CO-BENEFITS BETWEEN AIR QUALITY AND CLIMATE POLICIES IN GUANGDONG AND SHANDONG PROVINCES IN CHINA

By Center for Global Sustainability (CGS) at the University of Maryland and Department of Earth System Science at Tsinghua University

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List of Acronyms and Abbreviations

Acronym/Abbreviation	Stands For
BAU	Business as Usual
BECCS	Bioenergy with Carbon Capture and Storage
BHE	Best Health Effects
CCUS	Carbon Capture, Utilization and Storage
CO_2	Carbon Dioxide
CSG	China Southern Power Grid
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicles
FYP	Five-Year Plan
GDP	Gross Domestic Product
GHG	Greenhouse Gas
LUC	Land Use Change
NEA	National Energy Administration
NO_x	Nitrogen Oxides
PM	Particulate Matter
PM_{10}	Particulate Matter (diameter < 10 micrometers)
$PM_{2.5}$	Particulate Matter (diameter < 2.5 micrometers)
PV	Photovoltaics
SO_2	Sulfur Dioxide
VOCs	Volatile Organic Compounds
WHO	World Health Organization

Unit	Stands For
GW	Gigawatt
m^3	Cubic Meter
Mt	Million Tonnes
TWh	Terawatt-Hour
μg	Microgram

1. Introduction

China is engaged in the dual challenge of both improving air quality and reaching ambitious climate targets. While both air quality and climate change present significant difficulties, research suggests that coordinated and combined efforts to tackle both problems can maximize benefits. This report examines the co-benefits of air quality improvement from climate mitigation in China, with a focus on two provinces: **Guangdong and Shandong**. Both provinces have large gross domestic products (GDP) and populations, but vary in terms of the underlying economic and energy structure, dependence on fossil fuels and current levels of air pollution. By assessing their pathways toward carbon neutrality and air quality improvement, we identify specific strategies and policy opportunities that focus on co-reducing carbon dioxide (CO_2) and $PM_{2.5}$ concentration in each province, which can provide insights for other provinces that share similar opportunities and challenges. This report also identifies key provincial and sectoral policies for achieving both policy outcomes.

China faces both air quality health concerns and the challenge of mitigating greenhouse gas (GHG) emissions to reduce the threat of worsening impacts from climate change. In 2017, particulate matter (PM) was one of the top four leading risk factors related to deaths and disability-adjusted-life-years in China (M. Zhou et al., 2019). Using data from the Global Burden of Diseases (GBD) injuries and risk factors database, researchers found that 1.24 million people died in China in 2017 as a result of air pollution exposure (Yin et al., 2020). While air quality related deaths have been decreasing due to increased policy efforts in China, additional action is needed to achieve national air quality targets and limit impacts to human health (Yin et al., 2020). China has already started to experience some impacts from climate change, as surface temperatures across the country have been rising since the 20th century, which can lead to increased heat waves and extreme weather events such as flooding and droughts and impact agriculture and livestock yields (Shaw et al., 2022).

China's commitments to climate change mitigation and air quality improvements present an important opportunity for coordinated action toward both policy outcomes. These targets include the "30-60" decarbonization goal, which aims for China to achieve peak carbon dioxide (CO_2) emissions before 2030 and carbon neutrality before 2060, and the "Beautiful China" air quality strategy, which seeks to limit $PM_{2.5}$ concentration to an annual mean concentration of 35 $\mu g/m^3$ or below by 2035 (United Nations, 2021; Xing et al., 2020). China's current $PM_{2.5}$ target is less stringent than 10 $\mu g/m^3$, the World Health Organization (WHO) Phase IV recommended value, which underscores the need for continued air quality improvement efforts even beyond committed policy targets

(World Health Organization, 2021). Toward this policy goal, China has made significant progress in reducing air pollutant emissions since 2012, largely by strengthening end-of-pipe control of emissions and to a lesser extent through energy transition and economic structure changes (Geng et al., 2021). Recently, more diverse and flexible solutions for improving air quality have been adopted, such as involving non-state actors, both top-down and bottom-up policies and market-based solutions (P. Wang, 2021). However, as reduction potential through end-of-pipe controls is exhausted in the near term, the low-carbon transition becomes critical to achieve China's long-term air quality improvement (Cheng et al., 2021).

Research has extensively shown that there are strong synergies between global climate mitigation and local air quality improvement (Aunan et al., 2006; Scovronick et al., 2019; Yamineva & Liu, 2019), but the outcomes may vary, depending on specific mitigation technologies and strategies deployed. For example, bioenergy or carbon capture, utilization and storage (CCUS) technology, while reducing GHG emissions, may potentially exacerbate some air quality impacts due to continued use of fossil fuels or additional energy inputs (Koornneef et al., 2011). Maximizing the synergy between air pollution and carbon reduction requires taking into account air pollution emissions reduction when selecting carbon emissions reduction measures (Q. Zhang et al., 2023). This suggests that an integrated understanding and approach of GHG and air pollutant emissions reductions can help achieve both policy goals more effectively.

Moreover, both the low-carbon transition and air quality improvement require province-specific analysis and strategies. The pathways towards net-zero greenhouse gas emissions also vary across provinces, depending on both the existing energy and economic structure but also the potential to transform (Nilsson et al., 2021). Provinces and cities in China are heterogenous and require different climate actions and low-carbon transition strategies (P. Wang et al., 2021). Air quality and associated public health issues also have large regional variations, due to factors such as different climates, energy systems, and population concentration and demographic features (H. Chen et al., 2020; Y. Chen et al., 2013). While air pollution decreased nationally from 2014-2018, some regions, such as Beijing, Tianjin, Hebei and Shandong provinces, still face air quality concerns (H. Chen et al., 2020). As of 2017, 64% of China's 338 prefecture cities did not meet nationally-set $PM_{2.5}$ standards (Q. Zhang et al., 2019), suggesting both that additional action is needed to meet pollution targets across the country, and that air quality varies across regions. Therefore, a regional, localized approach may help meet national policy targets (P. Wang et al., 2021).

Subnational actors not only have an opportunity to participate in national climate ambition, but can also be drivers of enhanced action. Limitations of China's traditional state-centric model for accomplishing increasingly challenging environmental objectives have been identified, and policymakers have become more receptive to non-state actors' involvement in policy-making, including market and civil society actors (P. Wang, 2021). Non-state actors can help to increase ambition of national policies, by testing new mitigation technologies or strategies and exchanging best practices across state and non-state actors (Hsu et al., 2018). Action at the subnational and local level is explicitly mentioned in the Paris Agreement (United Nations, 2015) as a key area for capacity-building and adaptation. Air quality and public health improvement can provide a strong motivation for local governments to take enhanced actions on climate mitigation, especially in the near term. Research suggests that local health impacts, such as from the COVID-19 pandemic, can be motivation for policy action (Vandyck et al., 2021). An integrated strategy that can help achieve dual goals will provide stronger motivation for enhanced action at the local level and for delivering the national targets.

Evaluation of the energy system transition at the subnational level, as well as the regional and local air quality co-benefits that would result from mitigation, is needed to better understand the co-benefits from air quality and climate mitigation strategies in China. Previous research has evaluated air quality implications for China under various climate mitigation scenarios (Cai et al., 2018; Cheng et al., 2021; Tang et al., 2022; Y. Wang et al., 2022), but few studies have investigated sub-national impact and action (L. Zhang et al., 2022; W. Zhang et al., 2020). This report evaluates how different policy pathways impact carbon emissions and air pollution in two key provinces, as well as identifies sectoral and provincial policies for achieving decarbonization and air quality co-benefits. We ranked all provinces based on fossil fuel dependency, air pollution, and economic development, and selected two key provinces that could represent examples of two different mitigation and development pathways in China, Guangdong and Shandong (see Technical Appendix for further details). Guangdong and Shandong both have significant CO_2 and air pollution impacts due to their large economies and population sizes, but they diverge in terms of fossil fuel dependence, current air quality, and size of gross domestic product (GDP) per capita. Section 2 highlights some key national, regional, and sector specific policies China has already implemented to address air pollution and climate mitigation goals. Section 3 discusses the methods utilized to develop our mitigation pathways and air quality simulations. Section 4 discusses decarbonization strategies, sector-specific implications for all of China, Guangdong and Shandong. Section 5 discusses air pollutant concentration and ambient air pollutant health co-benefits in Guangdong and Shandong. Section 6 discusses policy implications for Guangdong and Shandong. Section 7 outlines conclusions and areas of future research.

2. Air Quality and Mitigation Policies

2.1. National Air Quality and Climate Change Mitigation Efforts

In the 12th Five-Year Plan (FYP), significant air quality policies were implemented, particularly the Air Pollution Control Action Plan in 2013 (The State Council, 2013a). In recent years China has implemented ambitious national policies to reach climate mitigation and air quality goals, including the "30/60" climate mitigation goals and the updated 2035 $PM_{2.5}$ concentration target. The most recent FYP, the 14th Comprehensive Work Plan for Energy Conservation and Emissions Reduction, which is set to conclude in 2025, includes benchmarks for a 13.5% reduction in energy consumption relative to 2020 values, as well as reduction in chemical oxygen demand (COD), ammoniacal nitrogen (NH_3-N), nitrogen oxides (NO_x) and volatile organic compounds (VOCs) by 8% to over 10% across pollutants, compared to 2020 values (The State Council, 2022). The 14th FYP builds upon the 13th FYP, which sets benchmarks for reduction in energy intensity and consumption, while limiting ammonia (NH_3), sulfur dioxide (SO_2), and NO_x emissions (The State Council, 2017). The 13th FYP further included a Volatile Organic Compound Pollution Prevention and Control Work Plan, which sought to reduce VOCs emissions by 15% by 2020 relative to 2015 levels (Agency of Environmental Protection & General Administration of Quality Supervision, Inspection and Quarantine, 2013). Additionally, policies such as the Three-Year Action Plan for Making China's Skies Blue Again explicitly mention reducing emissions from air pollutants in conjunction with greenhouse gas emissions, highlighting that China is taking steps to integrate air pollution and climate change policies (The State Council, 2018b). Additionally, several sectoral policies have been enacted that target GHGs and/or air pollutants across specific sectors (Table 2.1).

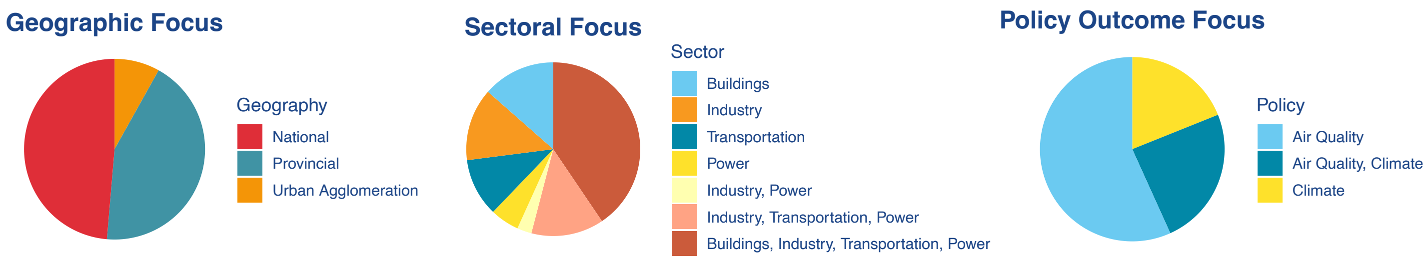
To get a sense of the make-up of policies across actors, sectors and focus areas and identify gaps, we evaluated 37 collected policies from 2012 to 2022 (Figure 2.1). The air pollutants in this analysis include $PM_{2.5}$, as well as $PM_{2.5}$ precursors NO_x, SO_2, and VOCs, which are mainly from fossil fuel-fired boilers in the industry sector, fossil fuel-fired power plants in the power sector, automobile exhaust in the transportation sector, and heating in the building sector (Liu et al., 2016). Around half of existing policies that we reviewed were at the national level, with the remaining policies coming from mostly from the provincial level, and a few urban agglomerations (ie: Beijing-Tianjin-Hebei area, Pearl River Delta, Yangtze River Delta). Policies were largely focused on the power, industry and transportation sectors, with fewer policies focused on the building sector. The majority of the policies we reviewed focused on more than one sector, suggesting that the multiple policy outcomes and objectives are being considered. In terms of policy objectives, the majority evaluated were air quality policies, which we defined as only targeting air pollutants via end-of-pipe control measures, not including any explicit energy or emissions target. Some policies considered both air quality and climate, which were defined as explicitly targeting energy use or GHG emissions reduction and air pollutant emissions reduction. This review of several recent policies suggests that while there is a pretty even split across policy actors with

TABLE 2.1: NATIONAL SECTORAL GHG AND/OR AIR POLLUTANT POLICIES.

Sector	Policy	Key outcomes
Buildings	Assessment Standard for Green Buildings (Ministry of Housing and Urban-Rural Development, 2006, 2014, 2019)	• Develop indoor air quality standards • Controls on materials used for civil construction projects
	Standard for Indoor Environmental Pollution Control of Civil Building Engineering (Ministry of Housing and Urban-Rural Development, 2018, 2020)	• Reduce energy consumption • Increase energy efficiency • Facilitate the low-carbon green development of the civil buildings
Industry	Industrial Green Development Plan (Ministry of Industry and Information Technology, 2016)	• Decrease emission intensity of carbon and air pollutants • Increase energy efficiency • Increase resource utilization • Improve green manufacturing system
	Implementation Plan for the Green Development Special Action of the National High-tech Zone (Ministry of Science and Technology, 2021)	• Transform towards pollution reduction and green industrial and high-tech development
Transportation	Air Pollution Prevention and Control Action Plan (The State Council, 2013b)	• Promote intelligent traffic management • Alleviate urban traffic congestion • Increase the proportion of public transport
	Technical Guidance for Motor Vehicle Pollution Prevention and Control (He & Li, 2018; Ministry of Ecology and Environment, 2017)	• Tighten emission limits for newly produced motor vehicles • Strengthen control of unconventional pollutants from motor vehicles • Promote the development of motor vehicles in a green, low-carbon and sustainable direction.
	Limits and Measurement Methods for Emissions from Light-duty Vehicles (Ministry of Ecology and Environment, 2016)	• Specify the requirements and judgment methods for light-duty vehicle pollutant emission requirements, production consistency and in-use compliance inspection
	Measures on Parallel Administration of Passenger Car Enterprise Average Fuel Consumption and New Energy Vehicle Credits (Ministry of Industry and Information Technology et al., 2017)	• Improving the energy saving of passenger cars • Alleviate energy and environmental pressure • Establish a long-term mechanism for the management of energy saving and new energy vehicles • Promote the healthy development of the automobile industry
Power	Recommendations on Comprehensively Strengthening Protection for Ecological Environment and Against Pollution (The State Council, 2018a)	• Transform and retire coal-fired power plants

FIGURE 2.1: NATIONAL AND SUBNATIONAL AIR QUALITY POLICIES.

Categorized by spatial reach, sector, and type.



many cross-sector policies, most of the policies we reviewed are focused on air quality and end-of-pipe controls, not energy transition or climate mitigation. This analysis is preliminary and limited by the time period we evaluated and the number of policies we identified. More extensive review of policies across all levels of government, sectors and policy outcomes is needed to fully identify policy gaps. See our technical appendix for additional information on our analysis.

2.2. Guangdong and Shandong: Current Emissions Levels and Policies

Assessing pathways toward carbon neutrality and air quality improvement at the subnational level is needed to identify policy mechanisms that focus on co-reducing GHG and air pollutant emissions. Subnational policies can have positive outcomes for both policy objectives as, for example, the Air Pollution Prevention and Control Action Plan, which set PM_{10} and $PM_{2.5}$ concentration limits in the Beijing-Tianjin-Hebei area, Pearl River Delta, and the Yangtze River Delta, was largely successful in reducing emissions, improving $PM_{2.5}$ air quality, and reducing mortality in these highly polluted areas (Q. Zhang et al., 2019). In this research, we will focus on Guangdong and Shandong provinces, and evaluate policies and pathways for decarbonization and air quality improvement, which can provide insights for other provinces that share similar opportunities and challenges.

Guangdong and Shandong both have significant CO_2 and air pollution impacts due to their large economies and population sizes, but they diverge in terms of fossil fuel dependence, current air quality, and size of gross domestic product (GDP) per capita. Both provinces represent examples of two different mitigation and development pathways in China. Current emission levels of air pollutants and carbon dioxide emissions vary across the two provinces. The 2020 annual average $PM_{2.5}$ in Guangdong was 22 μg/m^3 (Department of Ecology and Environment of Guangdong Province, 2021a), and 46 μg/m^3 in Shandong (People's Government of Shandong Province, 2021). Guangdong and Shandong have different climates, leading to differences in energy needs for heating and cooling and atmospheric dispersal conditions. Guangdong and Shandong have the 1st and 3rd largest GDPs and the 1st and 2nd largest populations, respectively, but vary in terms of the underlying economic and energy structure, as the 5th and 1st highest CO_2 emitting provinces, respectively (Carbon Emission Accounts and Datasets, 2023; Guan et al., 2021; National Bureau of Statistics, 2020; Shan et al., 2020). CO_2 emissions in Shandong are nearly twice as much as Guangdong, as the two provinces emitted around 940 and 570 $MtCO_2$ in 2019, respectively (Carbon Emission Accounts and Datasets, 2023; Guan et al., 2021; Shan et al., 2020). Their industrial makeups and economic structures vary (see appendix for details), and require different decarbonization and air pollutant reduction strategies (Yuan and Zhou, 2021; Zhang, 2017; Zhao, 2015).

Both provinces have started to implement climate mitigation and air quality improvement actions. During the 13th Five-Year Plan period in Guangdong, the CO_2 emissions per unit of GDP decreased 25.5% from 2015 to 2020 (People's Government of Guangdong Province, 2022a). Its 100-day service actions and sprints target key sources of air pollutants emissions, including VOCs-producing businesses, storage depots, tanker trucks, and gas stations; pollution sources of motor vehicle, dust, open burning, and industrial waste gas emissions; the use of unqualified refined oil diesel vehicles and other acts; industrial kiln emissions, site dust, and road dust (Department of Ecology and Environment of Guangdong Province, 2021b). Also, the Guangdong Province Carbon Peak Implementation Plan includes both air quality and climate mitigation initiatives (People's Government of Guangdong Province, 2022b). In terms of climate mitigation, Shandong's installed capacity of renewable energy increased by 17.7% from 2015 to 2020, and the installed capacity of solar and biomass generation ranked first around the country, and Haiyang City[1] has become the first zero-carbon heating city in China by using nuclear power (Energy Administration of Shandong Province, 2022; B. Zhou, 2022). Measures to reduce air pollution include the development of steel enterprises ultra-low emissions differential tariff policies, ultra-low emissions transformation of steel enterprises, and comprehensive treatment and upgrading for VOCs-related enterprises. In 2020, 14,000 dust sources were dealt with dust suppression measures, city and county highway machine sweeping rates were established, and more than 190,000 diesel trucks with National III or lower emissions standards were phased out (People's Government of Shandong Province, 2021).

Although both provinces have begun to take actions to address these key policy issues, additional action is needed to further improve air quality and meet climate mitigation targets. Evaluating policy opportunities and challenges for climate mitigation and air quality improvement in Guangdong and Shandong is important for achieving both policy outcomes.

[1] A prefecture city in Shandong province.

3. Methodology

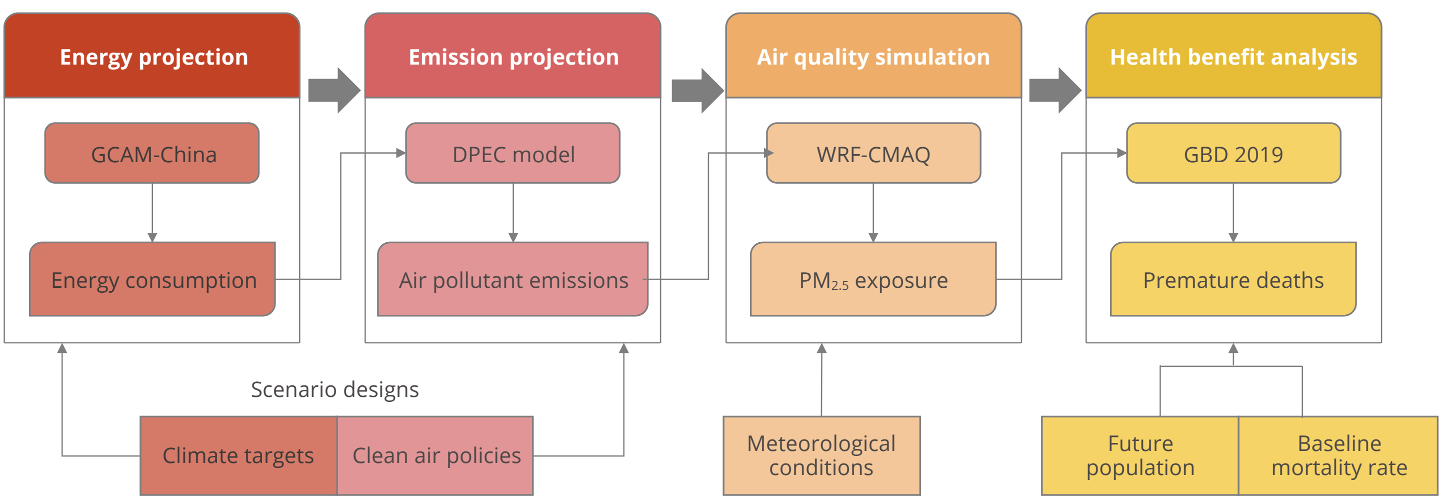
Here, we link a global integrated assessment model, the Global Change Analysis Model (GCAM-China)[2], and the Dynamic Projection model for Emissions in China (DPEC)[3] to produce GHG and air pollutant emissions pathways at the provincial level under alternative climate policy and clean air policy scenarios. We then use the Weather Research and Forecasting-Community Multiscale Air Quality Model (WRF-CMAQ)[4] to estimate $PM_{2.5}$ concentrations across scenarios (Cheng et al., 2021), and the concentration-response functions from the Global Burden of Disease report to estimate premature mortality impacts Global Burden of Disease (GBD 2019 Risk Factors Collaborators, 2020) (Figure 3.1). See the tech appendix for methodology details.

3.1. Scenario Development

We develop four scenarios to evaluate how climate and clean air policy choices could impact decarbonization and air pollutant emissions through 2060, including three core scenarios that vary across stringency of climate ambition and air pollutant control measures, and one additional scenario that explore the impact of excluding CCUS technology in climate mitigation (Table 3.1).

Climate ambition is modeled by implementing either a national target to reach net zero CO_2 by 2050 with differing provincial pathways (**NZ2050**) or by extending recent energy system trends (**Cpol**). In all **NZ2050** scenarios, a constraint is set for national CO_2 emissions to reach net zero in 2050, but the provinces don't have a specific

FIGURE 3.1: ENERGY, EMISSION, AIR QUALITY CONCENTRATION AND HEALTH IMPACTS MODEL INPUTS AND OUTPUTS.



[2] GCAM is a partial equilibrium model that examines long-term changes in the coupled socioeconomic, energy, agriculture/land-use, and climate systems with technology-rich representations of energy production, transformation, and consumption (GCAM, 2022). GCAM-China, a research branch of GCAM, further disaggregates the China region into 31 sub-regions and six electricity grid regions. The regional detail of China is embedded in the broader GCAM model, allowing us to assess changes in China's energy and environmental systems on a granular level while maintaining global constraints and context.

[3] DPEC was developed by combining GCAM-China and the emissions projection model built based on emissions inventory (Multi-resolution Emission Inventory for China, MEIC) model.

[4] WRF is a next-generation mesoscale numerical weather prediction system developed by the National Center for Atmospheric Research (NCAR) and used in this study for weather simulations. CMAQ is an air quality model developed by the U.S. EPA and used in this study for offline PM2.5 concentration simulations.

TABLE 3.1: ENERGY AND EMISSION PROJECTION SCENARIOS ACROSS CLIMATE AMBITION AND AIR POLLUTANT CONTROL.

		Climate Ambition	
		Net Zero CO_2 2050	*Continued Current Policy*
Air Pollutant Control	*Best Health Effects*	**NZ2050_BHE**	**Cpol_BHE**
		Sensitivity Analysis: NZ2050_BHE_noCCUS	
	Business-as-Usual		**Cpol_BAU**

climate mitigation target. The scenario without the national climate target does not have advanced sectoral policies and was calibrated to reflect recent trends, including the coal and renewable-based generation of electricity generation and coal use in industry, so it models a future with current energy policies in place. All the **NZ2050 scenarios** have immediate reduction of CO_2 emissions after 2020. In addition to a carbon dioxide cap in the **NZ2050 scenarios**, we also modeled several sector specific policy pathways, including coal phase-out in the power and buildings sector, electrification in buildings, industry and transportation, and hydrogen deployment in transportation and industry sectors. For additional information on how climate ambition was modeled in GCAM-China, please see appendix.

Air pollutant controls are modeled by varying end-of-pipe control policies, between enhanced end-of-pipe policies in the Best Health Effects (**BHE**) scenario, and existing air quality controls in the Business-as-Usual (**BAU**) scenario. Most of our analysis focuses on the scenarios with BHE, to show the air quality impacts when both end-of-pipe regulations and climate mitigation policies are implemented.

The pathway for China to achieve carbon neutrality in 2060 is unclear, and technology, policy and economic choices made will have a substantial impact on not only how sectors of society will make the transition toward a net zero economy, but also on air quality co-benefits. CCUS does not remove all air pollutants during the CO_2 removal process, and can allow for continued use of fossil fuels if added to fossil production facilities; and, CCUS also requires more energy inputs to operate, potentially exacerbating some air quality effects (Koornneef et al., 2011). Considering the impacts of different climate mitigation pathways on air pollution, including technologies like CCUS, and the multiple factors that could influence CCUS deployment by mid-century, we evaluated an alternative net zero CO_2 by 2050 and BHE scenario where CCUS technology is not available for commercial deployment (**NoCCUS**). Scenarios with CCUS technology deployment reach net-zero GHG emissions (carbon neutrality) in 2060. Our four scenarios compare how climate mitigation targets and end-of-pipe control policies impact decarbonization and air quality.

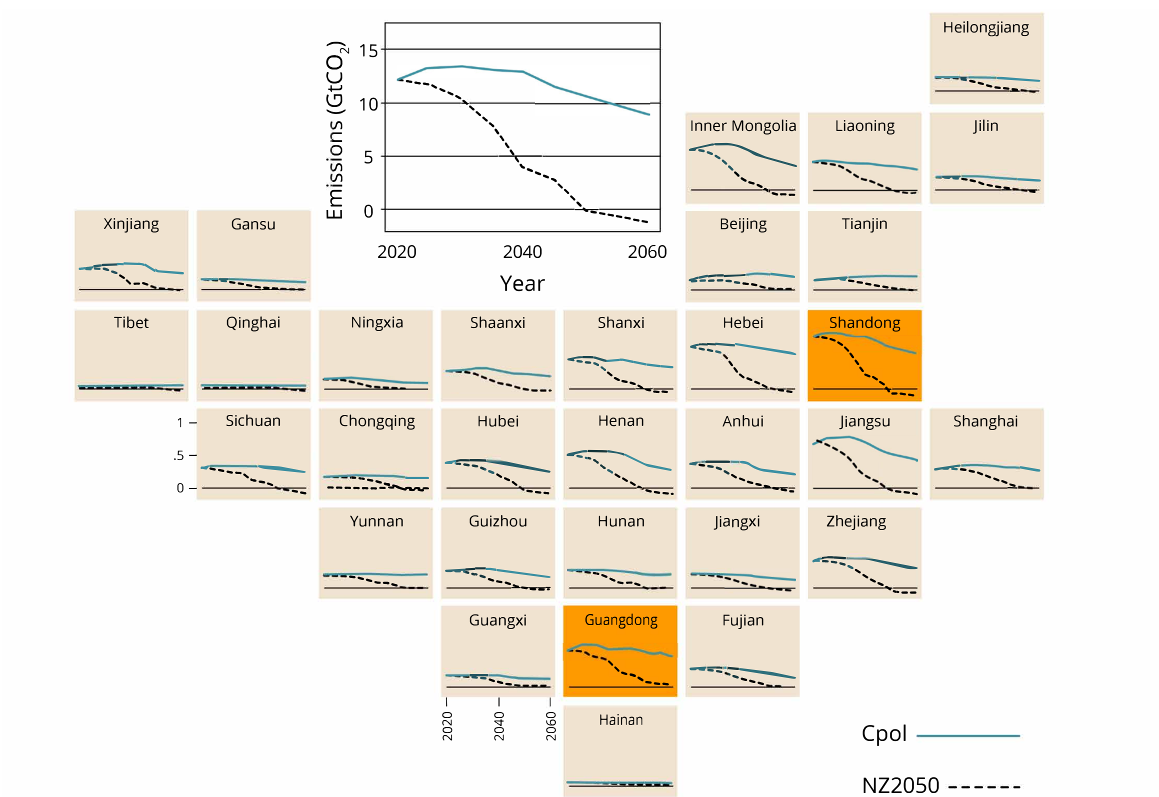
4. Decarbonization

4.1. National and Provincial Emissions Pathways

We develop scenarios that vary in stringency of national climate ambition to evaluate the potential pathways toward decarbonization each province may take. Reaching national net zero CO_2 by 2050 requires that all provinces substantially reduce emissions from the current trend, but emissions reduction pathways can vary, with different levels of near-term emissions reduction and net zero years (Figure 4.1.1). In the near-term, rates of emissions reduction from 2020 to 2030 vary across provinces, between 5% and 42%. Almost all provinces reach net zero CO_2 emissions between 2045 and 2065, and the majority reach net zero by 2055. Additionally, some provinces achieve negative emissions in the NZ2050 scenarios

FIGURE 4.1.1: CARBON DIOXIDE EMISSIONS PATHWAYS UNDER CURRENT POLICY (CPOL) AND NET ZERO CO_2 2050 (NZ2050) SCENARIOS ACROSS PROVINCES AND NATIONALLY.

Climate ambition is modeled by implementing either a national target to reach net zero CO_2 by 2050 with differing provincial pathways (NZ2050) or by extending recent energy system trends (Cpol).



Note: NZ2050 scenario emissions peak before 2025, which exceeds the nationally determined contribution (NDC) target of peaking before 2030.

around mid century through the deployment of bioenergy with carbon capture and storage (BECCS) and/or land offsets, which is essential to offset residual emissions of CO_2 and especially non-CO_2 greenhouse gases across all provinces.

Based on the provincial pathways under alternative climate and clean air policies, we then take a deep-dive look at two provinces: Guangdong and Shandong. Both provinces have large GDPs and populations, but vary in terms of the underlying economic and energy structure. By assessing their pathways toward carbon neutrality and air quality improvement, we identify specific strategies and policy opportunities that focus on co-reducing GHG and air pollutant emissions in each province, which can provide insights for other provinces that share similar opportunities and challenges.

4.2. Guangdong Decarbonization Approach and Energy Transition

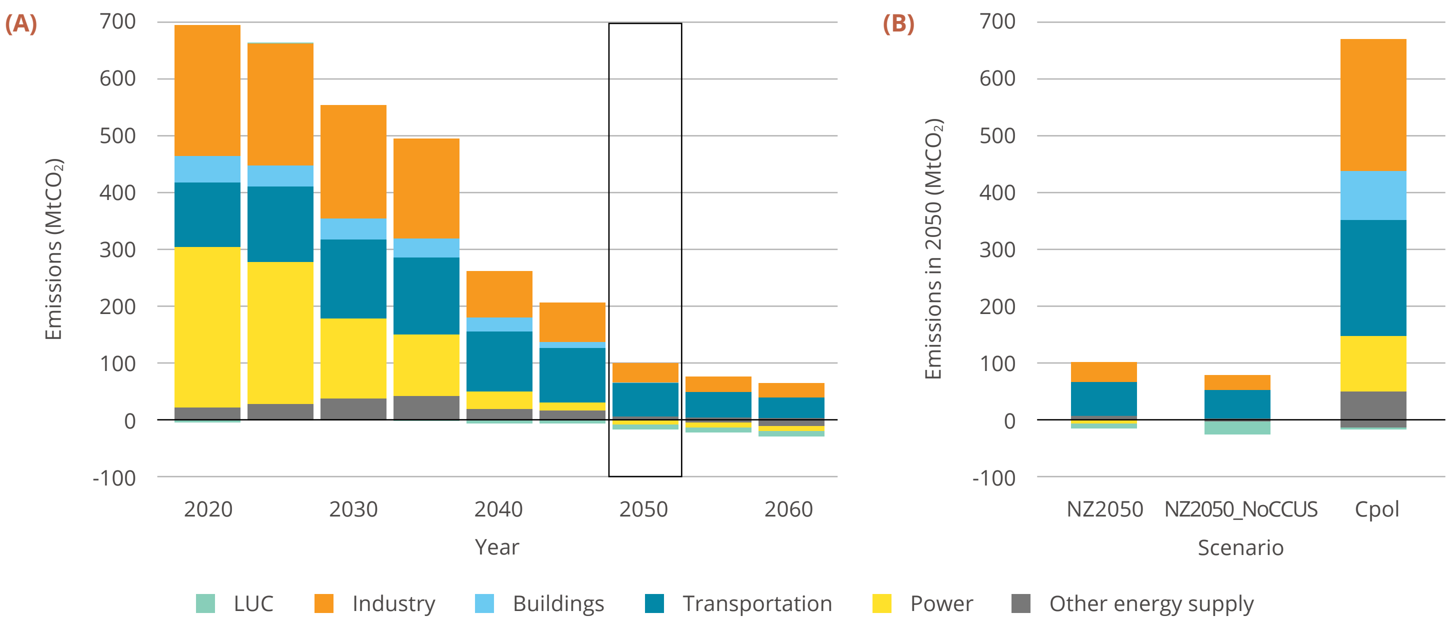
As a service-based economy with lower overall emissions and limited energy production, compared to other provinces, emissions reduction in both the industry and power sectors is important, but significant reductions can also come from the buildings and transportation sectors. Guangdong may have to rely on other provinces to offset the remaining greenhouse gas emissions, via negative emissions technologies, in order for China to meet the national net zero target. Reducing emissions from all sectors in Guangdong will be critical to achieve national carbon neutrality.

Guangdong has limited CCUS capacity and land sinks, compared to other provinces, presenting a barrier to achieving net-zero emissions. Guangdong is estimated to have less than 100 $MtCO_2$ of onshore storage capacity, while other provinces have on the order of 100,000 $MtCO_2$ (Yu et al., 2019). Limited storage capacity in Guangdong makes offsetting remaining positive emissions in hard-to-abate sectors difficult, as Guangdong only reaches 88% reduction in net CO_2 emissions by 2050 under the NZ2050 scenario, with only 16 $MtCO_2$ negative emissions coming from BECCS and LUC in 2050. In the NZ2050_NoCCUS scenario, transportation and industry emissions are partially offset by LUC negative emissions (Figure 4.2.1), which increase by 160% from the NZ2050 scenario (Figure 4.2.1), and Guangdong reaches 93% reduction in net CO_2 emissions by 2050, compared to 2020. Not only are negative emissions from LUC higher in the NoCCUS scenario, remaining emissions in the industry and transportation sectors are lower in 2050, suggesting that widespread CCUS technology may allow some provinces to have less sectoral emissions mitigation and/or preserve fewer land sinks.

While the timing, magnitude and duration of emissions reduction varies across sectors, emissions reduction in all sectors is needed. By 2050, in the NZ2050 scenario, Guangdong reduces electricity emissions by over 100% compared to 2020, and a substantial portion (~ 60%) of the remaining positive emissions in 2050 are in the transportation sector (Figure 4.2.1). Passenger vehicles can electrify quickly, but decarbonization options are limited for some modes of transportation, such as aviation and heavy-duty trucks. Industrial emissions only begin to substantially decline in 2040, but by 2050, 80% of emissions reduction comes from industry and electricity sectors (~500 $MtCO_2$) and only 17% of emissions reduction comes from the buildings

FIGURE 4.2.1: CO_2 EMISSIONS BY SECTOR IN GUANGDONG. (A) CO_2 EMISSIONS BY SECTOR FROM 2020 TO 2060 IN NZ2050 SCENARIO, (B) 2050 CO_2 EMISSIONS BY SECTOR IN NZ2050, NZ2050_NOCCUS AND CPOL SCENARIOS.

Other energy supply includes production of gases, liquids, hydrogen, and heat. LUC refers to land use change emissions.



and transportation sectors (~100 $MtCO_2$). In 2050, the bulk of remaining emissions in the NZ2050 scenario are in the transportation and industry sectors, which need to be offset by negative emissions.

Across scenarios emissions pathways vary, but suggest significant decarbonization efforts across all sectors, especially the power sector. The 2050 CO_2 emissions in the Cpol scenario are nearly six times as much as the positive emissions from the NZ2050 and the NZ2050_NoCCUS scenarios. To get to zero CO_2 emissions, emissions across the buildings, industry, power and transportation sectors will need to decline significantly by 2050, by 99%, 85%, 103% and 48%, respectively. Cpol emissions in 2050 are comparable to 2020 in magnitude, but transportation emissions are 79% greater in 2050, and electricity emissions are 65% less in 2050 than 2020, suggesting that some decarbonization in the power sector will occur regardless with sectoral policies or climate target setting, but that without enhanced action, emissions in other sectors, especially transportation, will remain relatively constant or increase.

Achieving carbon neutrality in Guangdong will require an all-sector approach. Identifying near and long-term mitigation priorities across all sectors will be critical for enabling energy system transition and decarbonization. To better understand these strategies, we evaluated the NZ2050 climate and energy pathway, which underpins the scenarios, in further detail.

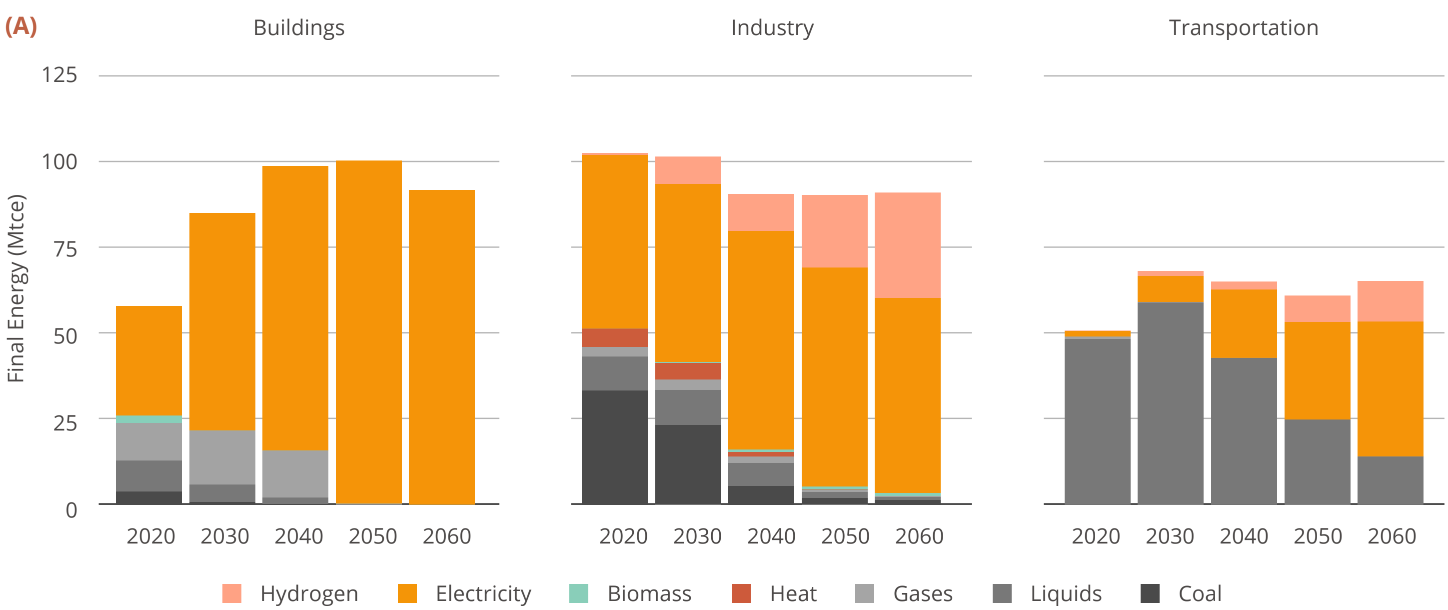
Energy demand in the buildings sector in Guangdong is projected to grow and become more than one third of the total energy demand by 2060, and increase through 2050, making the residential and commercial buildings sector an important component of both near and long-term mitigation. Given the already relatively high rate of electrification in Guangdong, about 55% in 2018 compared to 28% for all of China (International Energy Agency, 2022), fossil fuels are continuing to be phased out of the buildings sector. By mid-century, the province phases out all fossil fuels, with an 80% reduction of coal use by 2030 (Figure 4.2.2). In the near-term, use of gas increases slightly, but is phased out by mid-century, and almost 100% electrification is achieved by 2050.

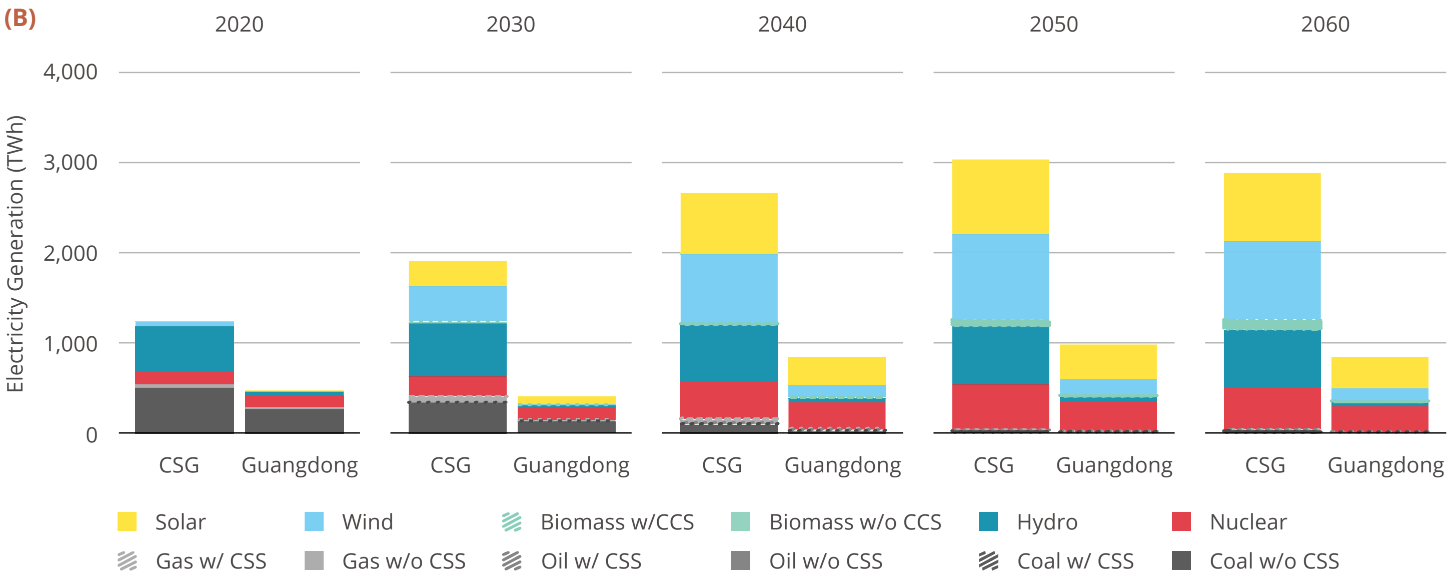
Adopting mitigation policies in the industry sector is extremely important, as the industry sector consumes about half of total final energy in Guangdong in 2020 (Figure 4.2.2). Industry energy demand decreases between 2030 and 2050, due to an anticipated decrease in demand for industrial products and increasing energy efficiency. The NZ2050 scenario displays high levels of fuel switching as a means to decarbonize the industry sector. Fossil fuels and heat are largely replaced by 2050 by electricity and hydrogen. In Guangdong, by 2030, coal use decreases by about 30%, and by 2050 by about 94%, compared to 2020, through fuel-switching and energy efficiency improvement.

Guangdong has a high level of transportation energy use, and high levels of demand not only

FIGURE 4.2.2: ENERGY SYSTEM TRANSFORMATION UNDER THE NZ2050 SCENARIO IN GUANGDONG. (A) FINAL ENERGY USE BY FUEL ACROSS END-USE SECTORS, (B) ELECTRICITY GENERATION BY TECHNOLOGY IN CHINA SOUTHERN POWER GRID (CSG) AND GUANGDONG.

Guangdong is located within the Guangdong is located within the China Southern Power Grid (CSG).





continue through the mid-century, but increase. Overall demand increases through 2030, and declines between 2030 and 2050, before increasing again in 2060 (Figure 4.2.2). Our results project Guangdong adopting a pathway of rapid electrification, especially in passenger vehicles, reaching 77% of total passenger final energy by 2050. Remaining oil use in passenger vehicles is primarily from domestic aviation and shipping. In the freight sector, the province sees deployment of fuel cell electric vehicles (FCEV) technologies, particularly in large and medium trucks and shipping after 2040. Electricity and hydrogen make up 10% and 28% of total freight final energy by 2050, respectively. Oil will remain a major source of energy for freight transport by 2050 as many modes of freight transit are difficult to decarbonize. By 2050, the total transportation sector will reach an electrification rate of 47%. Developing viable energy alternatives for modes of freight transport, along with expanding passenger electrification, is needed to further reduce emissions in the transportation sector.

Substantial electrification throughout all end-use sectors, including buildings, industry and transportation sectors, will be required during the energy transition, which will require increasing electricity generation (Figure 4.2.2). Our results suggest the end-use electrification rate in Guangdong will increase from about 40% in 2020 to about 76% in 2050. Corresponding power generation peaks in 2050, as the push for carbon neutrality drives up electricity demand, before overall energy demand begins to decline in the second half of the century.

Ensuring decarbonization occurs in the power sector amid high rates of electrification is critical for ensuring end-use electrification contributes toward meeting carbon neutrality goals (Figure 4.2.2). Coal-fired generation makes up about 60% of the total electricity generated in Guangdong in 2020. Coal electricity generation without CCUS is phased out around 2040, despite more than half of the generation in 2020 coming from coal power plants built later than 2010, suggesting early retirement for coal plants built after 2010 may be necessary. Both at the provincial and at the grid region level, decreasing coal power generation is more than compensated by increasing wind, solar, and nuclear power generation, and to a lesser extent biomass with CCUS. Nuclear power generation is expected to grow substantially, with Guangdong expected to have 343 TWh (35% of total electricity generation) by 2050. By 2050, wind and solar are expected to have a combined generation of about 560 TWh, or about 57% of total electricity generation, in Guangdong and 1770TWh, or about 62% of total electricity generation, in the CSG region[5], which also includes Yunnan, Guangxi, Guizhou, and Hainan.

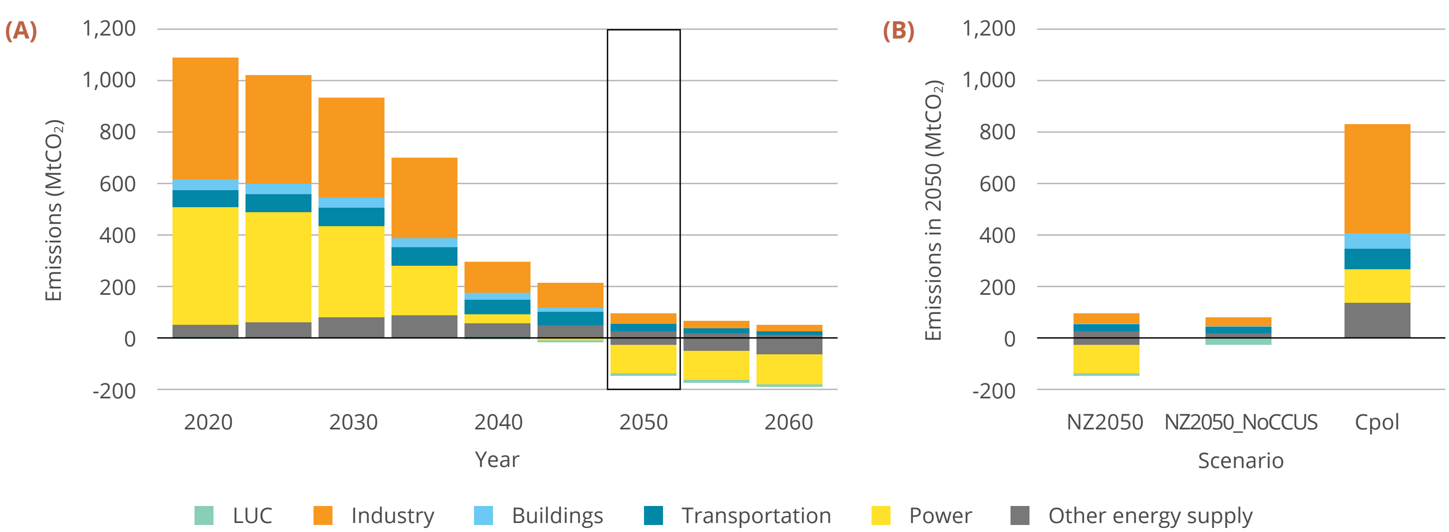
In addition to decarbonization of the power sector within the province, Guangdong will need to consider the mitigation measures of other provinces in the CSG region, as Guangdong is projected to be an electricity importer, not exporter, through 2050. The province uses more electricity from the grid than it produces, particularly in 2030. Within the period of 2020-2050, Guangdong will use between 140% and 240% of the amount of electricity that is generated within the province, so it will be reliant on electricity produced by other provinces within the China Southern Power Grid region. Investments or partnerships with other provinces may be necessary for emissions reduction across the entire grid region.

4.3. Shandong Decarbonization Approach and Energy Transition

As it is a significant energy and material goods producer with a large CCUS capacity, the bulk of Shandong's decarbonization will likely come from the industrial and power sectors (Figure 4.3.1). Expanded CCUS capacity may help offset emissions from Shandong, as well as other provinces with

FIGURE 4.3.1: CO_2 EMISSIONS BY SECTOR IN SHANDONG. (A) CO_2 EMISSIONS BY SECTOR FROM 2020 TO 2060 IN NZ2050 SCENARIO, (B) 2050 CO_2 EMISSIONS BY SECTOR IN NZ2050, NZ2050_NOCCUS AND CPOL SCENARIOS.

Other Energy Supply includes refining and production of gases, liquids, hydrogen, and heat. LUC refers to land use change emissions.



[5] Data from Hong Kong and Macau have not been included in this study.

reduced capacity for negative emissions from CCUS or LUC, or with higher remaining emissions. However, action across all sectors is needed, and policy choices, technology availability, and costs will determine how Shandong will meet the national carbon neutrality target.

CCUS is anticipated to play a significant role in Shandong's decarbonization approach (Figure 4.3.1). Shandong is estimated to have up to 100,000 $MtCO_2$ (Yu et al., 2019) of storage capacity, with high potential in the power, cement and hydrogen production sectors. The vast majority of negative emissions in 2050 in the NZ2050 scenario are from BECCS, with some additional land use change offset. However, without CCUS deployment, Shandong struggles to achieve net zero emissions. Under the NZ2050_NoCCUS scenario, Shandong doesn't quite reach net zero CO_2 emissions by 2050, only reaching 95% reduction in net CO_2 emissions. In the NZ2050_NoCCUS scenario, negative LUC emissions are 140% higher, and industry and transportation emissions are 8% and 14% lower in 2050 than the NZ2050 scenario, suggesting that technology availability may impact afforestation rates and emissions in hard-to-decarbonize sectors.

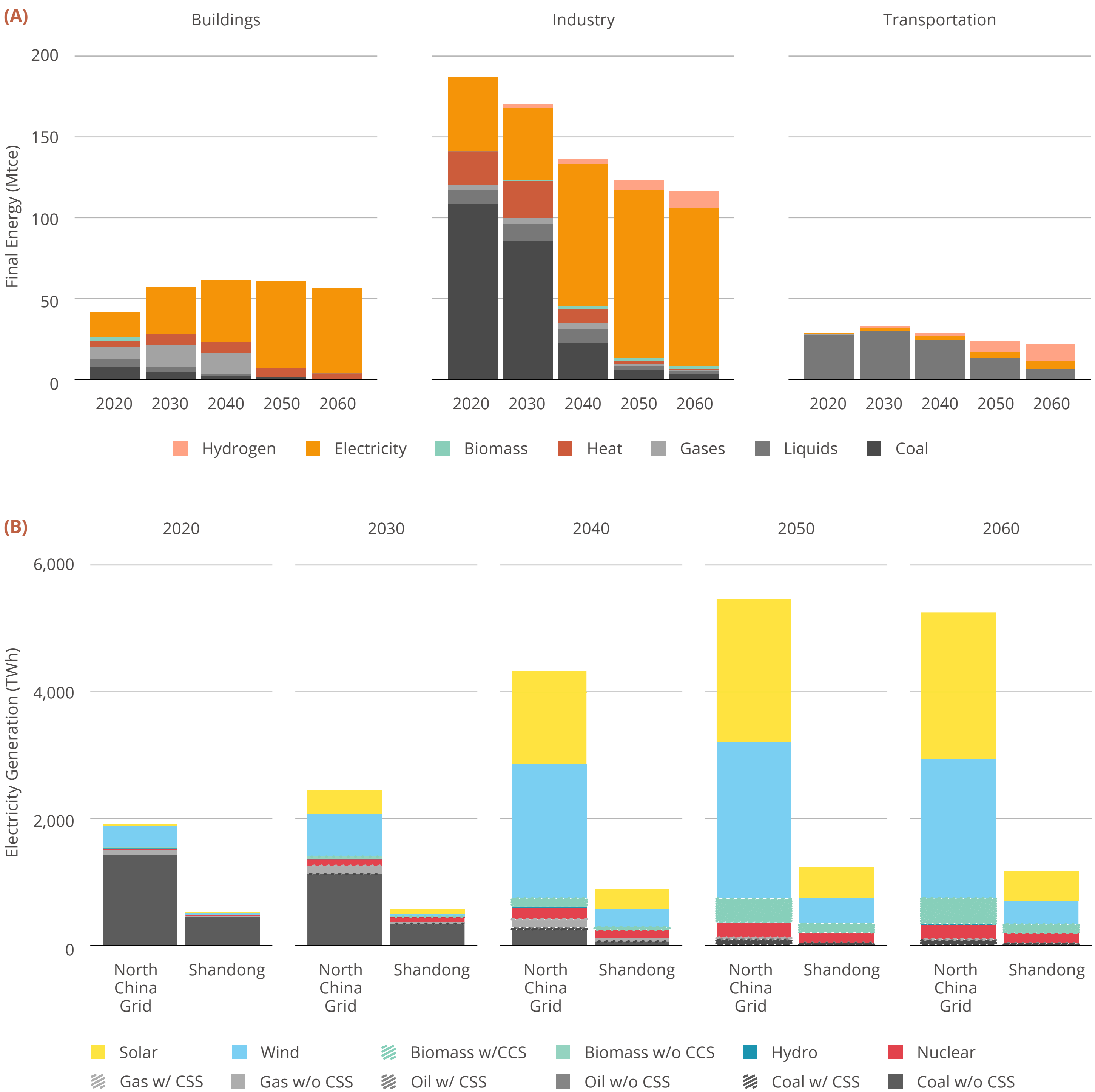
Current CO_2 emissions in Shandong are relatively high compared to other provinces, particularly in the power and industry sectors. To meet carbon neutrality targets, Shandong relies heavily on reductions in power and industry sector emissions (Figure 4.3.1). By 2050, Shandong has a 124% reduction in power sector emissions compared to 2020. Even though transportation emissions are limited in 2020, only about 6% of total in 2020, a substantial portion (30%) of the remaining positive emissions in 2050 are in the transportation sector. Only about 7% of emissions reduction from 2020 comes from the buildings and transportation sectors, combined, in 2050. Industrial emissions reductions start in 2030, and by 2050, comprise 25% of total positive emissions. Shandong's reduction in the power and industrial sectors make up about 1,000 $MtCO_2$ or 88% of total emissions reduction from 2020, as Shandong reaches net zero in 2050, and both sectors become a significant source of negative emissions after 2050.

However, reductions across all sectors are needed in Shandong to reach carbon neutrality. Without a net zero CO_2 target, positive emissions in the Cpol scenario will reach about 8 times as much as the positive emissions in NZ2050 scenario in 2050, and emissions from other energy supply sources will increase from 2020 to 2050 by 180% (Figure 4.3.1). To get to zero CO_2 emissions, emissions across the buildings, industry, power and transportation sectors will need to decline significantly by 2050, by 93%, 93%, 124% and 57%, respectively. Emissions in the Cpol scenario in 2050 are slightly lower than 2020 emissions, mostly from the power sector reductions of 71%, suggesting that some decarbonization of the power sector occurs even without setting ambitious climate mitigation goals.

Decarbonization in the building sector requires fuel-switching, especially for heating and cooking in rural areas, from traditional biomass and/or fossil fuels to electricity, while facing increasing energy demands. The buildings sector is the second largest end-use energy consumer in 2020, and energy use increases until 2030, then declines toward 2050, suggesting that decarbonization amid near-term growth will be critical (Figure 4.3.2). In rural areas, homes in Shandong typically use biomass, coal or

FIGURE 4.3.2: ENERGY SYSTEM TRANSFORMATION UNDER THE NZ2050 SCENARIO IN SHANDONG. (A) FINAL ENERGY USE BY FUEL ACROSS END-USE SECTORS, (B) ELECTRICITY GENERATION BY TECHNOLOGIES IN NORTH CHINA GRID.

Shandong is located within North China Grid.



gas for heating (Ma et al., 2021; Zou et al., 2022). Phasing out the use of solid fuels and replacing them with electricity is key for meeting national decarbonization goals. In the NZ2050 scenario, the province achieves nearly 89% electrification by 2050, with traditional biomass phasing out by 2030, and all fossil fuel use by mid-century. Shandong has a 42% reduction in coal use in buildings by 2030, which is primarily used for heating buildings. While Shandong is projected to temporarily increase the use of gas in buildings by 2030, gas is still phased out by mid-century. Heat increases in 2030, and decreases in 2050, but continues to be used for urban residential heating and some commercial heating, even in 2060.

Electrifying industry and improving efficiency is critical for decarbonizing the industry sector, which is critical for Shandong, as industry consumes about 73% of the province's total final energy in 2020 (Figure 4.3.2). Industrial energy use starts to decline after 2020 (Figure 4.3.2), in part from energy efficiency improvement but also in part due to an anticipated drop in demand for industrial products by 2060 (J. Zhang & Wen, 2022). Fossil fuels and heat are largely replaced by 2050 by electricity and hydrogen, with coal use decreasing by about 20% by 2030 and more than 90% by 2050. Within the industry sector, cement is an important industry in Shandong, as it is the second largest producer of cement in China, producing about 7% of the national total, or almost 4% of the world total, given that China produced just over half of the worlds' cement in 2020 (Shandong Provincial Bureau of Statistics, 2021; Statista, 2023). Cement production makes up 10% of total final energy use in 2020, and reduces coal use by 83%, and overall energy by 72% from 2020 to 2050. While cement production is a significant consumer of coal in the industrial sector, there are methods for decarbonization. Coal use potentially can be substituted in cement production with the combustion of alternative fuels, such as biomass and bio-based waste products (Rahman et al., 2015).

To meet carbon neutrality targets, Shandong adopts a pathway toward electric and hydrogen-based fuels in transportation. Shandong electricity and hydrogen use in the transportation sector reaches 16% and 29% of total transportation energy use by 2050, respectively (Figure 4.3.2). Oil is no longer the dominant fuel for transportation starting in 2060. Electrification is especially high in passenger transportation, which reaches 79% electrification by 2050. Remaining oil use in passenger vehicles is primarily from domestic aviation and shipping. In the freight sector, electricity and hydrogen make up 10% and 32% of total freight final energy in 2050, respectively. The province sees deployment of FCEV, particularly in large and medium trucks and shipping after 2040. However, oil will remain the dominant source of energy for freight transport by 2050 as many modes of freight transit are difficult to decarbonize. Shandong transportation demand is relatively low, but our results suggest an increase in heavy-duty vehicle (HDV) for commercial industrial transport, along with international shipping from current levels. Growth in these hard-to-abate sectors suggests that developing strategies and viable alternatives in the commercial transportation sector is especially important for Shandong.

Without decarbonization in the power sector, end-use electrification will have a limited impact on achieving carbon neutrality targets. Quickly decarbonizing the power sector, while expanding capacity to meet increasing demand from end-use sectors, is critical for meeting climate targets. As end sectors electrify, demand will increase, with the share of electricity used in total final energy increasing from 24% in 2020 to about 78% in 2050. To meet this demand, power generation increases and peaks in 2050, before declining in the second half of the century.

To reduce emissions from the power sector, coal powered electricity generation without CCUS is phased out by 2045 and is replaced by solar, wind, nuclear and CCUS technologies. Shandong generates a significant amount of electricity from coal technologies in 2020 compared to other provinces, such as Guangdong, as about 90% of the total electricity generated in Shandong is from coal today. Phasing out coal by 2045 may require some coal-fired power plants to retire before their end of useful life, as more than 2/3 of coal generation in 2020 comes from plants built later than 2010. Reduction in coal powered generation is more than compensated by increasing wind and solar power generation, and to a lesser extent nuclear, biomass with CCUS and coal with CCUS. By 2050, wind and solar are expected to have a combined generation of about 877 TWh, or about 72% of total electricity generation in Shandong and 4,731 TWh, or about 87% of total electricity generation, in the North China grid region, which includes Tianjin, Shanxi, Inner Mongolia, Hebei, and Beijing, in addition to Shandong. Nuclear power generation in Shandong is also expected to grow substantially, from about 20 TWh in 2020 to about 150 TWh, or 13% of total electricity generation, by 2050.

5. Air Quality Co-Benefits

Achieving carbon neutrality requires phasing out fossil fuels in electricity generation and increasing generation of low-carbon sources, along with increasing the electrification of end-use sectors. Given that a number of key air pollutants are driven by fossil fuel use, our results suggest that the long-term energy transition will reduce most major air pollutants and implementing both end-of-pipe and climate mitigation policies can maximize air pollutant emissions reduction.

5.1. Guangdong Air Quality Co-Benefits

In the future, even without climate mitigation or enhanced air pollution policies, the concentration of $PM_{2.5}$ gradually decreases as industries shift from high-energy consuming sectors to service-oriented ones, leading to overall less industrial activity and $PM_{2.5}$ emissions. Under the Cpol_BAU scenario, the $PM_{2.5}$ concentration will decrease from 19.8μg/m³ in 2020 to 16.6μg/m³ in 2030 and 16.4μg/m³ in 2050. By strengthening end-of-pipe control policies under the Cpol_BHE scenario, the concentration will further decrease to 12.6μg/m³ (2030) and 9.7μg/m³ (2050) (Figure 5.1.1). The transformation of energy systems and achievement of net-zero CO_2 emissions by 2050, along with enhanced end-of-pipe control policies in the NZ2050_BHE scenario results in the $PM_{2.5}$ concentration in 2030 and 2050 dropping to 10.2μg/m³ and 5.2μg/m³, respectively, approaching the recommended value of 5μg/m³

FIGURE 5.1.1: $PM_{2.5}$ CONCENTRATION IN GUANGDONG ACROSS SCENARIOS IN 2050.

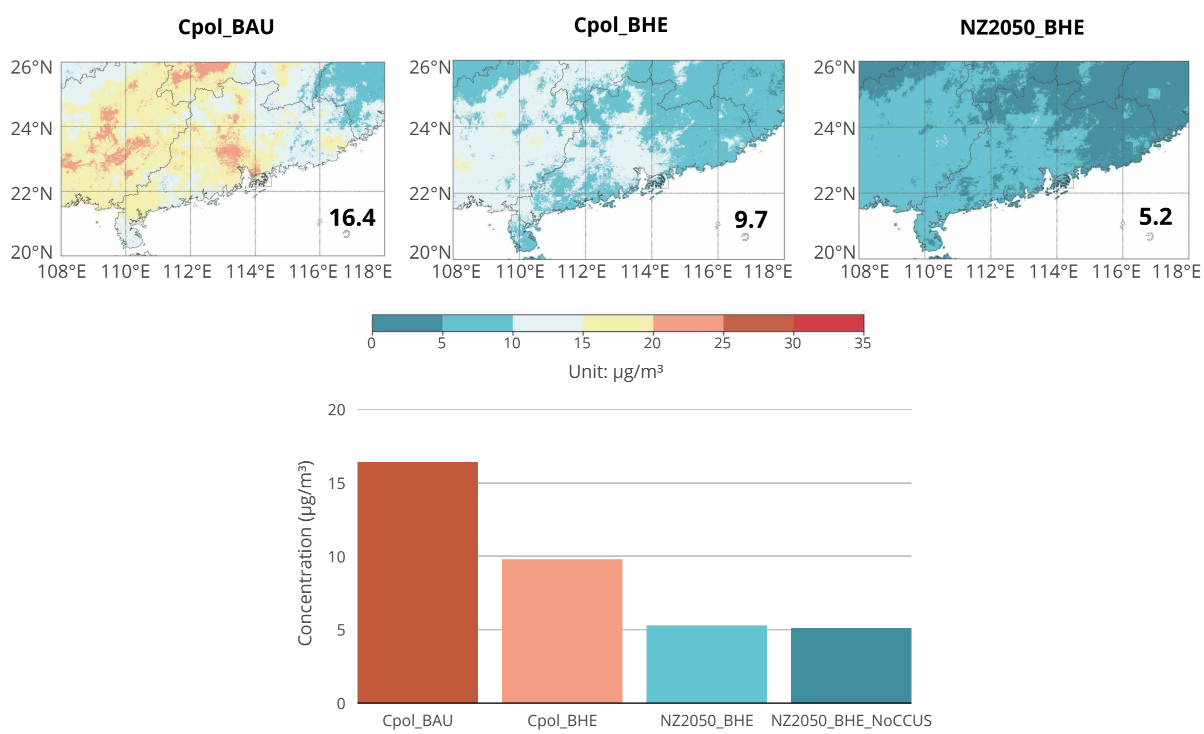
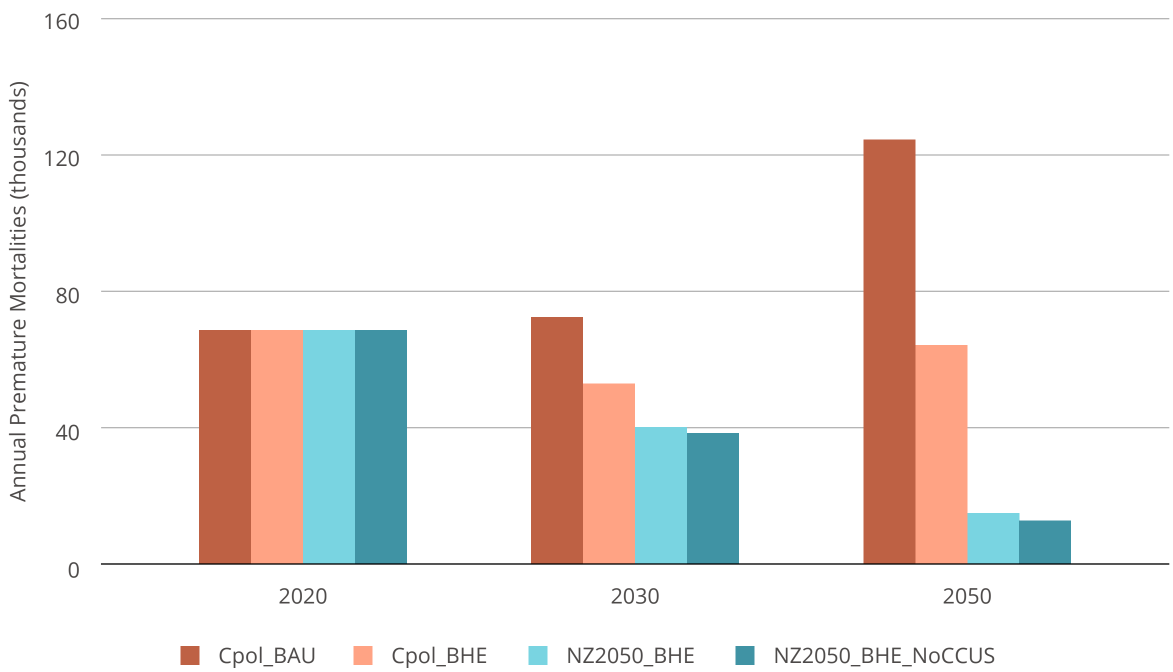


FIGURE 5.1.2: $PM_{2.5}$-RELATED MORTALITY ACROSS DIFFERENT SCENARIOS IN GUANGDONG.

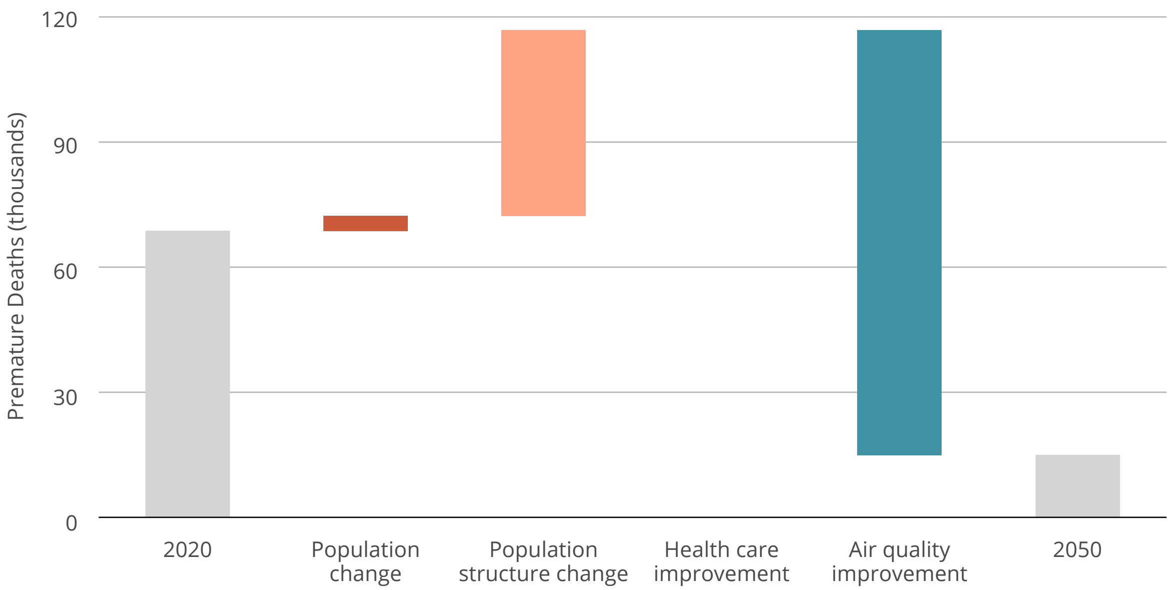


by the WHO in 2050. These results suggest that end-of-pipe controls will play a significant and important role in the near-term to improve air quality, but that maximizing $PM_{2.5}$ improvement requires decarbonization.

Along with improvements in $PM_{2.5}$ concentration, achieving climate mitigation targets also reduces premature mortality. In the Cpol_BAU scenario, despite small improvements in $PM_{2.5}$ concentration, it is estimated that the number of $PM_{2.5}$-related deaths in Guangdong province will reach 70 thousand by 2030 and increase to 120 thousand in 2050 (Figure 5.1.2), due to increasing population and changing age structure. With enhanced end-of-pipe controls, premature deaths are reduced by 60 thousand in 2050 compared to the BAU scenario. However, premature deaths only decline by 4 thousand from 2020 to 2050, as premature mortality increases from 50 thousand in 2030 to 60 thousand in 2050, due to changes in population structure. With the addition of climate mitigation targets, under the NZ2050_BHE and NZ2050_BHE_NoCCUS scenarios, around 110 thousand and 50 thousand $PM_{2.5}$-related deaths are avoided in 2050, compared to the Cpol_BAU and Cpol_BHE scenarios, respectively. Despite an increasing aging population, premature mortality declines significantly under the NZ2050_BHE scenario due to improvements made to air quality (Figure 5.1.3), emphasizing the importance of air quality improvement to avoid increasing premature mortalities from today.

While our results suggest that climate mitigation improves air quality, the technologies selected for decarbonization may impact premature

FIGURE 5.1.3: $PM_{2.5}$-RELATED MORTALITY CONTRIBUTION DECOMPOSITION IN GUANGDONG.



mortality. In our sensitivity scenario without CCUS technology (N2050_BHE_noCCUS), $PM_{2.5}$ concentrations are lower than in the NZ2050_BHE scenario (Figure 5.1.2). Under the scenario without CCUS deployment, the $PM_{2.5}$ concentration in 2030 and 2050 can be further reduced by 0.5μg/m³ and 0.2μg/m³, respectively and premature mortality by 2 thousand in 2050.

5.2. Shandong Air Quality Co-Benefits

Shandong Province is currently suffering from significant air pollution, and will benefit significantly from air quality improvement. Under the Cpol_BAU scenario, the $PM_{2.5}$ concentration in Shandong Province will slightly decrease from 45.9μg/m³ in 2020 to 39.7μg/m³ in 2030 and 38.3μg/m³ in 2050 (Figure 5.2.1). However, this still exceeds the WHO recommended limit, and suggests that current air quality control policies alone cannot achieve significant air quality improvement. Therefore, further strengthening of pollution control policies is necessary. With enhanced air quality control policies, as demonstrated by the Cpol_BHE scenario, the $PM_{2.5}$ concentration will decrease to 31.1μg/m³ in 2030 and 26.2μg/m³ in 2050. With energy industry transformation and achieving net-zero emissions by 2050, the concentration in 2030 and 2050 will drop to 28.7μg/m³ and 10.6μg/m³, respectively, demonstrating the significant long-term impact energy transformation can have on $PM_{2.5}$ concentration.

In Shandong province, the Cpol_BAU scenario foresees a significant surge in $PM_{2.5}$-related deaths, reaching 220 thousand, respectively, in the year 2050 (Figure 5.2.2). Enhanced end-of-pipe control policies reduce premature mortality by 54 thousand deaths annually in 2050, as compared to

FIGURE 5.2.1: $PM_{2.5}$ CONCENTRATION IN SHANDONG ACROSS SCENARIOS IN 2050.

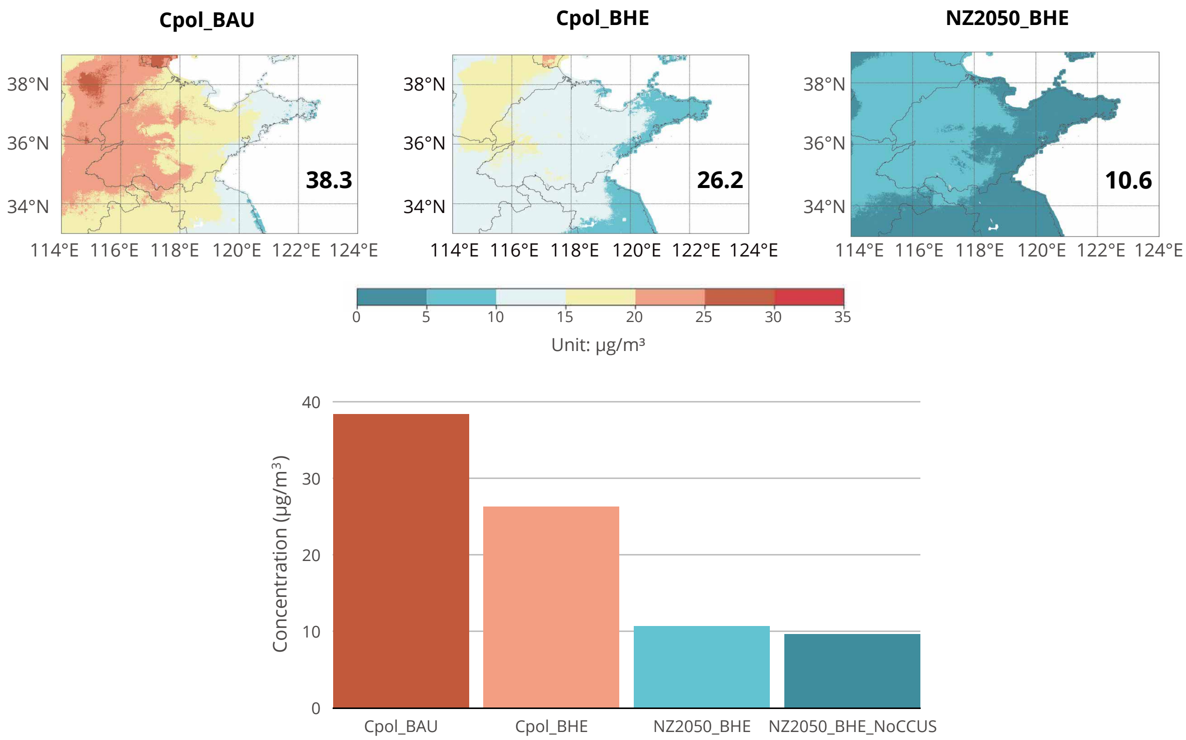


FIGURE 5.2.2: $PM_{2.5}$-RELATED MORTALITY ACROSS DIFFERENT SCENARIOS IN SHANDONG.

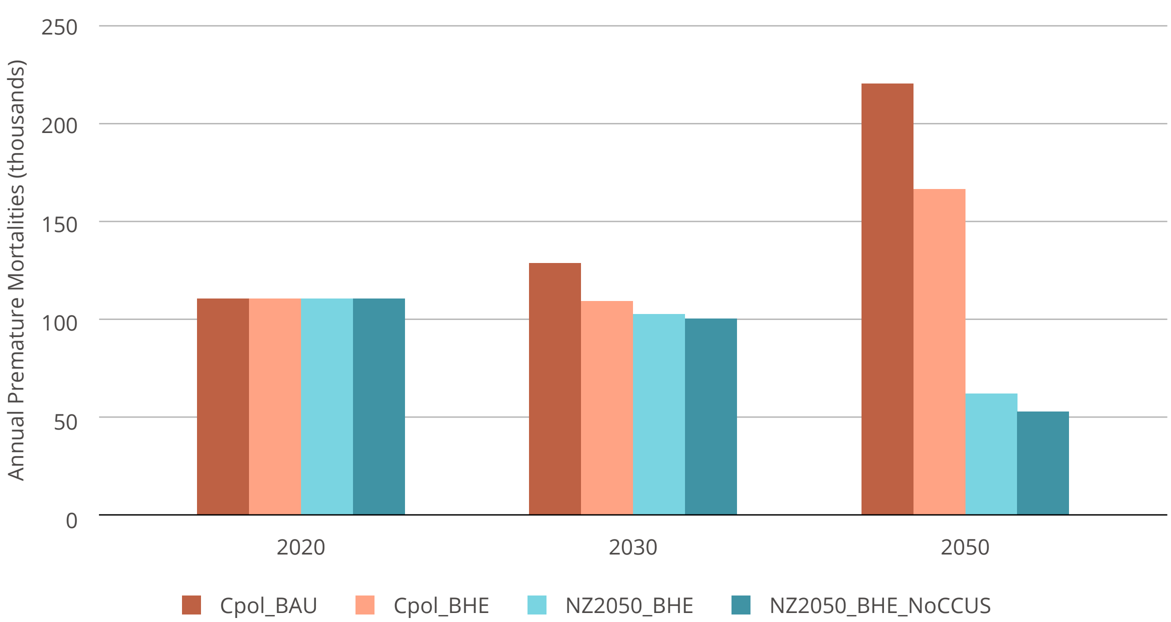
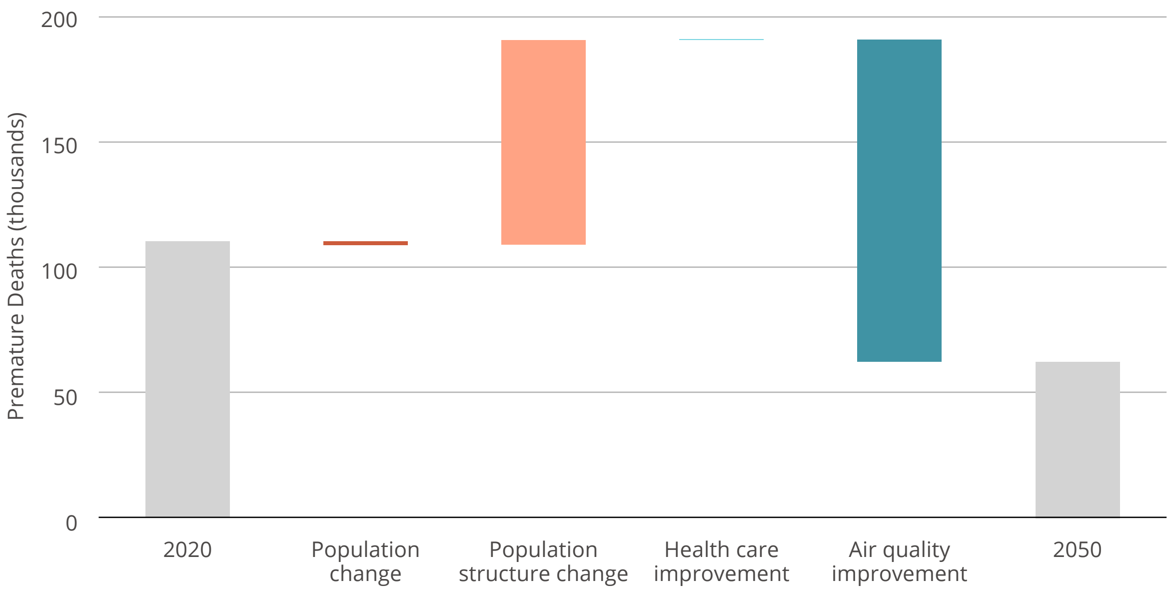


FIGURE 5.2.3: $PM_{2.5}$-RELATED MORTALITY CONTRIBUTION DECOMPOSITION IN SHANDONG.



Cpol_BAU. However, when national climate targets are achieved, as demonstrated by the NZ2050_BHE and NZ2050_BHE_NoCCUS scenarios, annual $PM_{2.5}$-related deaths are reduced. In the year 2050, these ambitious scenarios successfully reduce deaths by around 160 thousand, as compared to the Cpol_BAU scenario. Premature mortality declines significantly under the NZ2050_BHE scenario despite changes in population structure largely due to air quality improvements (Figure 5.2.3). This highlights the importance of air quality improvement to avoid increasing premature mortalities from today.

Results suggest that premature mortality is improved with climate mitigation, but varies across decarbonization pathways. Sensitivity scenarios testing the effects of CCUS technology on air quality indicate that without adopting CCUS technology, $PM_{2.5}$ concentration in 2030 and 2050 can be further reduced to 27.9μg/m^3 and 9.5μg/m^3, respectively. When compared with the NZ2050_BHE scenario, the scenario without CCUS further reduces annual premature mortality by 9 thousand premature deaths, suggesting that the technologies deployed in a decarbonization strategy may impact health outcomes.

6. Policy Recommendations

Our results suggest that mitigation approaches are needed across all sectors (Table 6.1). Connecting high-level policies with sector-specific, facility-level actions, where policies will be implemented, is critical for improving air quality (P. Wang et al., 2023). While co-reduction of GHG and air pollutant emissions can be achieved, certain measures have larger potential in reducing GHG emissions (e.g. coal phasedown in power generation), while others can generate larger air quality and health benefits (e.g. phasing out diesel trucks in heavily-trafficked urban areas). Co-design of climate mitigation and air quality policies can go beyond assessing the co-benefits of one policy on the other and help maximize outcomes on both goals. Prioritizing mitigation policies based on not only technology availability and cost, but also air quality co-benefits can help to increase public health outcomes in the near-term.

6.1. Guangdong

Buildings: One of the major challenges in the buildings sector in Guangdong is the growing residential and commercial demand, particularly in urban residential areas. Our results suggest that electrification in Guangdong, while already high, can reach almost 100% by 2050. Policies that incentivize electrification, such as subsidies for electrified water boilers and electric stoves would help to decarbonize the buildings sector, as highlighted in the Carbon Peaking Implementation Plan for Guangdong Province (People's Government of Guangdong Province, 2022b). Among various mitigation strategies in the building sector, expanding distributed photovoltaics (PV) use in buildings can help improve air quality, through a reduction in burning fossil fuels that create particulate matter.

Additionally, national efforts should continue to develop building-sector-specific policies that target building energy use efficiency to enable growing building stock without increasing emissions. Here, China can continue to build upon some existing building codes, such as Three-Star and Leadership in Energy and Environmental Design (LEED), which are mandatory building requirements for all new urban and commercial buildings; here, China can expand compliance in rural areas (Yu et al., 2014). In addition, China can further develop its Green Building Action Plan, which previously set floorspace goals for retrofits, both in the residential and commercial sectors by 2015 (Yu et al., 2014) and/or develop mandates to utilize only electric cooking stoves, water heaters and other appliances. Guangdong should expand on these national policies, and develop provincial-specific approaches for mitigating air pollution and GHG emissions from new building stock.

Industry: Industry is one of the top emitting sectors of precursors for $PM_{2.5}$. It is also the second largest share of CO_2 emissions in 2050, suggesting the mitigation of pollutant emissions in the industrial sector is especially difficult. Our results suggest that reducing coal use and improving energy efficiency in industry is key for meeting climate targets. Energy efficiency complements fuel-switching as part of a decarbonization strategy, as it decreases the total energy needed in the industrial sector, and is particularly important for sub-sectors of industry without a commercially viable power alternative to fossil fuels. Some high-temperature industrial processes may continue using fossil fuels as an energy source, and will require emissions offset from other sectors. For industry, electrifying light industries and developing alternative fuel sources for high-heat and heavy industry can have significant air quality impacts, by reducing the combustion of fossil fuels, which creates SO_2, NO_x and $PM_{2.5}$ emissions. Prioritizing these policy actions, especially in areas with high air pollution can maximize public health impacts.

Policies such as the Air Pollution Prevention and Control Action Plan do address these various avenues together, but additional support is needed. Given that not all industrial processes can be readily electrified, efforts should focus on electrifying the low-temperature industrial processes, while switching some of the high-temperature industrial processes to hydrogen. The paper, textile, and electrical equipment manufacturing industries are important consumers of energy, but often their main energy source is used to provide low-temperature heat and mechanical power, so electrification in these industries could be further enhanced (Guangdong Provincial Bureau of Statistics, 2021). The steel and chemical industries, whose energy consumption is currently dominated by redox reactions, are likely to use large amounts of clean hydrogen in the long term, given the near-term support (Falcone et al., 2021; Guangdong Provincial Bureau of Statistics, 2021). Electronic devices and electrical machinery industries comprise approximately 10% of the overall industrial energy consumption, suggesting that enhancing electrification within this sector could be quite important. It is recommended to continue and strengthen the Industrial Green Development Plan during the 14th Five-Year Plan period, which aims to decrease the carbon and pollutant emission intensity and increase the energy efficiency and the level of resource utilization.

Transportation: As Guangdong has a significant urban population and high transportation demand, mitigation of transportation emissions for improving air quality and meeting climate goals will be critical. By 2060, CO_2 emissions from the transportation sector will be the largest source of remaining emissions. Given the emissions in some transportation sub-sectors are hard to abate, increasing electrification in road transit should be a majority priority for Guangdong. Our results suggest that passenger transit, which includes rail, aviation and road, can be 77% electrified by 2050. Provincial and city governments should prioritize incentives and policies that expand electric vehicle (EV) technology, such as public or municipal fleet electrification targets and expansion of public EV charging infrastructure. In the Energy-Saving and New Energy Vehicle Industry Development Plan, China has already begun implementing more stringent fuel consumption standards and increasing production and sales of electric vehicles, with the goal of new energy vehicles accounting for 20% of new car sales by 2025 (The State Council, 2020). These standards should continue to increase and policies should be bolstered to facilitate passenger vehicle electrification.

Guangdong should focus on reducing transportation demand, through public transit development and incentives, work from home policies and community planning. Given the increasing energy consumption of the freight transportation sector over time, Guangdong should also facilitate technological deployment of hydrogen fuel-cell vehicles and other bio-fuels alternatives for shipping, aviation and trucks. Expanding BEV and FCEV use in freight vehicles, particularly trucks delivering goods in urban areas, can help to reduce the production of NO_x, a precursor of $PM_{2.5}$. While several policies have been enacted to facilitate FCEV adoption in China, most policies have focused on the supply side, rather than demand, and further policies are needed to reduce costs and commercialize long-range FCEV batteries (F. Zhao et al., 2020).

Power: Decarbonizing the power system is essential for improving climate and health outcomes in an increasingly electrified province and nation. In the power sector, expanding renewable energy deployment, especially through expanding citing policies and increasing storage capacity can help to reduce air pollutants from fossil fuel combustion. Recent construction of new coal-fired power plants in Guangdong (Energy Bureau of Guangdong Province, 2023) put at risk the decarbonization goals, air quality and public health. Coal power phase-out is critical for meeting climate mitigation goals and reducing air pollutants emissions and structuring coal fired-power plant phase-out based on air pollutant emissions intensity can maximize air quality impacts (Cui et al., 2022). This could be through a continuation of policies such as the Recommendations on Comprehensively Strengthening Protection for Ecological Environment and Against Pollution (The State Council, 2018a), which specified that coal-fired power plants in key areas, which are not eligible to complete ultra-low emissions transformation, should gradually retire. In addition to retirement of existing plants, decreased utilization of existing coal power plants can help to mitigate emissions.

In Guangdong and nearby provinces connected by the electrical grid, expanding wind and solar capacity is critical for decarbonization. Our results suggest that the renewable percentage of consumed electricity will be about 23% and 36% for the NZ2050 scenario in 2025 and 2030, respectively, which is considerably higher than the National Energy Administration (NEA) incentive targets of 12.5% and 20.6%, for those years (National Development and Reform Commission, 2021). The Cpol scenario has renewable percentages of about 14% and 19% in 2025 and 2030, respectively, suggesting that Guangdong should increase their provincial NEA target to be aligned with a national net zero CO_2 scenario. Other low-carbon sources of energy include nuclear power generation, which is a significant part of the power generation mixture in Guangdong, and ensuring proposed plants are constructed is critical. Our results suggest that total nuclear capacity would reach about 44 GW by 2050, which is nearly all nuclear power plants (capacity of 52 GW) that are planned or proposed, as tracked by the World Nuclear Agency (World Nuclear Association, 2022).

Additionally, Guangdong is a net energy importer, and will likely rely on electricity production in surrounding provinces in the CSG for electricity generation. Guangdong policy makers should work with other provinces within their grid region on energy projects and planning, as well as provinces in other grid regions. Building additional long distance transmission lines will be important especially for Guangdong, since it may consume more energy than it produces, as demand for clean energy increases.

6.2. Shandong

Buildings: Phasing out fossil and traditional biomass fuels in cooking and heating in rural residential buildings should be prioritized to improve air quality. Our results suggest that fossil fuels are phased out in Shandong buildings by 2050, with electricity largely replacing coal, oil and gas. Traditional biomass is used in rural buildings in 2020, but is rapidly phased out by 2030. This rapid phase-out will have a significant impact on indoor air quality and associated human health impacts. A strong effort will be needed from the Shandong provincial government and local governments to achieve this ambitious switch in rural heating and cooking fuels. Efforts will likely need to include financial support and educational outreach to promote the use of electric heating and cooking equipment. As a starting point, the Air Pollution Prevention and Control Action Plan can be strengthened and expanded to not only target coal phase-out, but also liquids, gases and biomass burning in residential households as well.

Additionally, the significant use of district heat in Shandong requires continued efforts to decrease the carbon emissions intensity of this sector. In particular, increased support and standards for co-generation and waste heat recovery, as well as the development of geothermal systems and small modular reactors are promising methods for decarbonizing district heat. Overall, more stringent and sweeping policies will be needed to achieve full electrification of buildings, which will have human health benefits in addition to contributing to climate goals. Additionally, Shandong province should continue to develop building-sector-specific policies that target energy efficiency in both new and existing buildings.

Industry: In Shandong, the growth rate of both heavy and light industry in the province has been declining, as has industry overall (Shandong Provincial Bureau of Statistics, 2021). Also, it is anticipated that demand will decrease in the future for certain products, such as cement (J. Zhang & Wen, 2022), for which Shandong is a major producer. However, industry is one of the highest emitting sectors of $PM_{2.5}$ precursor pollutants and GHG emissions, and will continue to play a significant role in both GHG and air pollutant emissions through mid-century. Prioritizing the electrification of light industries and developing alternative fuel sources for high-heat and heavy industry can have significant air quality co-benefits, by reducing the combustion of fossil fuels. Integrating use of alternative fuels for hard-to-electrify industry subsectors, along with energy efficiency, can help to decarbonize and reduce air pollutant emissions while alternatives for high-temperature processes are developed.

Policies such as the Air Pollution Prevention and Control Action Plan do address these various avenues together, but additional support is needed. In Shandong, it will be beneficial to focus on the automotive and electronics manufacturing industries for further electrification. Around half of industry in the province, by number of enterprises, is heavy industry, including substantial numbers in manufacture of chemicals, metals, and nonmetals, and coal mining and washing (Shandong Provincial Bureau of Statistics, 2021). The chemical, aluminum processing, and iron and steel industries may be suitable for partial substitution of hydrogen fuel (Kovač et al., 2021). It is recommended to strengthen the Industrial Green Development Plan, so that energy efficiency can be further increased. This will also decrease resource use by decreasing use of industrial feedstocks.

Transportation: Given the relatively large share of freight transportation demand in Shandong, prioritizing decarbonizing freight modes of transportation, such as setting low carbon fuel standards for trucks is critical. This can have a significant air quality impact in the near-term, as trucks delivering goods and services in urban areas create NO_x emissions, a $PM_{2.5}$ precursor. Our results suggest that in 2020, 69% of total service comes from freight transportation, and that 51% can be electrified or use hydrogen by 2060. Given the potentially long-time horizon on decarbonizing freight transportation, especially for long-distance travel, investing in research and development early will be beneficial. Several provinces have developed hydrogen fuel cell and/or production demonstration projects or deployed pilot projects (F. Zhao et al., 2020) but additional projects and policies are needed.

Additionally, prioritizing incentives and policies that expand passenger EV technology, such as public or municipal fleet electrification targets and expansion of public EV charging infrastructure will also help to decarbonize and improve air quality. Our results suggest that up to 80% of passenger transport can be electrified by 2050.

Power: In the power sector, expanding renewable energy deployment, especially through expanding citing policies and increasing storage capacity can help to reduce air pollutants from fossil fuel combustion. Structuring coal fired-power plant phase-out based on air pollutant emissions intensity can maximize air quality impacts (Cui et al., 2022). Reducing coal powered-generation could be through a continuation of policies such as Recommendations on Comprehensively Strengthening Protection for Ecological Environment and Against Pollution (The State Council, 2018a), which specified that coal-fired power plants in key areas that are not eligible to complete ultra-low emissions transformation, should gradually retire. Importantly, the recent construction of new coal-fired power plants in Shandong puts at risk the decarbonization goals, increases the risk of stranded assets and worsens emissions of $PM_{2.5}$, NO_x, and SO_2. Retirement of coal plants or phased down coal power through other means, such as through decreased utilization of existing coal power plants, is needed in the near-term to meet carbon neutrality goals and reduce air pollution.

Replacing coal with low-carbon resources is critical for decarbonization. Our results suggest that the renewable percentage of consumed electricity in Shandong will be about 37% and 44% for the NZ2050 scenario in 2025 and 2030, respectively, and 27% and 34% in the Cpol scenario in 2025 and 2030, respectively. Both of these scenarios are higher than the NEA incentive targets of 20.2% and 28.4% (National Development and Reform Commission, 2021), for those years, suggesting that Shandong should consider increasing their provincial NEA target. Given the level of renewable energy deployment needed in Shandong and relatively high potential for renewable energy in 2060 (Lou et al., 2022), building expanded inter-provincial transmission lines between Shandong and provinces with limited renewable energy deployment may help to increase diversity of grid energy portfolio make-up, reduce intermittency and limit curtailment of renewable energy projects. In addition to renewables, our results also suggest that total nuclear capacity would need to reach about 19.7 GW by 2050, which is slightly higher than all planned or proposed nuclear power plants in the province (capacity of 19.1 GW), as tracked by the World Nuclear Agency (World Nuclear Association, 2022). Enhancing nuclear power capacity deployment in Shandong is needed to meet carbon neutrality goals and maximize air quality improvements.

TABLE 6.1: GUANGDONG AND SHANDONG NEAR AND LONG-TERM DECARBONIZATION AND AIR QUALITY IMPROVEMENT ACTIONS.

Sector	Near-Term Opportunities	Long-Term Strategies
Buildings	1. **Incentivize fuel switching in rural homes through subsidies,** especially for traditional biomass and coal heating in *Shandong* 2. Promote and **provide subsidies for heat pumps, PV and storage, and electric appliances** 3. **Improve efficiency standards** of appliances/building equipment (*Guangdong* and *Shandong*), centralized hot water supply, and hot water systems (*Shandong*) 4. **Increase energy efficiency standards for new buildings,** especially in *Guangdong* amid rapid urban residential growth These actions should aim to: • Phase out coal use by 80% (*Guangdong*) and at least 40% (*Shandong*) by 2030 • Completely phase out traditional biomass in residential rural areas by 2030	1. **Increase renewable energy (distributed photovoltaic, solar thermal systems)** in buildings 2. Further **improve electrification in heating, domestic hot water, and heating through subsidies** and other investment mechanisms 3. **Renovate existing buildings** and construct ultra-low energy and near-zero energy buildings These actions should aim to: • Reach nearly 100% electrification by 2050 • Phase out coal, gas and liquids use by 2050
Industry	1. Invest in **high efficiency machinery and manufacturing techniques** (such as TRT, CDQ, and Jet BOF)[6] 2. **Recycle** steel, cement, aluminum, and plastic in production 3. **Electrify light industries** including paper, textile, equipment manufacturing (*Guangdong*), and electronics and automotive (*Shandong*) 4. **Create a database of operations efficiency** and equip low-performers with meters to monitor energy use closely These actions should aim to: • Decrease coal use by about 30% by 2030 (compared with 2020) • Improve energy efficiency by 1.5% per year from 2020 to 2035 • Increase electrification to greater than 50% (*Guangdong*) and 25% (*Shandong*) by 2030	1. **Transition from blast furnace to electricity furnace use** and develop new steel making techniques, such as electrolytic processes 2. **Switch high temperature processes** (chemicals, metals, and iron and steel) and other heavy industry **to use hydrogen fuel**, especially in *Shandong* These actions should aim to: • Decrease coal more than 90% by 2050 (compared with 2020) • Increase hydrogen use and electrification to greater than 20% and 70%, respectively, in *Guangdong* and 5% and 80%, respectively, in *Shandong*, by 2050

[6] TRT, CDQ, and Jet BOF are manufacturing techniques with high energy efficiency. TRT refers to Blast Furnace Top Gas Recovery Turbine Unit, CDQ to Coke Dry Quenching, while BOF to Basic Oxygen Furnace.

Sector	Near-Term Opportunities	Long-Term Strategies
Transportation	1. **Invest in research and development of alternative fuels for aviation, shipping, and other freight vehicles, including for long-distance heavy-duty transportation** especially in *Shandong* given size of freight vehicle fleet 2. **Increase passenger charging infrastructure** available for public use, especially in *Guangdong* given size of passenger vehicle fleet The above actions should aim to: • Peak fossil fuel use before 2035, with 2030 usage no more than 20% higher (*Guangdong*) or 10% higher (*Shandong*) than in 2020 • Achieve at least 25% (*Guangdong*) and 15% (*Shandong*) electrification of passenger transportation service by 2030	1. **Expand hydrogen fuel cell development, and large-scale deployment and incentivize hydrogen fuel cell vehicle purchases** by consumers and companies, especially in *Shandong* given size of freight vehicle fleet 2. Strengthen cooperation among departments to **maintain and continue development of charging infrastructure** 3. **Increase taxes for consumers and companies using conventional oil/diesel cars and trucks** The above actions should aim to: • Reach at least 85% (*Guangdong*) and 80% (*Shandong*) passenger transportation service electrification by 2050 • Increase total transportation electrification rate to greater than 45% (*Guangdong*) and 15% (*Shandong*) by 2050 • Reduce fossil use at least 50% by 2050 (compared with 2020) • Increase hydrogen share of final energy to nearly15% (*Guangdong*) and 30% (*Shandong*) by 2050
Power	1. **Create citing policies to expand wind and solar installations** 2. Increase grid stability through **demand-side management programs and incentives** 3. **Expand ambitious offshore wind power plans** 4. **Expand centralized & distributed solar PV** 5. Invest in **nuclear power safety and efficiency** and improve uranium resource security in *Guangdong* given current nuclear capacity 6. Invest in **storage capacity expansion** and research and development *These actions should aim to (Guangdong):* • Decrease coal use by about 50% (*Guangdong*) and 20% (*Shandong*) by 2030 (compared with 2020) • Increase solar and wind to a combined generation share of about 25% (*Guangdong*) and 20% (*Shandong*) by 2030	1. Continue to **increase wind and solar generation, with added storage capacity** 2. **Support the development of clean electricity supply sources in other provinces** and expand importing infrastructure, especially in *Guangdong* 3. **Develop additional, alternative clean energy sources,** such as biomass energy, waste incineration power generation, agricultural/ forestry biomass power generation, and biogas projects 4. **Promote the construction of nuclear power bases** and nuclear energy small reactor use in *Shandong* These actions should aim to: • Decrease the use of fossil fuels by at least 95% (*Guangdong*) and 90% by 2050 (*Shandong*) (compared with 2020) • Phase out coal generation without CCUS by 2045 • Expand solar, wind, and nuclear to at least 90% (*Guangdong*) and 85% (*Shandong*) of power generation by 2050

7. Conclusions and Areas of Future Research

Air pollution is a significant contributor to negative health outcomes, particularly mortality related to $PM_{2.5}$ exposure. Our analysis varied the use of end-of-pipe control policies, climate ambition and CCUS technology to evaluate the impact of different policy pathways on air pollutant emissions reduction in two key provinces, Guangdong and Shandong. Our results suggest that not only does decarbonization have air quality benefits for Guangdong and Shandong, but also that decarbonization and resulting energy system transformation is essential to achieve significant GHG and air pollutant emissions reductions. End-of-pipe control policies were found to improve air quality, but in the long-term, both end-of-pipe control and climate mitigation are needed to achieve maximum air quality improvement and premature mortality reduction in both Guangdong and Shandong. The scenario that combined best health effects and climate mitigation measures (NZ2050_BHE) had lower $PM_{2.5}$ concentration and premature deaths than the scenario with just enhanced end-of-pipe controls (Cpol_BHE). Additionally, our analysis suggests that $PM_{2.5}$ concentration is higher under scenarios with CCUS deployment, suggesting that the impacts of decarbonization policy options should be considered when developing climate mitigation strategies. Additional research is needed to understand the relationship between CCUS deployment and public health impacts.

Non-state actions at the provincial level in Guangdong and Shandong can help to realize climate goals and improve air quality. Our results suggest that both provinces will play a significant, but different role in meeting national climate targets, and will rely on different strategies, policies and measures to attain climate goals. Shandong, for example, will likely rely heavily on carbon capture, utilization, and storage technology, as it has a large storage capacity and will need to focus on transitioning from sources of fossil fuel for heating in colder months. Guangdong, as a service industry province, will need to prioritize both near and long-term actions to minimize emissions from the transportation sector, using both commercialized and in-development technologies. Despite underlying differences across provinces, many of the actions needed are similar - such as promoting electrification of light industries, passenger vehicles and heating and cooling in buildings. Collaboration across provinces on these shared challenges and strategies will help to achieve national targets.

Meeting both air quality targets and climate mitigation goals will require ambitious action. Guangdong should focus on increasing the proportion of renewable energy in power energy supply and phasing out fossil use in the power, buildings, industry and transportation sector, along with implementing end-of-pipe control policies. Developing more dual-focused policies can help to achieve both policy outcomes simultaneously, such as closing old, inefficient and high-polluting coal plants. Guangdong should prioritize electrification in key sectors - buildings, passenger transportation and light industry in the near-term, while investigating decarbonization approaches for harder-to-abate sectors, like freight transit and heavy industry.

Shandong faces both air pollution and GHG emissions reduction challenges, given the high level of coal-fired power generation and industry in the province. Shandong can improve air quality and achieve climate mitigation targets, through decarbonizing the power sector and promoting electrification across end-use sectors. To achieve these goals, Shandong should set provincial ambient air quality improvement targets and provincial carbon peaking and carbon neutrality timelines. Key policy measures include accelerating the pace of coal reduction and expanding renewable energy deployment; and promoting industrial low-carbon development, industrial optimization and upgrading, especially in iron and steel, non-ferrous metals, building materials and chemical industry sectors, and expanding low-carbon innovation and digital transformation in various fields.

While both provinces have different decarbonization pathways, and current levels of $PM_{2.5}$ and CO_2 emissions, some similar strategies are needed in both provinces. Phasing out fossil fuels, expanding renewable energy deployment and electrifying end-use sectors will be key for both provinces to decarbonize in alignment with the national carbon neutrality goal and to achieve WHO air quality targets. Shandong, as a province with high CCUS capacity will help offset emissions from densely populated provinces like Guangdong, while Shandong can potentially learn from Guangdong's successes in terms of building electrification rates and EV charging infrastructure.

Further evaluation of decarbonization and end-of-pipe controls across additional provinces and sectors is needed, as different approaches across all levels of government and sectors are needed to meet ambitious climate targets and improve air quality. Additionally, the spatial distribution of air pollutant emissions may vary within provinces, and more granular analysis would be valuable for understanding public health impacts. We also did not consider ozone concentration, or non-CO_2 emissions, which would be an interesting area for future study to evaluate achieving climate targets and resulting air quality impacts. Additionally, there is some ambiguity in the stated "30/60" goals, in terms of peaking and carbon neutrality timeline. We only evaluated one interpretation of this target, with peaking before 2030 and achieving net-zero GHGs by 2060, but evaluating a later peaking time could result in different findings. We also were unable to fully evaluate the pathways in the industry sector, as we did not have detailed, subsector modeled results. More detail subsectors could help to provide additional information on climate and health impacts, as well as policy pathways. We also couldn't model hydrogen production by province, so we didn't include it in this discussion. Finally, there is a great deal of uncertainty surrounding modeling projections, including projected energy demand, technology costs, GDP and population growth. Additional research and modeling analysis focused on China, especially Guangdong and Shandong, would be helpful to compare our findings, and identify areas of agreement and areas of future research.

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