



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

SUMMARY FOR POLICYMAKERS

By the Center for Global Sustainability (CGS) at the
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Earth System Science at Tsinghua University

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SUMMARY

There are strong synergies between climate change mitigation and air quality improvement. Coordinated strategies that deliver reductions of both greenhouse gas and local air pollutant emissions can help China achieve its goals on both fronts. Overall, 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. At the national level, China has set a climate target to achieve carbon neutrality before 2060 and a 2035 air quality target as an essential element of its “Beautiful China” strategy. At the provincial level, pathways towards net-zero emissions vary largely, depending on both the existing energy and economic structure but also the potential to transform. Similarly, if not more so, air quality and the associated public health issues have large regional variations, due to different climates, energy structures, and population concentration and demographic features. It is therefore critical to better understand the province-specific challenges and pathways for emissions reductions in line with delivering the national climate and air quality goals.

In this analysis, we develop provincial decarbonization pathways to achieve China’s carbon neutrality before 2060 using a global integrated assessment model with provincial details of China (GCAM-China), and conduct a deep dive analysis of local air quality improvement in two provinces - Guangdong and Shandong - by coupling GCAM-China with an air pollutant emissions model. Both provinces are economically significant, have varying reliance on fossil fuels, and are exposed to different levels of air pollution. Our analysis provides the first assessment of policy opportunities and strategies to reduce carbon dioxide and local air pollutant emissions in the two provinces.

The key findings are:

- ▶ Significant emissions reductions are needed across all provinces and all sectors to achieve China’s carbon neutrality goal.
- ▶ Individual provinces may take different pathways to achieve deep decarbonization, driven by variations in the underlying economic and energy structures and available resources.
- ▶ Shandong’s transition focuses largely on reducing emissions from the power and industry sectors as well as in space heating.
- ▶ Guangdong’s transition requires significant reductions in the transportation and buildings sectors, amid near-term growth in demand, especially in urban areas.
- ▶ Climate change mitigation is not only helpful but also necessary to achieve sustained air pollutant (SO₂, NO_x, and PM_{2.5}) emissions reduction in both Guangdong and Shandong; as end-of-pipe controls have larger impacts in the near term, combining both policy objectives can maximize the reduction potentials in local air pollution emissions.
- ▶ While the availability of carbon capture, utilization and storage (CCUS) technology may affect Shandong’s ability to reach net-zero CO₂ emissions by 2050, it has a limited impact on air pollutant emissions in either province.
- ▶ Further research is needed to better understand the impacts of sector-specific pathways and technologies for decarbonization and improved air quality.

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 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 µg/m³ or below by 2035 (United Nations, 2021; Xing et al., 2020). As China's current PM_{2.5} target is less stringent than the WHO's Phase IV recommended value of 10 µg/m³, this underscores the need for continued air quality improvement efforts (World Health Organization, 2021). On the other hand, 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). Nevertheless, 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 (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 greenhouse gas (GHG) emissions, may potentially exacerbate some air quality impacts due to continued use of fossil fuels or additional energy inputs (Koornneef et al., 2011).

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 emissions vary across provinces, depending on both the existing energy and economic structure but also the potential to transform (Nilsson et al., 2021). Air quality and associated public health issues also have large regional variations, due to different climates, energy systems, and population concentration and demographic features (Chen et al., 2020). To achieve its national targets, subnational action will likely play a key role in mobilizing regional air quality and climate action. 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. Overall, 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.

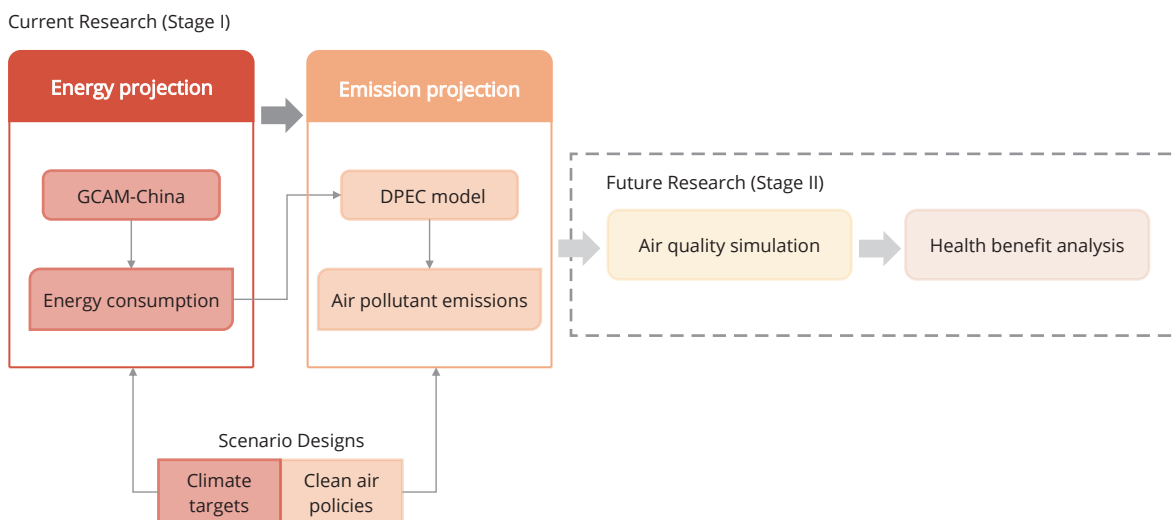
Here, we link a global integrated assessment model, the Global Change Analysis Model (GCAM-China)¹ and the Dynamic Projection model for Emissions in China (DPEC)² to produce air pollutant emissions pathways at the provincial level under alternative climate policy and clean air policy scenarios. Outputs of the models will provide inputs for the air quality simulations and health benefits analysis in the next stage of future research (Figure 1). See full report for methodology details.

¹ 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.

² 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.

FIGURE 1: ANALYTICAL APPROACH AND MODELING TOOLS.

This paper focuses on the energy and emission pathways using GCAM-China and the DPEC models; air quality simulation and health benefit analysis (shown in the dashed box) are not included in this report. Future research (Stage II) will focus on air concentration and health impacts.



We develop five scenarios to evaluate how climate and clean air policy choices could impact decarbonization and air pollutant emissions through 2060, including four core scenarios that vary across stringency of climate ambition and air pollutant control measures, and one additional scenario to explore the impact of excluding CCUS technology in climate mitigation (Table 1). Specifically, two climate ambition levels are modeled: first, national CO₂ emissions decline immediately after 2020 and reach net zero CO₂ by 2050 and further net-zero GHG by 2060 (**NZ2050**); second, climate ambition continues as reflected in the current policies without additional effort (**Cpol**). In addition, two levels of air pollutant controls are modeled, including the enhanced end-of-pipe policies in the Best Health Effects (BHE) scenario and existing air quality controls in the Business as Usual (BAU) scenario. Moreover, given the uncertainties in CCUS technology deployment, we also include a sensitivity analysis of reaching net zero CO₂ by 2050 where CCUS technology is assumed not available (**NZ2050_BHE_noCCUS**). Our five scenarios compare how climate mitigation targets and end-of-pipe control policies impact decarbonization and air quality.

Reaching national net zero CO₂ 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 with different timing of reaching net-zero emissions in the long run (Figure 2). In the near-term, rates of emissions reduction from 2020 to 2030 vary across provinces, between 5% and 42%. Net-zero year differs as well, with almost all provinces reaching net zero CO₂ emissions between 2045-2065, and the majority reaching net zero by 2055. Additionally, some provinces achieve negative emissions in the NZ2050 scenarios 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 CO₂ and especially non-CO₂ greenhouse gases.

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. 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 CO₂ emitting provinces,

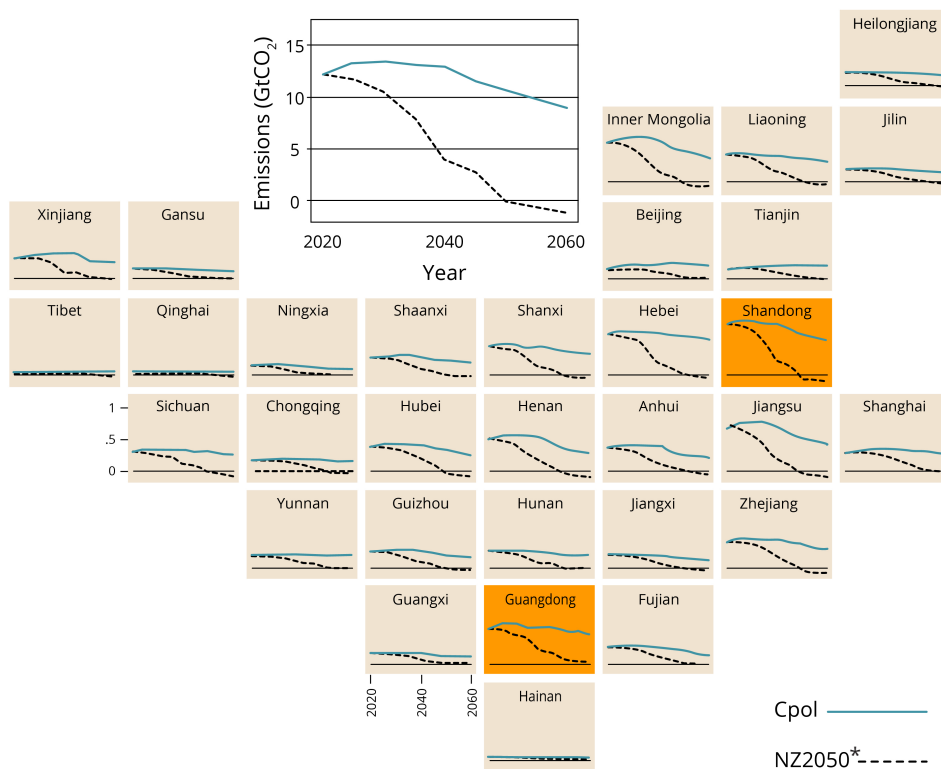
respectively (Carbon Emission Accounts and Datasets, 2023; Guan et al., 2021; National Bureau of Statistics, 2020; Shan et al., 2020). By assessing their pathways toward carbon neutrality and air quality improvement, we identify specific strategies

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.

TABLE 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
		<i>Sensitivity Analysis: NZ2050_BHE_noCCUS</i>	
	Business-As-Usual	NZ2050_BAU	Cpol_BAU

FIGURE 2: CARBON DIOXIDE EMISSIONS PATHWAYS UNDER CURRENT POLICY (CPOL) AND NET ZERO CO₂ 2050 (NZ2050) SCENARIOS ACROSS PROVINCES AND NATIONALLY.



* Note: NZ2050 scenario emissions peak before 2025, which exceeds the NDC target of peaking before 2030.



CURRENT AIR QUALITY AND CARBON DIOXIDE EMISSIONS IN SHANDONG AND GUANGDONG

Differences in underlying energy structure impact current emission levels of air pollutants and carbon dioxide across the two provinces. Guangdong and Shandong have different climates, leading to different energy needs for heating and cooling. Shandong has a colder climate, higher reliance on fossil fuels, higher emissions from heavy industry and poorer atmospheric dispersal conditions than Guangdong, increasing both air pollutants and carbon dioxide emissions.

Air pollution and carbon dioxide emissions are higher in Shandong than Guangdong. The annual average PM_{2.5} in Guangdong is 22 µg/m³ (Department of Ecology and Environment of Guangdong Province, 2021), which is not only lower than the national standard (35 µg/m³), but also the WHO Phase II target (25 µg/m³), though above the WHO Phase IV recommended value (10 µg/m³) (World Health Organization, 2021). In 2020, the annual average PM_{2.5} concentration in Shandong was 46 µg/m³ (People's Government of Shandong Province, 2021), which is higher than the national standard and WHO targets. CO₂ emissions in Shandong are nearly twice as

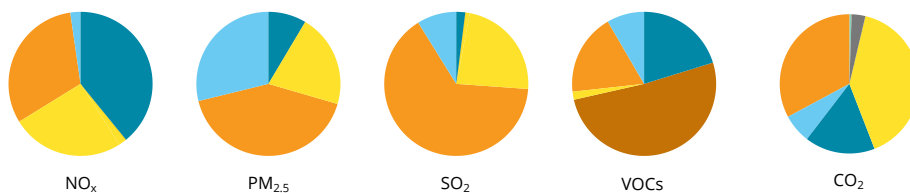
large as Guangdong, as the two provinces emitted around 940 and 570 MtCO₂ in 2019, respectively (Carbon Emission Accounts and Datasets, 2023; Guan et al., 2021; Shan et al., 2020).

Differences in energy sector make-up can impact current air pollutants and carbon dioxide emissions (Figure 3). For both provinces, the industry sector and the electricity sector contribute to high proportions of multiple air pollutants and CO₂, making them key sectors to achieve either climate or clean air outcomes. Industry is either the largest or second largest source of pollutant and CO₂ emissions in 2020 in both provinces, highlighting the need for dual-focused policies in the industry sector. While the transportation sector and the building sector have a limited share of CO₂ emissions in both provinces (though Guangdong has a larger share than Shandong), they produce a high proportion of emissions from a single pollutant (NO_x and PM_{2.5}, respectively). In both provinces, current levels of VOCs emissions are largely driven by solvent use.

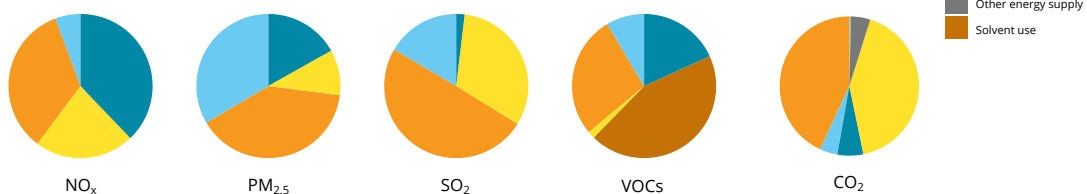
FIGURE 3: SECTOR BREAKDOWN OF AIR POLLUTANTS AND CARBON DIOXIDE EMISSIONS IN 2020 IN GUANGDONG AND SHANDONG.

AFOLU stands for Agriculture, Forestry and Other Land Use emissions and Other energy supply includes production of gases, liquids, hydrogen, and heat.

(a) Guangdong



(b) Shandong



Under China's carbon neutrality goal, both Shandong and Guangdong achieve significant emissions reductions across all sectors. Following the continuation of current policies, CO₂ emissions continue to increase in both provinces through 2030, and decline from the peak level by 36% in Shandong and by 27% in Guangdong by 2060 (Figure 2). Under the 2050 national net-zero pathway, CO₂ emissions decline immediately after 2020 in both provinces, with the largest reductions realized between 2030 and 2040, and reach net zero in 2050 in Shandong and a 88% reduction by 2050 and a 95% reduction by 2060 from 2020 in Guangdong. Large emissions reductions need to be achieved across the power, buildings, industry, and transportation sectors, and require enhanced actions and strengthened policy support in both provinces.

Specific pathways to enact the necessary energy system transition and emissions reductions, however, vary across the two provinces based on current and future demand in services and goods, economic and energy structure, as well as resource availability. For example, due to substantial emissions from difficult to decarbonize sectors, such as transportation, combined with very limited capacity for CCUS, Guangdong has residual net CO₂ emissions in the second half of the century, and its net emissions remain positive after 2050. By contrast, Shandong achieves a substantial rate of negative emissions, primarily through BECCS in the power sector as well as in hydrogen production. Shandong also achieves more rapid emissions reductions after 2030 when the high consumption of coal in electricity generation and industry is phased down.

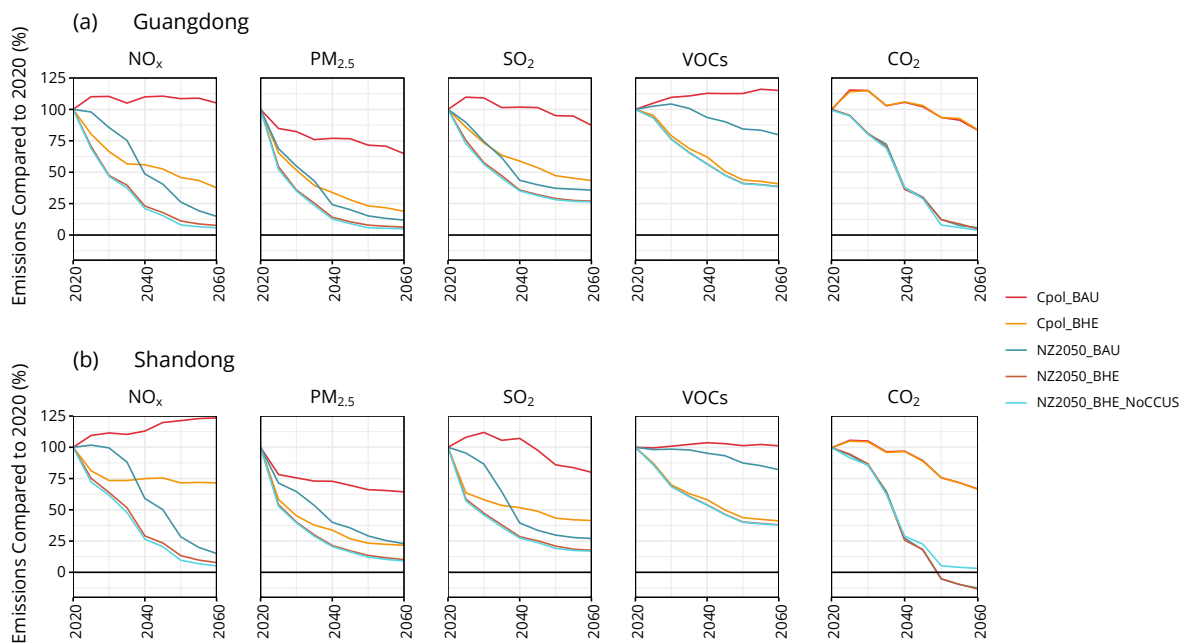
In addition to the large reductions in CO₂ emissions, we also observe strong decreases in the emissions of three air pollutants of importance to human health, NO_x, SO₂, and PM_{2.5}, under deep decarbonization in both provinces, especially when combined with the enhanced end-of-pipe control measures (Figure 4). In the near-term, end-of-pipe controls have a large impact, reducing all air pollutant emissions across both provinces by 25% or more from 2020 levels when implemented in absence of climate mitigation, under scenario Cpol_BHE (Figure 4). However, the low-carbon transition plays a larger role in the long run to lower air pollutant emissions. In 2040, emissions of NO_x, PM_{2.5}, and SO₂ are lower (by 13-29%) under the net zero scenario (NZ2050_BAU), compared to the scenario with just end-of-pipe controls, except for PM_{2.5} emissions in Shandong. Finally, when combining the best health effects and climate mitigation measures (NZ2050_BHE), the largest long-term reductions in air pollutant emissions are achieved. Both end-of-pipe and climate change mitigation measures are needed for delivering the maximum air pollutant emissions reductions.

While other air pollutants see a significant decline in emissions reduction from climate mitigation measures compared to scenarios with just end-of-pipe controls, VOCs emissions are determined primarily by air pollutant controls (Figure 4). VOCs emissions reduction from climate policies is limited in both Guangdong and Shandong, because more than half of VOCs come from solvent use, which is not impacted by climate mitigation measures. Including end-of-pipe controls, especially for VOCs, but also all pollutants, is critical for achieving maximum pollutant emissions reduction.

Although air pollutant emissions reduction is greater when the climate target is achieved without using CCUS technology, the impact may be limited (Figure 4). Our scenario results suggest that CCUS deployment has a minimal impact on

air quality emissions, only a 1-3% and 1-4% additional reduction in pollutants in Guangdong and Shandong, respectively, in the scenario without CCUS in 2050 compared to emissions in 2020.

FIGURE 4: EMISSIONS PROJECTIONS OF AIR POLLUTANTS AND CARBON DIOXIDE ACROSS SCENARIOS IN GUANGDONG AND SHANDONG.



Our results suggest that different mitigation approaches are needed in different sectors and for different pollutants. The following near-term and long-term strategies are recommended for

the building, industry, transportation, and power sectors in Guangdong and Shandong to reduce greenhouse gas and air pollutant emissions (Table 2).

TABLE 2: GUANGDONG AND SHANDONG NEAR AND LONG-TERM DECARBONIZATION AND AIR QUALITY IMPROVEMENT ACTIONS.

Sector	Near-Term Action	Long-Term Action
Buildings	<ol style="list-style-type: none"> Promote and provide subsidies for heat pumps, solar photovoltaics (PV) and storage, and electric appliances Improve efficiency standards of appliances/building equipment (<i>Guangdong</i>), centralized hot water supply, and hot water systems (<i>Shandong</i>) Develop targeted campaign for fuel switching in rural homes, especially traditional biomass and heating in <i>Shandong</i> Increase energy efficiency standards for new buildings, especially in <i>Guangdong</i> amid urban residential growth 	<ol style="list-style-type: none"> Increase renewable energy (distributed photovoltaic, solar thermal systems) in low and medium-rise residential buildings, hotels, dormitories, apartments, and other buildings Further improve electrification in heating, domestic hot water, and heating through subsidies and other investment mechanisms Renovate existing buildings and develop and construct ultra-low energy and near-zero energy buildings
Industry	<ol style="list-style-type: none"> Invest in high efficiency machinery and manufacturing techniques (such as TRT, CDQ, and Jet BOF)³ Recycle steel, cement, aluminum, and plastic in production Create a database of operations efficiency and equip low-performers with meters to monitor energy use closely 	<ol style="list-style-type: none"> Transition from blast furnace to electricity furnace use and develop new steel making techniques, such as electrolytic processes Electrify light industries including paper, textile, equipment manufacturing (<i>Guangdong</i>), and electronics and automotive (<i>Shandong</i>) Switch high temperature processes (chemicals, metals, and iron and steel) and other heavy industry to use hydrogen fuel
Transportation	<ol style="list-style-type: none"> Invest in research and development of alternative fuels for aviation, shipping, and other freight vehicles, especially in <i>Shandong</i> Incentivize hydrogen fuel cell vehicle purchases by consumers and companies, especially in <i>Shandong</i> Reduce electric vehicle (EV) cost for consumers through subsidies, waving taxes, deducting toll prices, and free parking, especially in <i>Guangdong</i> Increase charging infrastructure available for public use, especially in <i>Guangdong</i> 	<ol style="list-style-type: none"> Strengthen cooperation among departments to maintain and continue development of charging infrastructure Expand hydrogen fuel cell research, development, and large-scale deployment Increase taxes for consumers and companies using conventional oil/diesel cars and trucks
Power	<ol style="list-style-type: none"> Shut down high-emitting coal-fired power plants, especially under-performing & inefficient plants Promote onshore and offshore wind power Expand centralized & distributed solar PV Create citing policies to expand wind and solar installations, especially in <i>Shandong</i> Invest in nuclear power efficiency and improve uranium resource security in <i>Guangdong</i> 	<ol style="list-style-type: none"> Continue to increase wind and solar generation Support the development of clean electricity supply sources in other provinces and expand importing infrastructure in <i>Guangdong</i> Promote the construction of nuclear power and nuclear energy small reactor use in <i>Shandong</i> Develop additional, alternative clean energy sources, such as biomass energy, waste incineration power generation, agricultural/ forestry biomass power generation, and biogas projects

³ 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.

CONCLUSIONS AND FUTURE RESEARCH

Subnational actions at the provincial level in Guangdong and Shandong are critical to achieve climate goals and improve air quality. Our results suggest that each province 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, especially passenger vehicles, using both commercialized and in-development technologies. Despite underlying differences across the provinces, many of the actions needed are similar - such as promoting the electrification of light industries, passenger vehicles, and heating and/or cooling in buildings. Collaboration across provinces on these shared challenges and strategies will help to achieve national targets.

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. Our results suggest that end-of-pipe control policies have a near-term benefit for air pollution, but in the long-term, both end-of-pipe control and climate mitigation are needed to achieve significant air

quality improvement in both Guangdong and Shandong. These findings suggest that not only does decarbonization have air quality benefits for Guangdong and Shandong provinces, but also that decarbonization and resulting energy system transformation is essential to achieve significant air pollutant emissions reductions. Additionally, our analysis suggests that while emissions of some pollutants may be higher under scenarios with CCUS deployment, it may be limited, and additional research is needed to understand the spatial distribution of emissions and how small increases in air pollutants can translate to public health impacts.

Future research should continue to examine provincial differences in air quality and climate mitigation co-benefits, and expand analysis to other key regions in China. In addition, future research should examine additional GHGs and air pollutants, such as methane and ozone, and determine strategies for phasing these GHGs out of the energy system and evaluate resulting air quality impacts. As discussed, future research should also further evaluate the impact of CCUS technology on air pollution. Finally, examining pollutant concentrations and their health impacts will be critical in assessing undue pollution and health burdens on key demographics and regions, as well as help national and subnational policymakers better quantify the co-benefits of reaching China's climate and air quality targets at the local level.

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