way is essential for China, and it is important to understand better how such strategies would be achieved at the provincial level. This study explores cost-optimized pathways for achieving the dual targets in the rapidly developing but unevenly balanced southern China including Guangdong, Guangxi, Hunan, Hainan, Jiangxi and Fujian provinces. We use a multi-model assessment approach which consists of the macro-economic model (IMED|CGE), the GAINS model, multi-objective cost optimization model and public health model (IMED|HEL) to investigate the costs and benefits of achieving carbon neutrality and the $PM_{2.5}$ air quality goal. We found that in the baseline without carbon emission constraint under the current legislation, all 6 provinces cannot achieve China’s National Ambient Air Quality Standard class I (15ug/m^3) by 2050. Only by implementing the strictest air pollution control measures can it be possible to approach the air quality level under the carbon-neutral scenario, which will increase the control cost by 20%~200%. While in the Net zero carbon scenarios, Fujian, Guangxi, and Hainan are expected to reach the WHO guidance value under the current control measures with substantial health co-benefits. Furthermore, in order to achieve the same air quality goals, the air pollution control cost under the carbon neutrality scenario would also be significantly lower than the baseline scenario. The contribution of end-of-pipe measures will gradually decrease, due to the cleaner energy mix. In the long term, the transition of the transportation, industrial and energy structure in line with the carbon neutrality target would lay an important foundation for further improvements in air quality.

Keyword

Carbon neutrality, $PM_{2.5}$, Cost-optimized solutions, Southern China

1. Introduction

As the world's largest carbon emitter, China is closely related to the global climate mitigation process. In September 2020, China announced its goal of reaching carbon neutrality before 2060[1], which will be challenging because the country has high-carbon energy and industrial structure yet, of which fossil energy accounted for 85% in 2019. Industrialization and urbanization are still in progress and on a path towards peak carbon emissions in approximately 2030. Although air quality has improved in recent years, $PM_{2.5}$ concentrations still have a gap from WHO guideline values (5μg/m^3)[2] with $PM_{2.5}$ concentrations as high as 34μg/m^3 in 2020 even under the impact of the COVID-19. Furthermore, the aging population will be rising sensitive to $PM_{2.5}$ air pollution in China in the future, and the health impacts are expected to increase over time[3, 4]. Reducing public health risk by satisfying the standards of the WHO Air Quality Guidelines therefore requires more ambitious clean air actions. How to achieve these two goals simultaneously in a cost-effective way is an important question that needs to be answered urgently.

Studies on least-cost control strategy optimization have been conducted for $PM_{2.5}$, mostly in the United States, Europe, and Jing-jin-ji region in China[5]. However, these studies almost only address air quality attainment without CO_2 constraints. In this study, six provinces including Guangdong, Guangxi, Hunan, Hainan, Jiangxi and Fujian provinces in southern China are selected as examples to explore a coordinated path for carbon emission reduction and air quality improvement. These six provinces accounted for 16.8% of China's total carbon emissions in 2017, and are showing an increasing trend. At the same time, the air pollution situation in southern China is still severe. Among them, the $PM_{2.5}$ concentration in Guangdong Province in 2020 is as high as 35μg/m^3, and the $PM_{2.5}$ concentration in Hainan, the cleanest province, is also 13μg/m^3, 1.6 times higher than the WHO guideline (Figure 1). These six provinces have different levels of economic development and environmental pressure. In this context, finding an effective way to reduce CO_2 emissions while improving air quality is crucial to sustainable development in southern China.

In this study, we propose an integrated assessment model which mainly based on the GAINS model coupled with the macro-economic model (IMED/CGE) and public health model (IMED/HEL), and cost optimization analysis to investigate the control cost and health benefits of achieving the climate mitigation and the air quality goal. Then the scenario-based approach is used to identify economically efficient and feasible pathways to achieve dual goals. This will be an important reference and inspiration for other regions in China and the world. This study aims to answer the following research questions. (1) Under the current policies without further CO_2 mitigation and air pollution control measures, how large will the CO_2 and air pollutant emissions be by 2050? What are the impacts on air quality and health? (2) To achieve carbon neutrality, how should the provinces act under this vision? What are the synergistic benefits for air quality, and how much additional effort will be required if the air quality goal cannot be achieved by carbon emission reduction alone? (3) Which measures have synergistic control effects? Which emission reduction measures are technically feasible and economically effective, and what are the emission reduction routes that are economically effective in achieving the dual-attainment goals?

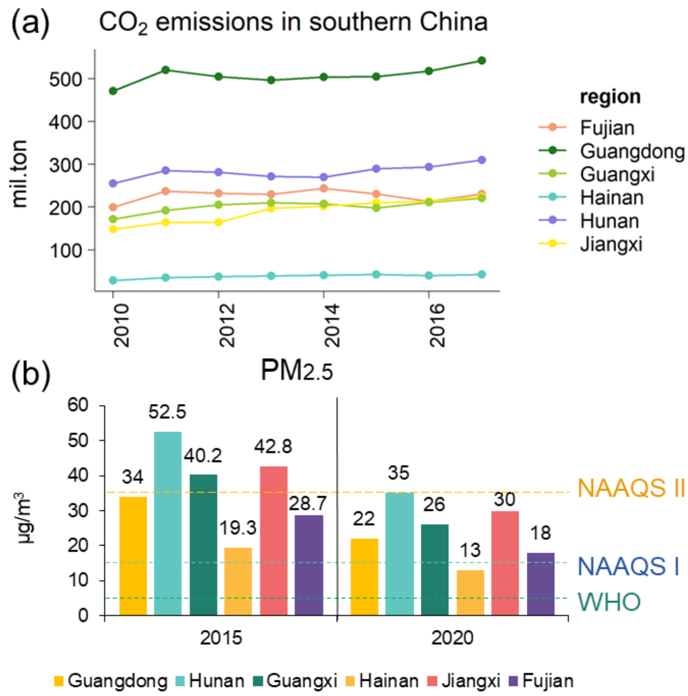

Figure 1. (a) CO_2 emissions and (b)ambient $PM_{2.5}$ concentration in south China. The yellow horizontal line indicates China's Class 2 limit values of current National Ambient Air Quality Standard (NAAQS II) for annual $PM_{2.5}$ concentration (35 μg/m^3), blue one indicates China's Class 1 limit values of current NAAQS (15 μg/m^3) and the green one for WHO's air quality 4th interim target (10 μg/m^3).

2. Method

2.1 Overview of the integrated modeling framework

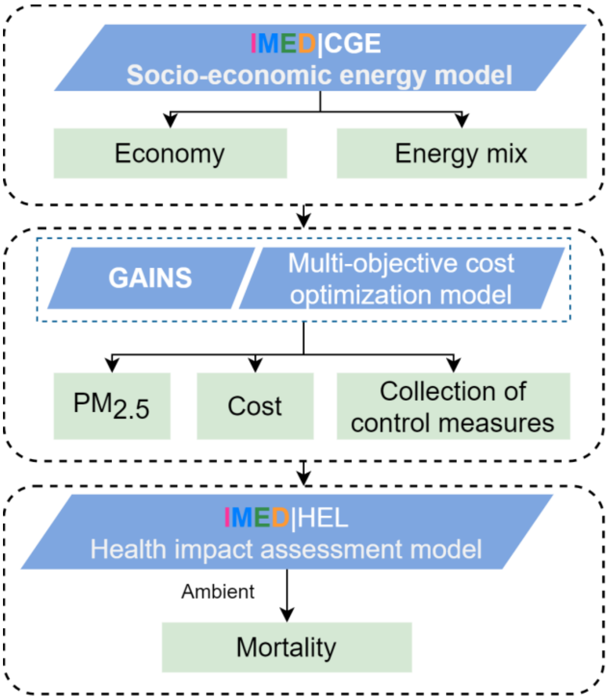

Figure 2. Integrated modeling framework

This study establishes an integrated assessment framework based on the GAINS model, GAINS optimization module, , coupled with the IMED/CGE (Integrated Model of Energy, Environment and Economy for Sustainable Development/Computable General Equilibrium) model and the IMED/HEL (Health) model developed by the LEEEP Group of Peking University.

First, using IMED/CGE model, we investigated the social-economic trend and energy consumption in line with current policy as well as carbon neutrality goal from the base year 2017 to the target year 2060. The resulting energy mix is converted to GAINS combined with GAINS optimization module to estimate air pollutant emissions, concentrations, control costs and the target attainment routes. Then health co-benefits, including avoided premature deaths in $PM_{2.5}$ concentrations reductions were quantified by the IMED|HEL model.

2.2 IMED|CGE

A computable general equilibrium model (CGE) typically involves a certain degree of policy disturbance to certain variables in an economic system in equilibrium, and assessing the impact of changes in economic indicators when that economic system returns to equilibrium again. The CGE model comprehensively portrays the relationship between economic development, energy demand, greenhouse gas and air pollutant emissions. The model uses the input-output table as the basis for socio-economic data, combined with energy balance table and industry statistical yearbook data to form the base year data. The model is modeled by GAMS/MPSGE and solved by the PATH algorithm, which dynamically simulates the economic trends, industrial structure changes, energy consumption and carbon emission trends of each region in one-year step from the base year to a future target year. The sector division is flexible according to the research questions and objectives. The model and its generic version have been systematically applied in recent years to systematically evaluate air pollution reduction, population health, energy and climate change response policies at national and provincial levels in China[10, 11].

The IMED|CGE model consists of a production module, a market module for domestic and foreign trade, and a module for government and resident revenues and expenditures. The production behavior of firms is portrayed by a constant elasticity of substitution production function, with production inputs classified as material inputs, energy inputs, labor and capital inputs. The model only simulates carbon emissions associated with energy consumption. Generally speaking, future energy and CO_2 emissions are driven by a complex mechanism of economic growth rates, energy efficiency measures and changes in the relative price of energy. The IMED|CGE model used in this study is a two-region model covering 25 sectors, including Guangdong Province (or Guangxi, Hunan, Hainan, Jiangxi, Fujian Province) and the rest of China. The base year is 2017 and the target year is 2060.

2.3 GAINS and optimization model

The GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model is a well-established tool for air and climate strategies developed by International Institute for Applied Systems Analysis providing a systems approach for negotiations. The model uses energy data and control strategies as inputs to estimate air quality and control costs. The model covers over 2000 control measures for 10 air pollutants and 6 greenhouse gases. The model has highly integrated modules, including technology, cost, emissions, air quality and impact modules, which facilitate the analysis of technology costs, emission pathways and air quality impacts of the green transition. This model has been widely used to explore cost-effective multi-sectoral pollution control options under certain CO_2 or air quality targets. [10, 12-15]

The GAINS optimization is a linear optimization module of air pollution control strategies in GAINS that can minimize costs, such that environmental effects do not exceed pre-defined limits and satisfy additional technology constraints including maximum application rates and vintage structure.

The optimization is formulated as a Linear Programming (LP) problem, i.e., all equations, definitions and constraints are linear in the decision variables. This allows us to use very fast solvers (CPLEX) that are commercially available.

2.4 IMED|HEL model

The IMED|HEL (Integrated Model of Energy, Environment and Economy for Sustainable Development | Health) model developed by LEEEP group in Peking University is a health impact assessment model that can assess the burden of disease caused by air pollution and the monetized economic loss caused by it. This model has been widely used to analyze the health effects of air pollution control policies at different scales and the synergistic benefits under climate change mitigation policies[16-19]. It can conduct a comprehensive health and economic impact assessment of $PM_{2.5}$ pollution, and can choose exposure-response functions (ERFs) and gridded socioeconomic data flexibly. The input data of the model includes air pollution exposure or concentration levels, the exposed population, and the latest exposure-response functions (ERFs) from epidemiological studies[20-22].

2.5 Scenario design

As shown in Table 1, this study sets up 8 scenarios with 2 dimensions. The first is different climate mitigation efforts, including a baseline scenario (BaU) with no carbon emission constraint versus a carbon neutrality scenario (Net zero). The second dimension is the levels of end-of-pipe air pollution control measures. This study considers 4 different scenarios including levels of controls following current legislation trend (CLE), cost-optimal baseline (COB) that achieves the CLE levels with least cost, POLICY that achieves certain regional $PM_{2.5}$ concentration targets with least control cost and level of controls that realize maximum technically feasible reduction (MTFR).

We set uniform targets across different climate mitigation efforts for the same year for different scenarios in different regions in the POLICY scenario, as shown in Table 2. This target value should be somewhere between CLE and MTFR. In 2050, the $PM_{2.5}$ concentration range in the BaU scenario does not overlap with the Net Zero scenario, so no uniform target value is set. Same as the Hainan province in 2035.

Table 1. Scenario setting

Air pollutant control \ Climate target	BaU	Net Zero
CLE	BaU CLE	Net zero CLE
COB	BaU COB	Net zero COB
POLICY	BaU POLICY	Net zero POLICY
MTFR	BaU MTFR	Net zero MTFR

Table 2. $PM_{2.5}$ concentration target in the POLICY scenario

	2025	2035	2050
Fujian	15	12	-
Guangdong	20	15	-
Guangxi	15	11.5	-
Hainan	6.5	-	-
Hunan	26	19.7	-
Jiangxi	18	16	-

2.6 Data sources

The social accounting matrix used to establish the IMED|CGE model is constructed based on the input-output tables of Guangdong, Guangxi, Hunan, Hainan, Jiangxi and Fujian province in 2017[23]. The future population for each province is estimated from the results of provincial projections under the SSP2 pathway in the literature [24].

GDP growth rate for 31 provinces is set as follows. First, we divide China into six regions: North China, Central China, South China, Northeast China, East China, Southwest China, and Northwest China, and calculates the proportion of each region's GDP from 1978 to 2019. North China includes Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia provinces. Central China includes Hubei, Hunan, Henan provinces. South China includes Guangdong, Guangxi, Hainan provinces. Northeast includes China Liaoning, Jilin, Heilongjiang provinces. East China includes Shanghai, Jiangsu, Zhejiang, Shandong, Anhui, Jiangxi, Fujian provinces. Southwest China includes Sichuan, Chongqing, Guizhou, Yunnan provinces. Northwest China includes Xinjiang, Ningxia, Gansu, Qinghai, Shaanxi provinces. Then the Autoregressive Integrated Moving Average model is used to forecast the GDP share of each region from 2021-2060. Taking into account the relevant policies for the revitalization of Northeast China, appropriate adjustments have been made to the trend of the low GDP ratio in the Northeast, while maintaining the sum of the regional ratios to always 1. Next, based on the calculated GDP ratio of each region and the overall growth rate of China which is referred to from the research of the Economic Research Centre of the State Council[25], the GDP growth rate of the six regions can be obtained. Finally, we combined with the ambitions in the 14th Five-Year Plan for each province and downscaled from the regions to the provinces.

Total carbon sinks and negative emissions are estimated at 2.1 billion tons in 2060 in China under the carbon neutrality scenario[26, 27]. We assume emissions per capita in each province will converge, which is around 1.6 tons in 2060 and then set carbon neutral emission constraints for each province.

3. Result

3.1 General socio-economic energy trends towards 2060

Figure 1 shows that in the absence of further climate mitigation policy in the BaU scenarios, 6 provinces' primary fossil energy and carbon emissions will rise continuously as a result of rapid economic growth by 2030. Guangdong has the highest carbon emissions, followed by Hunan, Fujian, Guangxi, Jiangxi, and Hainan province. Along with the transformation of the energy structure, fossil fuel demand begins to decline slowly after around 2030. Electricity consumption continues to increase, by 1.4, 1.9, 1.9, 2.7, 3.4 and 1.1 times in Guangxi, Fujian, Guangdong, Hunan, Jiangxi and Hainan province respectively by 2060. The per capita GDP will rise by around 3.3, 4.3, 4.3, 4.5, 5.4 and 7.4 times respectively in 2060. Carbon emissions will also slowly decline after reaching a peak around 2030. But it's insufficient to meet the carbon neutrality target.

The emission constraints of the carbon neutrality target will drastically reduce the use of fossil fuels, but the per capita GDP will only be slightly affected, falling by 0.1%, 0.6%, 0.9%, 0.7%, 1.0%, and 5.4% in Guangxi, Fujian, Guangdong, Hunan, Jiangxi and Hainan province, separately in 2060. At the same time carbon intensity will be reduced by an additional 6.2%, 11.8%, 7.8%, 10.0%, 5.8% and 4.9% in 2060.

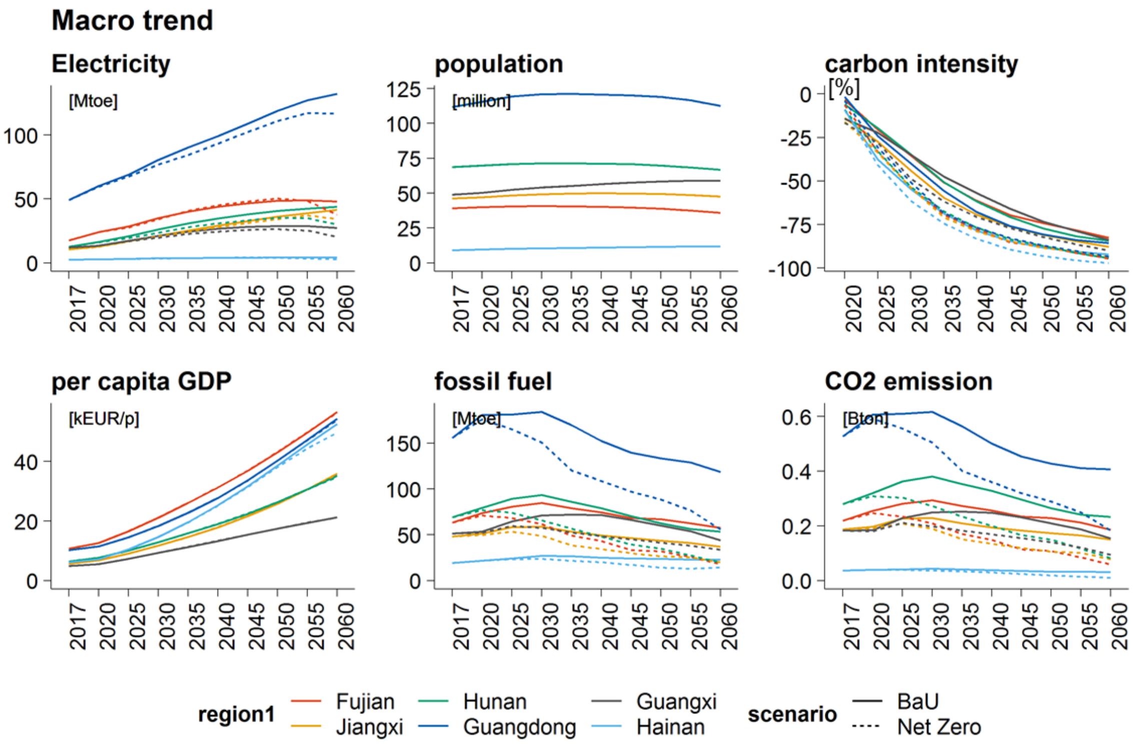

Figure 3. Main social, energy, economic and environmental indicators change trends in Southern China.

Under the BaU scenario, output in 2050 will reach 44120, 33160, 42294, 120965, 27227, and 9694 billion EUROS, in Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Hainan province respectively. Climate mitigation policy will reshape the economic structure. The output of energy-intensive industries will decrease. For instance, the textile sector in Fujian Province will decline by 4.9% in 2050, the paper sector in Jiangxi Province will decline by 5.8%, and the metal smelting sector in Hainan will decline by 21.2%.

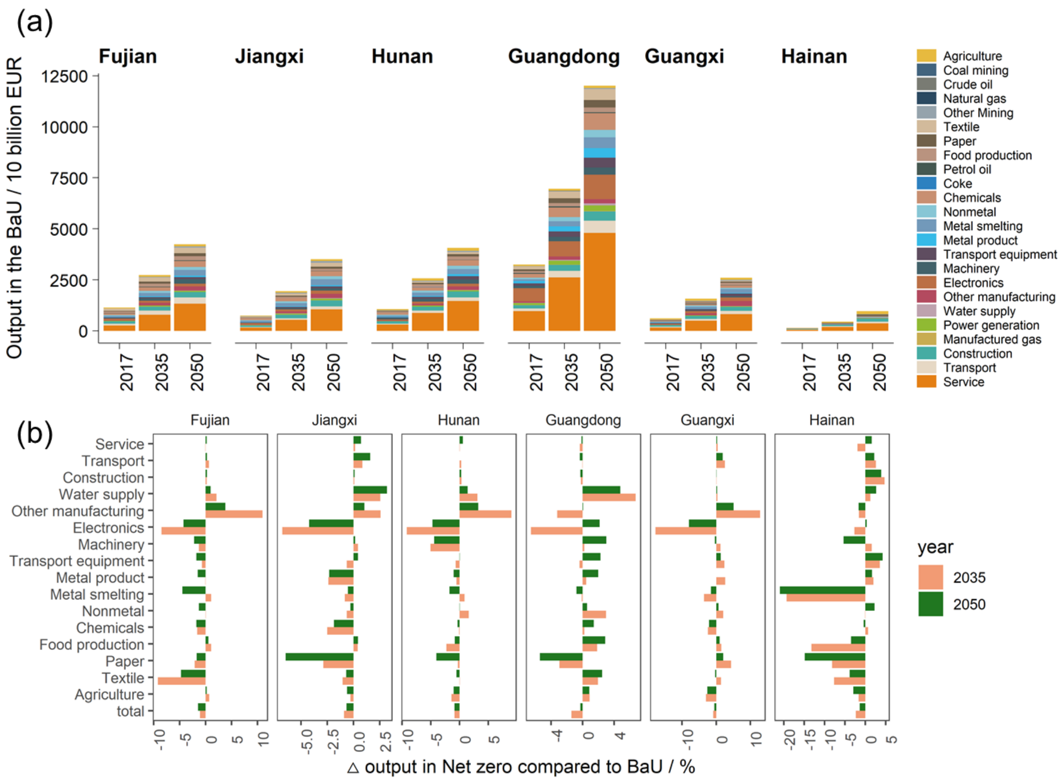

Figure 4. Economic structure: (a) Output in the BaU and (b) output change in the Net Zero scenarios compared to BaU

3.2 Energy structure and CO_2 emissions

The implementation of stringent carbon reduction policies would reshape the energy structure in south China (Figure 5). Primary fossil fuel consumption would peak in 2023,2024, 2022,2022,2026 and 2028 in Fujian, Jiangxi, Hunan, Guangdong, Guangxi and Hainan province separately under the Net zero scenario, 4-8 years ahead of that under the baseline scenario (BaU), and the peak volume would be substantially lower. Under the BaU scenario, final energy demand would increase from 44.5, 39.7, 71.3, 115.9, 49.3 and 9.2 Mtoe in 2017 to 79.2, 69.8, 104.2, 197.7, 62.3 and 12.8 Mtoe in 2060 in Fujian, Jiangxi, Hunan, Guangdong, Guangxi and Hainan province separately; while under the Net zero scenario, the growth would be moderate and electricity would dominate the final energy demand and account for more than 50%). While the total primary fossil energy consumption will decrease by 71.6%, 58.1%, 71.3%, 64.0%, 34.5% and 26.4% by 2060, electricity demand will be 2.3, 3.6, 2.5, 2.5, 1.8 and 1.4 times that of 2017 in Fujian, Jiangxi, Hunan, Guangdong, Guangxi and Hainan province respectively, as compared to 2017.

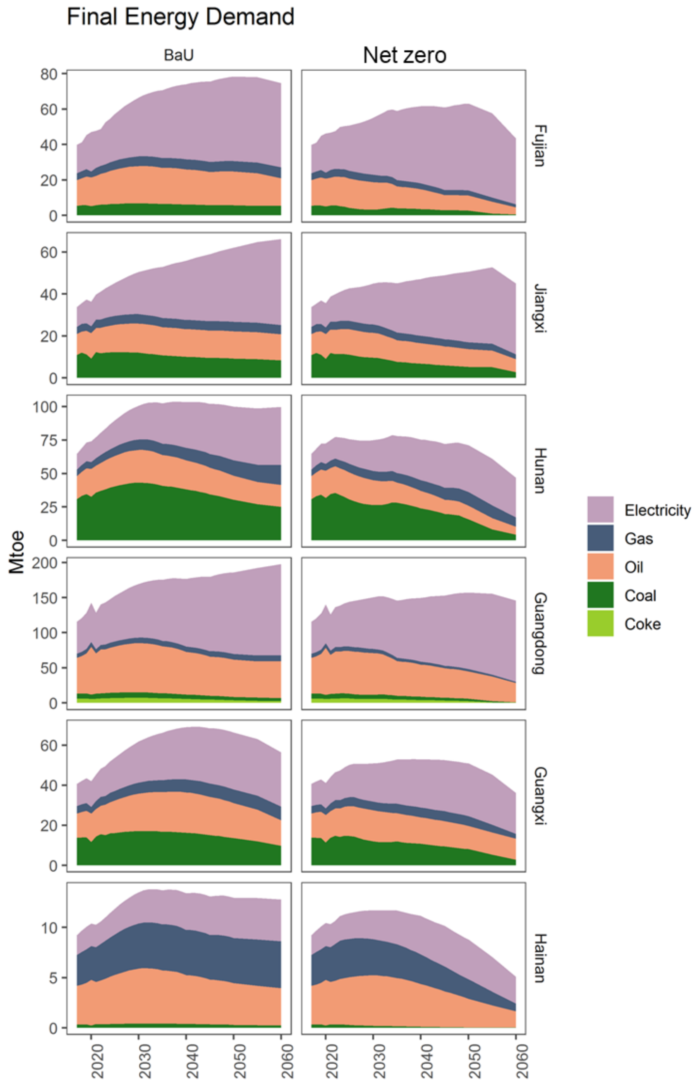

Figure 5. Final energy demand in 6 provinces

In the Net zero scenario, the limited carbon budgets would lead to significant and earlier reductions in CO_2 emission (Figure 6). In the baseline scenario (BaU), CO_2 emissions maintain a rising trend then decline after around 2030. While in the Net zero scenario, CO_2 emissions in south China would peak in 2023, 2024, 2022, 2022,2026 and 2024 in Fujian, Jiangxi, Hunan, Guangdong, Guangxi and Hainan province separately in advance. In the BaU scenario, CO_2 emissions would increase by around 53.2, 21.7, 73.66, 37.3 68.3 and 5.1 million ton in 2035 compared with 2017. In the Net zero scenario, CO_2 emissions would decrease substantially from the base year level by about 49.2, 35.8, 45.9, 126.0, 0.2, 2.5 Million ton in 2035. By 2060, carbon emissions will be reduced to 0.27, 0.42, 0.0, 0.35, 0.52 and 0.30 times of 2017. The decarbonization of the power generation is the main contributor, following by metal smelting in Fujian, Jiangxi, Guangxi, other manufacturing in Hunan, transportation in Guangdong and chemicals in Hainan.

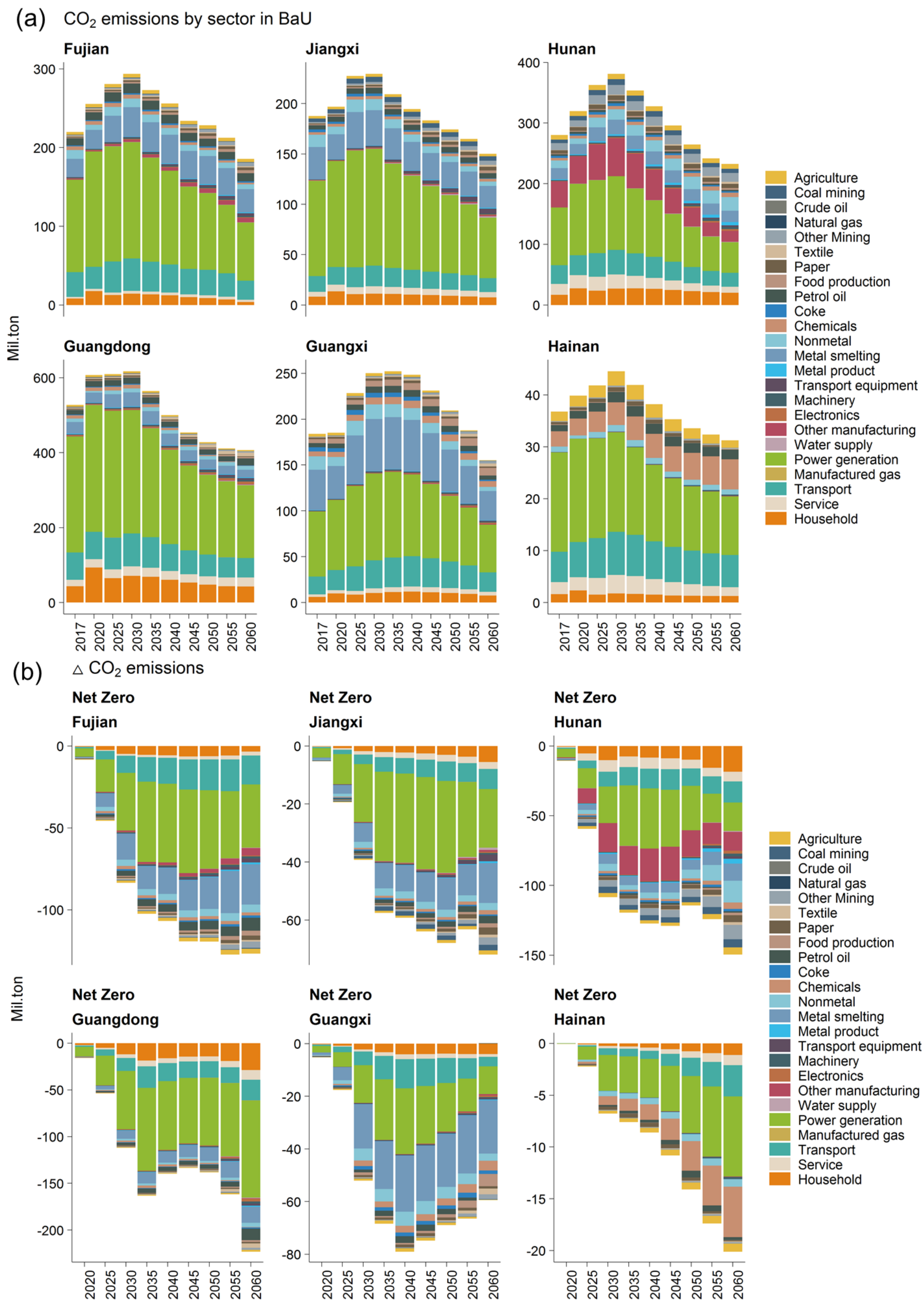

Figure 6. (a) CO_2 emissions by sector in BaU and (b) CO_2 emission change in Net Zero compared to BaU

3.3 Air pollutant emissions

The additional emission reductions required to achieve the air quality targets (POLICY) in the Net zero scenario are significantly less than in the BaU scenario (Figure 8). For example, to achieve $PM_{2.5}$ concentration of 15ug/m^3 in 2035 in Guangdong Province, reductions of 108.4, 314.5, 413.8 and 205.2 kilotons of PM, NH_3, NO_X and SO_2 respectively are required under the BaU scenario, while only 10.7, 19.2, 24.3 and 0.1 kilotons respectively are required under the Net zero scenario with the cleaner energy mix.It's also found that air pollutant reductions are greater in 2035 than in 2025 in the BaU scenario and vice versa in the Net zero scenario, which means that over time more end-of-pipe control measures are needed in the BaU scenario. The diminishing gap between CLE and MTFR in the Net zero scenario implies a reduction in end-of-pipe control potential as the energy mix becomes cleaner.

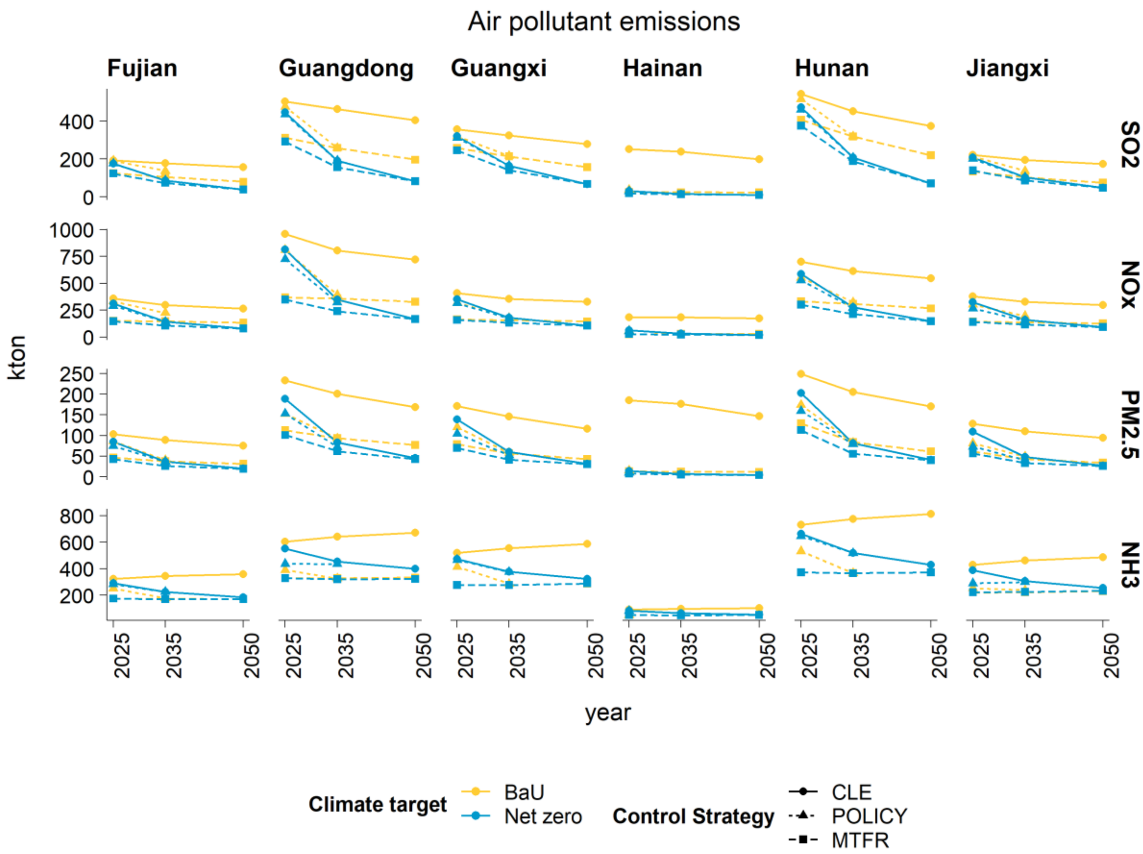

Figure 7. Air pollutant emissions in different scenarios

From the perspective of the sector, the main contributors to primary $PM_{2.5}$ emissions vary between years and scenarios, with power generation, residential and services and transport accounting for 32.5%, 20.3% and 19.1% of total emissions reductions in 2025 under the BaU scenario, while residential and services, industrial processes and transport become the main contributors under the Net zero scenario. The agricultural sector is the main control sector for NH_3, accounting for over 91% of the total emission reductions. The transport sector is the main control sector for NOx, followed by industrial processes. The industrial sector is the main sector for SO_2 reduction, but in Hainan it is the power sector.

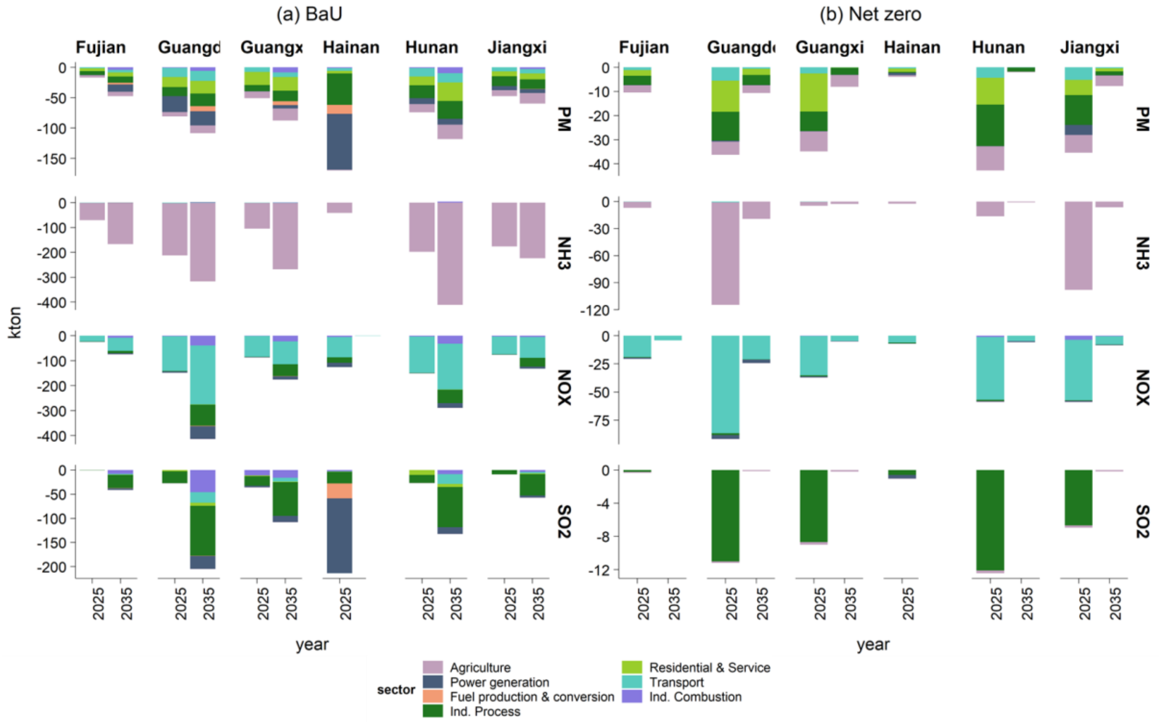

Figure 8. △Emissions in CLE compared to POLICY in (a) BaU and (b) Net Zero.

3.4 Air quality and control cost

In the BaU scenario, all regions in 2050 would not be able to achieve $PM_{2.5}$ concentrations at the current level of control measures (CLE) in the Net zero scenario, even with the maximum feasible control measures (MTFR) (Figure 9(a)). This indicates the limited potential for end-of-pipe control. With the current level of control measures (CLE) in the BaU scenario, there is a risk of increased pollution in Guangdong and Hainan provinces by 2025. Except for Hainan Province, the other five provinces are unable to reach the WHO 4th interim target value of 10 $\mu g/m^3$ by 2050 with the maximum technically feasible reduction (MTFR). Even Hunan Province will reach 18.1 $\mu g/m^3$ in 2050. Under the current control measures (CLE), the gap between BaU and Net zero is getting bigger and bigger (except Hainan Province); under the carbon neutrality scenario (Net Zero), the difference in $PM_{2.5}$ concentration under different control measures is gradually narrowing. This also reflects the important impact of energy structure and fossil energy consumption on air pollution. From the perspective of geographical distribution, most areas of central Hunan Province, central Jiangxi and southern Guangdong are more polluted (Figure 9(b)).

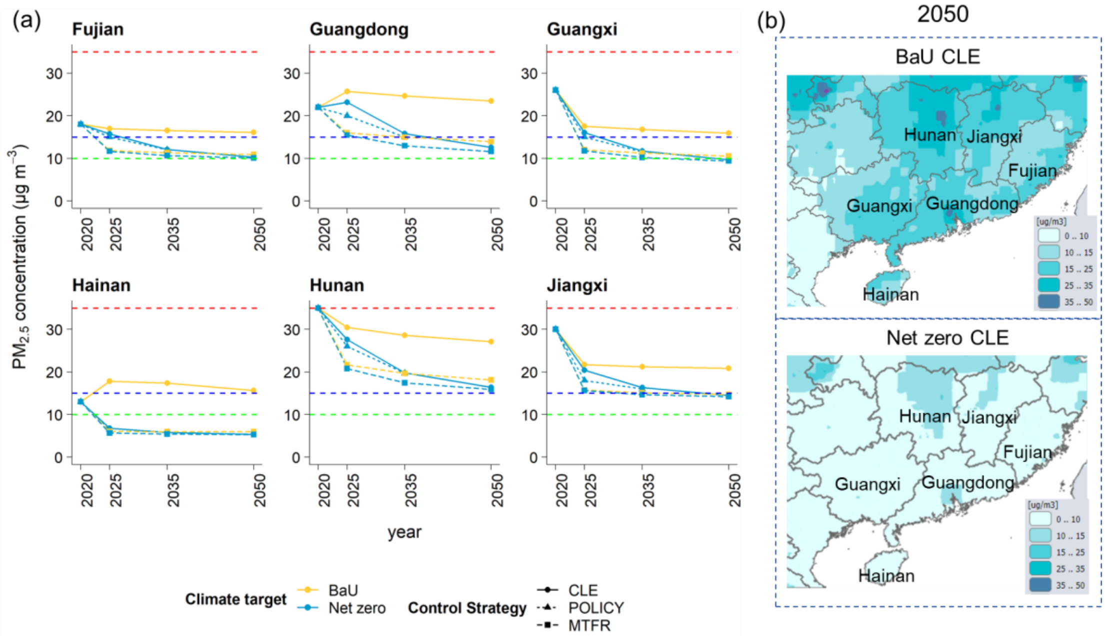

Figure 9. $PM_{2.5}$ concentration: (a) Population-weighted $PM_{2.5}$ concentration in different scenarios in line;(b) and $PM_{2.5}$ concentration in BaU CLE and Net zero CLE scenarios in 2050.

By 2035 in Net zero scenario with air quality (POLICY), Hunan will replace Guangdong as the province with the highest control cost, followed by Guangdong, Jiangxi, Guangxi and Fujian province. Hainan will always have the lowest control cost. To achieve the air quality target(POLICY) under the BaU scenario by 2025, the control costs of Fujian, Guangdong, Guangxi, Hunan and Jiangxi will be 1.7%, 3.0%, 4.5%, 4.6% and 8.2% higher than the COB scenario, respectively (Figure 10). While in the Net zero scenario, it is only 0.2%, 1.1%, 0.8%, 0.7% and 4.5% higher than BaU COB scenario, which could save 44.0, 156.4, 103.5, 182.6 and 86.8 MEUR. In 2035 under the BaU scenario, similar to 2025, to achieve the POLICY target, the control costs of Fujian, Guangdong, Guangxi, Hunan, and Jiangxi are 10.8%, 37.5%, 33.9%, 73.2% and 19.0% higher than the BaU COB scenario, respectively, while under the Net zero scenario, they are only 0.0 higher 0.01 %, 0.2%, 0.05%, 0.001% and 0.3%, can save about 315.6, 3205.4, 924.2, 3221.7 and 419.9 MEUR.

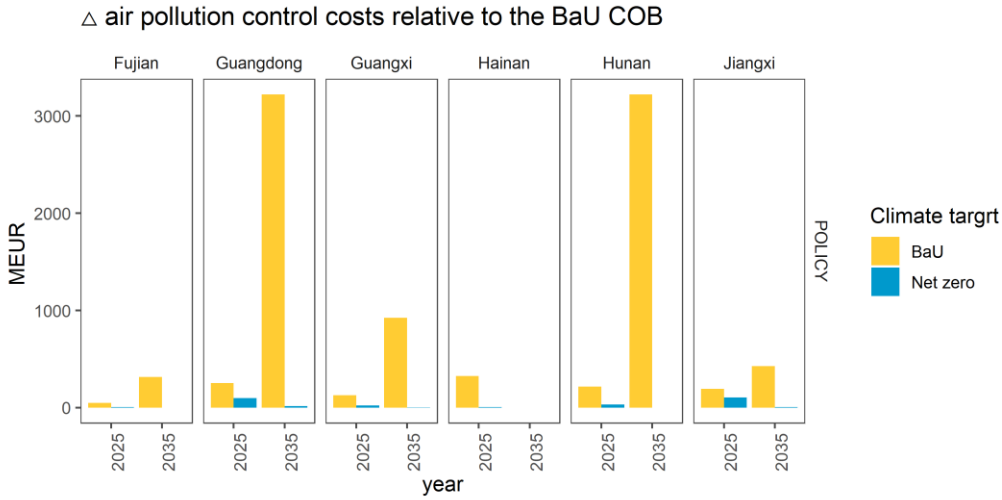

Figure 10. Change in control cost in POLICY scenario compared to BaU COB

From the perspective of sectors (Figure 11), the transportation and power generation sectors have the highest control costs. In addition, the cost of industrial processes in Hunan Province is relatively high which accounts for 18.9% and 19.6% in BaU POLICY and Net zero POLICY in 2035 respectively. Under the MTFR scenario, transportation, industrial processes, and agriculture can achieve further emission reductions while the cost of emission reductions is much higher. In the COB scenario by optimizing control measures, the transportation can save control costs most including upgrading motor vehicle emission standards. In the Net zero scenario with a cleaner energy structure, the power sector can save control costs.

Figure 11. Control cost: (a) control cost share; (b) control cost change by sector compared to BaU COB

3.5 Health impact assessment

Under the baseline scenario with current legislation control measures (BaU CLE), air pollution would result in approximately 3.6, 2.3 and 2.8 million incidences of diseases in 2025, 2035 and 2050 respectively in all six provinces, with upper respiratory tract infections being the main cause, followed by asthma and chronic bronchitis Figure 12(a). While achievement of the air quality target (POLICY) would avoid a significant number of incidences of diseases caused by $PM_{2.5}$ exposure and in 2035, 0.14, 0.19, 0.49, 0.86 and 0.21 million incidences of diseases could be avoided in Fujian, Jiangxi, Hunan, Guangdong and Guangxi provinces respectively. In 2050, the carbon neutrality target constraint, comparing Net zero CLE and BaU CLE, would avoid an additional 0.17, 0.22, 0.54, 0.94, 0.21 and 0.03 million incidences of diseases in Fujian, Jiangxi, Hunan, Guangdong, Guangxi and Hainan Provinces.

Figure 12(b) shows the number of premature deaths due to $PM_{2.5}$ pollution using the exposure-effects function of the non-linear GEMM exposure-response function[22] in the IMED|HEL to estimate mortality from five diseases caused by $PM_{2.5}$ including ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), lung cancer and lower respiratory infection (LRI). Among the causes, ischemic heart disease leads to most $PM_{2.5}$-related premature mortality, followed by stroke. Achieving the $PM_{2.5}$ concentration targets in the POLICY scenario in 2025 compared to the current legislation (CLE) control level, the implementation of end-of-pipe control policies can avoid 2.42 (95% Confidence Interval, CI95: 1.6-3.1), 4.9 (CI95: 3.2-6.2), 7.3 (CI95:4.9-9.0), 16.4 (CI95:10.9-20.5), 3.9 (CI95:2.5- 4.9) and 0.7 (CI95:0.5-0.9) thousand premature deaths in Fujian, Jiangxi, Hunan, Guangdong, Guangxi and Hainan separately; and 5.9 (CI95:3.9-7.6), 7.1 (CI95:4.6-9.0), 15.8 (CI95:10.5-19.7), 30.6 (CI95:20.2-38.8), 8.5 (CI95:5.6-11.0) and 1.1 (CI95: 0.7-1.3) thousand separately in 2035. Climate mitigation would also result in significant population health benefits. At current levels of control measures (CLE), a total of 17.5 (CI95: 11.6-21.8), 64.9 (CI95: 42.9-82.3) and 80.8 (CI95: 53.2-103.1) thousand premature deaths would be avoided in 2025, 2035 and 2050, respectively, in all six provinces of the Net zero scenario compared to the BaU scenario.

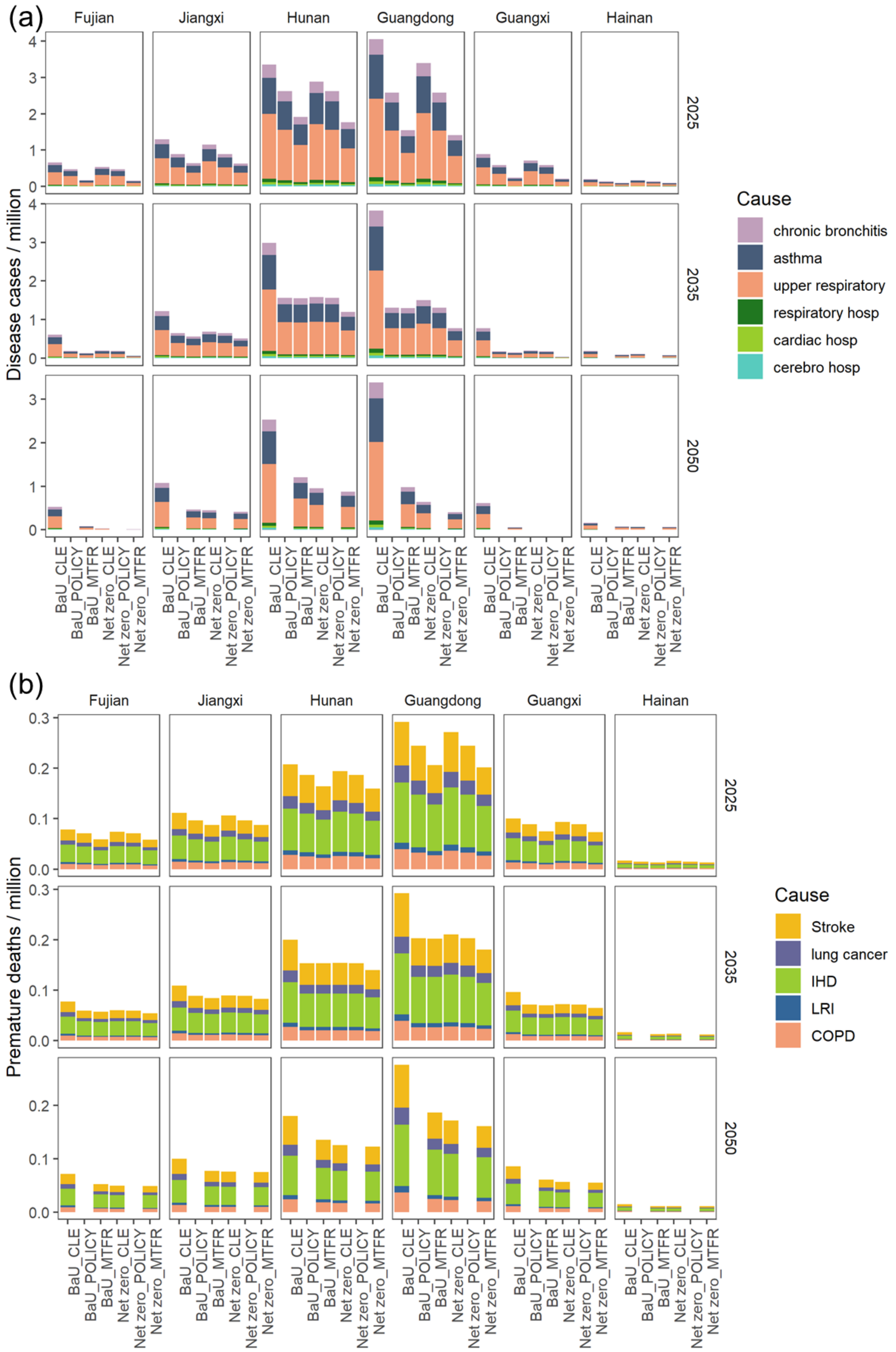

Figure 12. $PM_{2.5}$-related health burden: (a) cause-specific disease risks; (b) cause-specific premature deaths.

4. Discussion

4.1 Cooperation and transboundary effect

Regional joint prevention and control have become a key mechanism for air quality improvement in recent years in China. To examine the impact of transboundary and regional cooperation effect, we also set up a scenario in which only the Guangdong province achieves carbon neutrality and the other regions do not have carbon emission constraints, and thus simulate the changes in $PM_{2.5}$ concentrations. The results show that under the current level of control measures (CLE), $PM_{2.5}$ concentrations in Guangdong Province will decrease by 0.2, 0.4 and 0.5ug/m^3 in 2025, 2035 and 2050 respectively, compared to the scenario where all six regions achieve carbon neutrality target. Given the range of uncertainties in the simulation itself, we do not consider the transboundary impact to be significant. This may be due to the fact that $PM_{2.5}$ pollution is not as severe in southern China. The cooperation and transboundary effect may be more significant in other more heavily polluted regions in China such as the Beijing-Tianjin-Hebei region.

4.2 Limitation

The interaction between carbon emission reduction and air quality improvement has not been clarified in this study, and we have only considered the co-benefits of climate policies on air pollution improvement without conversely quantifying the synergistic effects of air control policies on carbon reduction. Xing et al[28] found that the quest for improved air quality is likely to drive China to continue to reduce its CO_2 and go beyond the Paris Commitment. In addition, the implementation of control measures can also promote investment and economic growth. The control cost can be further put back into CGE model to systematically assess the economic impact of air pollution control.

4.3 Policy implication

Our study on the green transformation pathways for reducing air pollution and CO_2 in southern China can provide useful insights not only in these six provinces but also in other regions of China. Carbon neutrality requires a rapid and profound transformation of the energy system, active measures to reduce carbon through energy efficiency improvements and non-fossil energy, and enhanced management of capacity regulation in key industries. For further air quality improvement quest, the emission reduction potential of end-of-pipe control measures is limited, making it more difficult to meet more stringent air quality standards. Our case studies show that it is possible to achieve multiple green growth targets at the same time. In the carbon neutrality scenario, not only can pollutant control costs be reduced, but significant health benefits can also be achieved. Policymakers should therefore combine air quality objectives with low-carbon development objectives when developing regional blueprints for green transformation, thus achieve an organic alignment of air pollution and carbon reduction management.

5. Conclusion

Using on the integrated assessment framework, this study evaluates the pathways to achieve the carbon neutrality and air quality target. We found that without further climate mitigation policies under the BaU scenario, the carbon emissions of the six southern provinces in China by 2050 will be 0.8 to 1.1 times the level of 2017. To achieve carbon neutrality, major changes in both the economic structure and the energy system will be required, including optimizing the industrial structure, improving energy efficiency and increasing the proportion of non-fossil energy and electricity. SO_2, NO_x, $PM_{2.5}$ emissions would gradually decrease and NH_3 may even increase in the baseline (BaU). Correspondingly, under the current control measures (CLE) all 6 provinces cannot achieve NAAQS I (15ug/m^3) by 2050. Only by implementing the strictest control measures (MTFR) can it be possible to approach the air quality level under the carbon neutrality scenario, which will increase the control cost by 1.2, 0.8, 2.2 and 3.0 times in Fujian, Guangdong, Guangxi and Jiangxi provinces respectively as compared to BaU COB. While in the Net zero, Fujian, Guangxi, and Hainan are expected to reach the 10ug/m^3 under the CLE. The additional emission reductions required to achieve the air quality targets (POLICY) in the Net zero scenario are significantly less than in the BaU scenario.

To achieve the specific air quality target (POLICY) under the BaU scenario by 2025, the control costs of Fujian, Guangdong, Guangxi, Hunan and Jiangxi will be 1.7%, 3.0%, 4.5%, 4.6% and 8.2% higher than the COB scenario, respectively. While in the Net zero scenario, it is only 0.2%, 1.1%, 0.8%, 0.7% and 4.5% higher than BaU COB scenario, which could save 44.0, 156.4, 103.5, 182.6 and 86.8 MEUR. The contribution of end-of-pipe measures will gradually decrease as the energy structure become cleaner in the carbon-neutral scenarios. In the long term, the transition of the transportation, industrial and energy structure in line with the carbon neutrality target would lay an important foundation for further improvements in air quality. That large numbers of PM2.5-related premature deaths could be avoided by implementing more stringent end-of-pipe controls, as well as by deep carbon mitigation in the long term.

Acknowledgments

Part of the research was developed in the 2021 Young Scientists Summer Program at the International Institute for Applied Systems Analysis with financial support from the National Natural Science Foundation of China.
After more than three months' work, the YSSP project is nearing its end.The author sincerely thanks Dr. Fabian Wagner and Prof. Shaohui Zhang for their attentive supervision and invaluable contributions throughout the project. The goodwill of the whole ECE group and the highly professional scientific environment at IIASA prompted me to finish the research in such a short time. The author also expresses her gratitude to her home supervisor, Prof. Hancheng Dai, for important support and encouragement. The achievement and results also reflect the continuous discussions we had during the whole summer. Special thanks for the support from all IIASA' staffs, especially Ms. Tanja Huber who provided a lot of helps for us and made the meaningful scientific and social events in this unforgettable summer.

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