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

SUMMARY FOR POLICYMAKERS

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

October 2023

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

SUMMARY FOR POLICYMAKERS

October 2023

Sha Yu[1], Jenna Behrendt[1*], Andy Miller[1], Yang Liu[2], Jacqueline Adams[1], Ryna Cui[1], Wenli Li[1], Haiwen Zhang[1], Jing Cheng[2], Dan Tong[2], Jiawei Song[1], Qiang Zhang[2], Nate Hultman[1]

[1] Center for Global Sustainability, School of Public Policy, University of Maryland, College Park, USA

[2] Department of Earth System Science, Tsinghua University, Beijing, China

* Corresponding Author: jbehrend@umd.edu

SUGGESTED CITATION

Yu S., J. Behrendt, A. Miller, Y. Liu, J. Adams, R. Cui, W. Li, H. Zhang, J. Cheng, D. Tong, J. Song, Q. Zhang, N. Hultman. 2023. "*Co-benefits between Air Quality and Climate Policies in Guangdong and Shandong Provinces in China: Summary for Policymakers.*" Center for Global Sustainability, University of Maryland & Tsinghua University. 11pp.

ACKNOWLEDGEMENTS

The authors acknowledge funding support from the Sequoia Climate Foundation. The authors gratefully acknowledge Jiehong Lou, Mengye Zhu, Haewon McJeon, Mel George Vallimyalil, Kowan O'Keefe and other reviewers from different research institutions in China, the United States and other countries for their helpful input on the report. The authors also acknowledge the high performance computing resources at the University of Maryland (http://hpcc. umd.edu) made available for conducting the research reported in this paper.

SCHOOL OF PUBLIC POLICY
CENTER FOR GLOBAL SUSTAINABILITY

清華大學地球系统科学系
Department of Earth System Science, Tsinghua University

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 $PM_{2.5}$ concentration 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.
- Without climate mitigation and energy transition efforts, neither of the provinces can achieve the most stringent WHO $PM_{2.5}$ concentration standards by 2050. Even with the best end-of-pipe control technologies and practices, $PM_{2.5}$ concentration in Guangdong exceeds Phase V and in Shandong is much higher than Phase IV WHO standards.
- Almost 300,000 $PM_{2.5}$ related deaths can be avoided in 2050 compared to current policies without enhanced air quality policies by implementing energy transition and end of pipe controls in both provinces.
- Availability of different decarbonization technologies can impact health outcomes; for example, $PM_{2.5}$ related premature deaths are further reduced in 2050 without carbon capture, utilization, and storage (CCUS) deployment in the net-zero transition.
- Specific climate mitigation measures can deliver large air quality and health benefits and can be prioritized for near-term action, such as phasing out solid fuels in rural residential buildings and targeting super polluting facilities in industry and power sectors.

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/m^3 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/m^3, 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 (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 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.

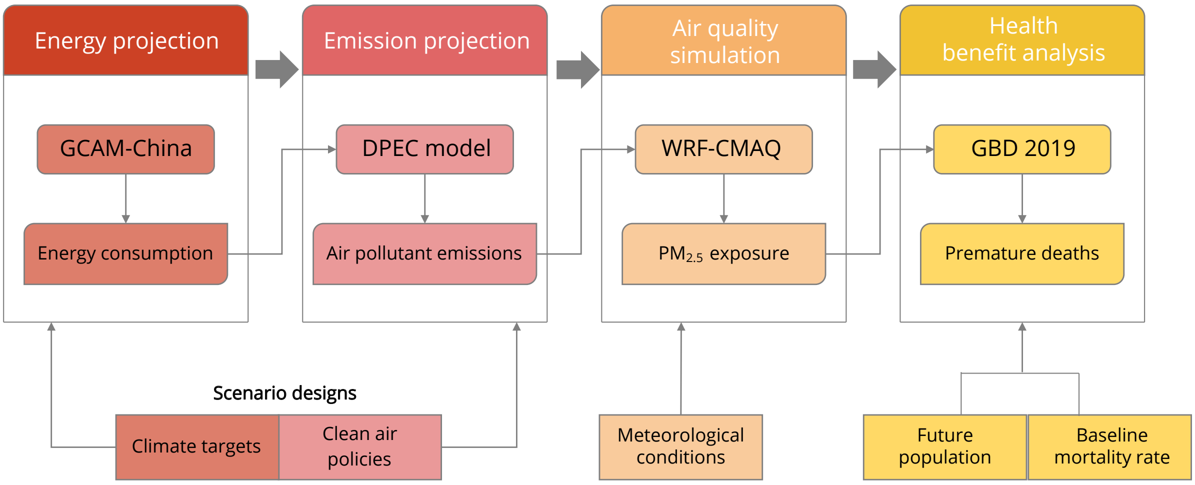
Here, we link a global integrated assessment model with provincial disaggregation of China, the Global Change Analysis Model (GCAM-China)[1], and the Dynamic Projection model for Emissions in China (DPEC)[2] to produce GHG and air pollutant emissions pathways at the provincial level under alternative climate policy and clean air policy scenarios.

[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 subregions 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.

We then use the Weather Research and Forecasting-Community Multiscale Air Quality Model (WRF-CMAQ)[3] to estimate $PM_{2.5}$ concentrations across scenarios (Cheng et al., 2021), and the concentration-response functions from the Global Burden of Disease (GBD) (GBD, 2019) report to estimate premature mortality impacts (Figure 1). See the tech appendix for methodology details.

FIGURE 1: ANALYTICAL APPROACH AND MODELING TOOLS.



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 to explore the impact of excluding CCUS technology in climate mitigation (Table 1). Specifically, two climate ambition levels are modeled: first, national CO_2 emissions decline immediately after 2020 and reach net zero CO_2 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 CO_2 by 2050 where CCUS technology is assumed not available (***NZ2050_BHE_noCCUS***). Our four scenarios compare how climate mitigation targets and end-of-pipe control policies impact decarbonization and air quality.

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 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 CO_2 emissions between 2045-2065, and the majority

[3] 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. Community Multiscale Air Quality (CMAQ) Version 5-2 is an air quality model developed by the U.S. EPA and used in this study for offline $PM_{2.5}$ concentration simulations.

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 CO_2 and especially non-CO_2 greenhouse gases.

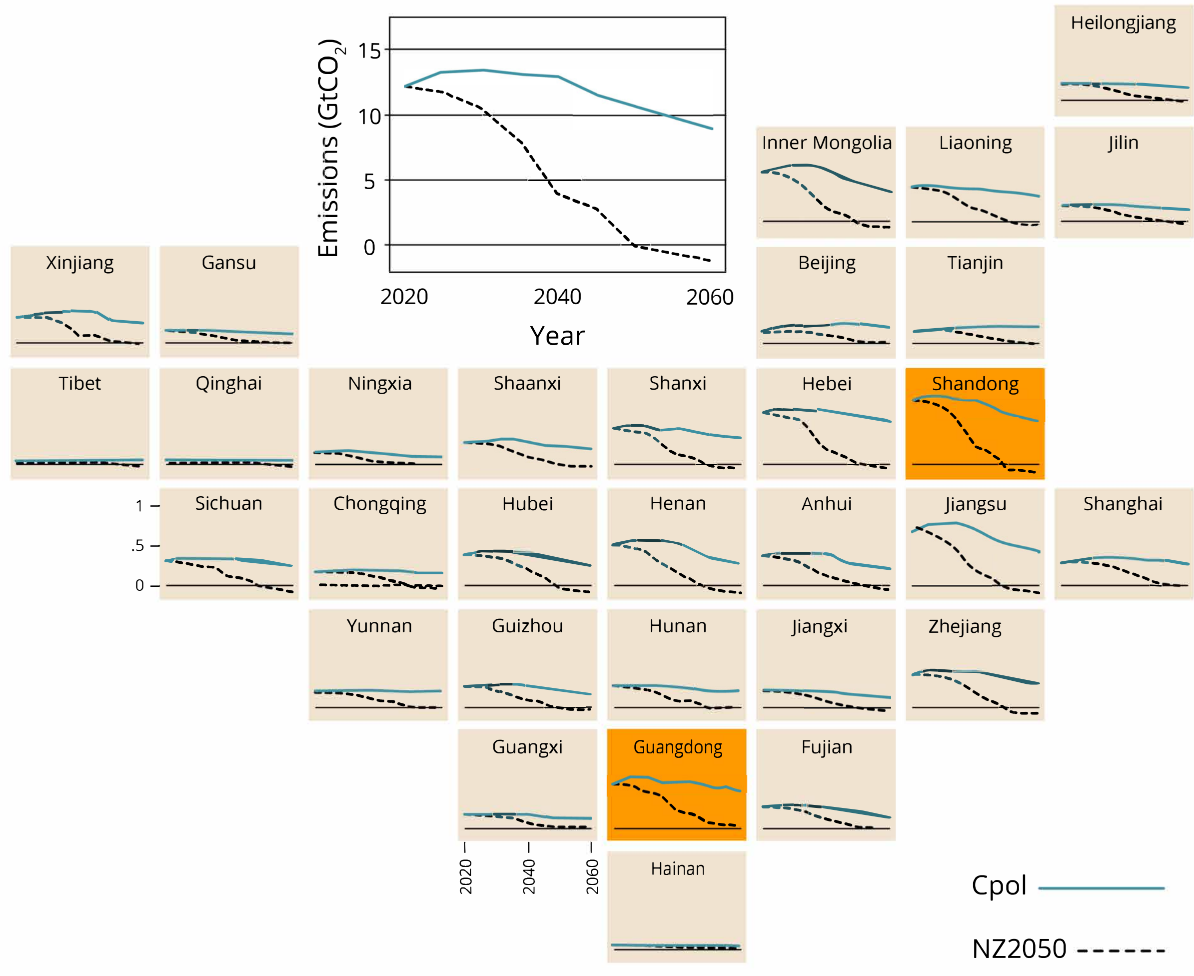
Based on the provincial pathways under alternative climate and clean air policies, we then take a deep-dive look at two provinces: Guangdong and Shandong. Guangdong and Shandong have the 1st and 3rd largest GDPs and the 1st and 2nd largest populations, respectively, but vary in terms of the underlying economic and energy structure, as the 5th and 1st highest CO_2 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**
		Sensitivity Analysis: NZ2050_BHE_noCCUS	
	Business-As-Usual		**Cpol_BAU**

FIGURE 2: CARBON DIOXIDE EMISSIONS PATHWAYS UNDER CURRENT POLICY (CPOL) AND NET ZERO CO_2 2050 (NZ2050) SCENARIOS ACROSS PROVINCES AND NATIONALLY.

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



CURRENT AIR QUALITY AND CARBON DIOXIDE EMISSIONS IN SHANDONG AND GUANGDONG

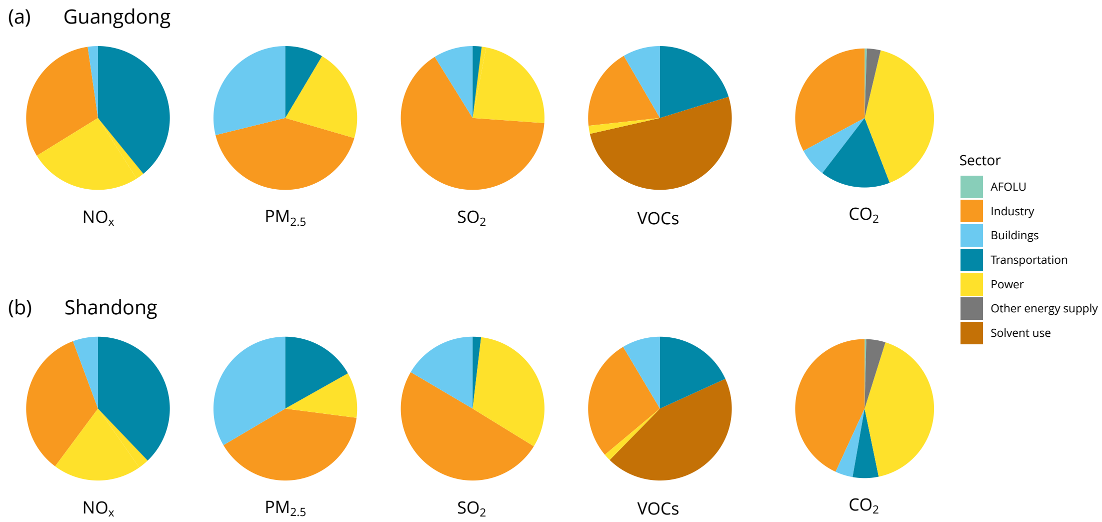
Differences in underlying energy structure impact current emission levels of air pollutants and carbon dioxide across the two provinces. Guangdong and Shandong have different climates, leading to different energy needs for heating and cooling. Shandong has a colder climate, higher reliance on fossil 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/m^3 (Department of Ecology and Environment of Guangdong Province, 2021), which is not only lower than the national standard (35 μg/m^3), but also the WHO Phase II target (25 μg/m^3), though above the WHO Phase IV recommended value (10 μg/m^3)(World Health Organization, 2021). In 2020, the annual average $PM_{2.5}$ concentration in Shandong was 46 μg/m^3 (People's Government of Shandong Province, 2021), which is higher than the national standard and WHO targets. CO_2 emissions in Shandong are nearly twice as large 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).

Differences in energy sector make-up can impact current air pollutants and precursors to $PM_{2.5}$ (NO_x, SO_2, VOCs) 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 CO_2, making them key sectors to achieve either climate or clean air outcomes. Industry is either the largest or second largest source of pollutant and CO_2 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 CO_2 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 Land Use emissions and Other energy supply includes production of gases, liquids, hydrogen, and heat.



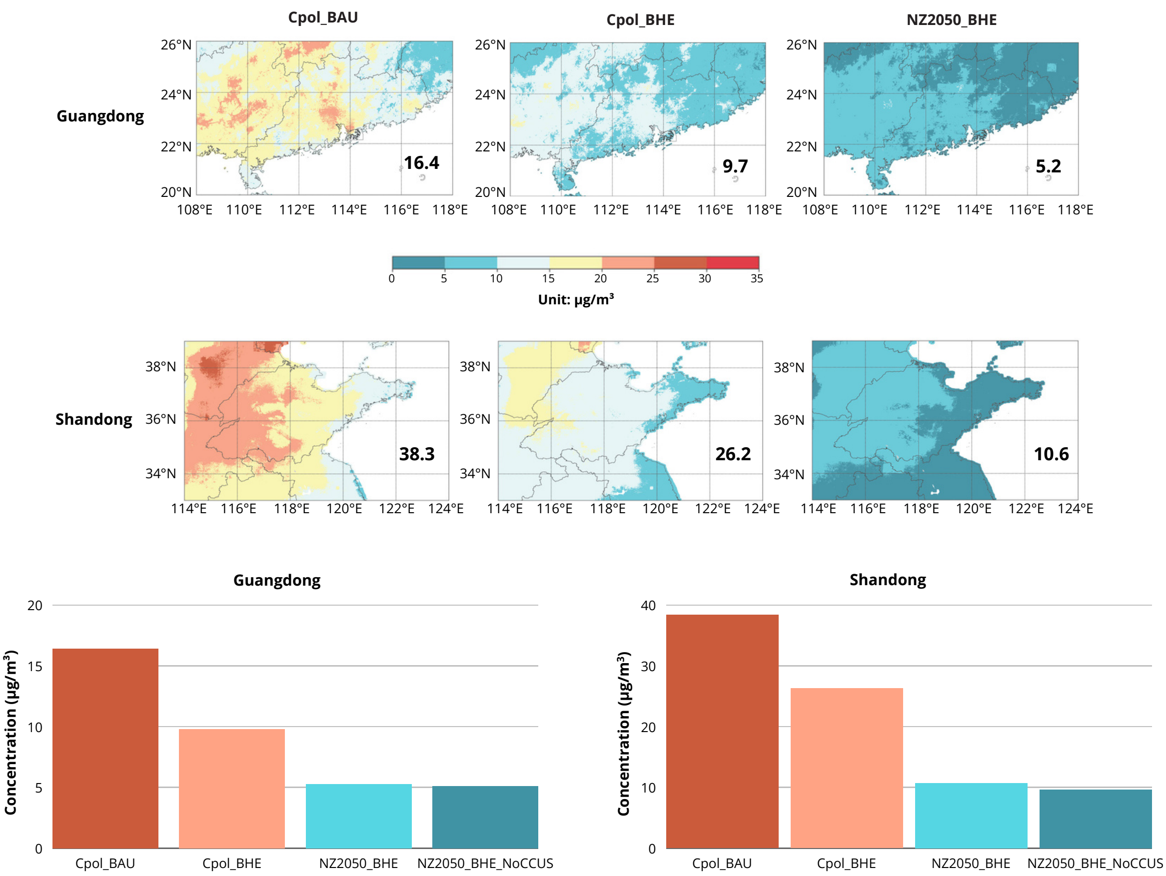
Under China's national carbon neutrality goal, both Shandong and Guangdong achieve significant emissions reductions across all sectors. Following the continuation of current policies, CO_2 emissions continue to increase in both provinces through 2030, and decline from the peak level by 36% in Shandong and by 27% in Guangdong by 2060 (Figure 2). Under the 2050 national net-zero pathway, CO_2 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 CO_2 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 CO_2 emissions, we also observe strong decreases in the $PM_{2.5}$ concentration under deep decarbonization in both provinces when combined with the enhanced end-of-pipe control measures. When combining the best health effects and climate mitigation measures (NZ2050_BHE), the largest long-term reductions in air pollutant emissions are achieved (Figure 4). $PM_{2.5}$ concentration across both provinces is lowest in the NZ2050 BHE scenarios, as compared to the current policy scenarios (Figure 4). Both provinces can achieve WHO $PM_{2.5}$ concentration standards by 2050 (Phase IV for Shandong, Phase V for Guangdong), but only under the NZ2050 scenarios. Climate mitigation policies result in 110 and 160 thousand premature deaths avoided in Guangdong and Shandong, a total of almost 300 thousand, in 2050, respectively. Both end-of-pipe and climate change mitigation measures are needed for delivering the maximum air pollutant emissions reductions.

Climate mitigation improves air quality, but the decarbonization pathway followed can impact public health. Air pollutant emissions reduction is greater when the climate target is achieved without using CCUS technology (Figure 4), and 11 thousand premature deaths are avoided across both provinces in the scenario without CCUS deployment.

FIGURE 4: $PM_{2.5}$ CONCENTRATION ACROSS SCENARIOS IN GUANGDONG AND SHANDONG IN 2050.



Our results suggest that mitigation approaches are needed across all sectors. While co-reduction of GHG and air pollutant emissions can be achieved, certain measures can be prioritized for large reduction in GHG emissions (e.g. coal phasedown in power generation), while others can be prioritized for large air quality and health benefits (e.g. phasing out diesel trucks in heavily-trafficked urban areas). In addition to assessing the co-benefits of one policy on the other, co-design of climate mitigation and air quality policies can help maximize outcomes on both goals. 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.

Among various mitigation strategies, there are specific measures that can deliver large air quality and health benefits that can be prioritized for near-term action. In the building sector, phasing out solid fuel (traditional biomass and scatter coal) consumption in residential rural homes can help improve air quality through a reduction in burning materials that create particulate matter. For industry, closing smaller boilers and super polluting facilities without end-of-pipe control equipment can have significant air quality impacts, by reducing SO_2, NO_x and $PM_{2.5}$ emissions. In transport, 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 $PM_{2.5}$. In the power sector, targeting the super polluting plants that have not completed the ultra-low emissions control for immediate retirements. Additional mitigation strategies are highlighted below in Table 2.

TABLE 2: GUANGDONG AND SHANDONG DECARBONIZATION AND AIR QUALITY IMPROVEMENT ACTIONS.

Actions are prioritized within near or long-term actions based on potential for air pollutant emissions reduction.

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, solar photovoltaics (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	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
Industry	1. Invest in **high efficiency machinery and manufacturing techniques** (such as TRT, CDQ, and Jet BOF)[4] 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	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***
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 charging infrastructure** available for public use, especially in ***Guangdong*** given size of passenger vehicle fleet	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**
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	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 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***

[4] 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 while end-of-pipe control policies improve air pollution, in the long-term, both end-of-pipe control and climate mitigation are needed to achieve WHO $PM_{2.5}$ concentration targets 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 and premature mortality reductions. 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.

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, further 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.

REFERENCES

Aunan, K., Fang, J., Hu, T., Seip, H. M., & Vennemo, H. (2006). Climate Change and Air Quality—Measures with Co-Benefits in China. *Environmental Science & Technology*, *40*(16), 4822–4829. https://doi.org/10.1021/es062994k

Carbon Emission Accounts and Datasets. (2023). Province. *CEADs*. https://www.ceads.net/data/province/

Chen, H., Zhang, L., Zou, W., Gao, Q., & Zhao, H. (2020). Regional Differences of Air Pollution in China: Comparison of Clustering Analysis and Systematic Clustering Methods of Panel Data Based on Gray Relational Analysis. *Air Quality, Atmosphere & Health*, *13*(10), 1257–1269. https://doi.org/10.1007/s11869-020-00880-0

Cheng, J., Tong, D., Zhang, Q., Liu, Y., Lei, Y., Yan, G., Yan, L., Yu, S., Cui, R. Y., Clarke, L., Geng, G., Zheng, B., Zhang, X., Davis, S. J., & He, K. (2021). Pathways of China's $PM_{2.5}$ Air Quality 2015–2060 in the Context of Carbon Neutrality. *National Science Review*, *8*(12), nwab078. https://doi.org/10.1093/nsr/nwab078

Department of Ecology and Environment of Guangdong Province. (2021). *2020 Report on the State of Guangdong Provincial Ecology and Environment*. http://gdee.gd.gov.cn/hjzkgb/content/post_3266052.html

GCAM. (2022). *GCAM v6 Documentation: Global Change Analysis Model (GCAM)*. https://zenodo.org/record/6619287

Geng, G., Zheng, Y., Zhang, Q., Xue, T., Zhao, H., Tong, D., Zheng, B., Li, M., Liu, F., Hong, C., He, K., & Davis, S. J. (2021). Drivers of $PM_{2.5}$ Air Pollution Deaths in China 2002–2017. *Nature Geoscience*, *14*(9), Article 9. https://doi.org/10.1038/s41561-021-00792-3

Guan, Y., Shan, Y., Huang, Q., Chen, H., Wang, D., & Hubacek, K. (2021). Assessment to China's Recent Emission Pattern Shifts. *Earth's Future*, *9*(11), e2021EF002241. https://doi.org/10.1029/2021EF002241

Koornneef, J., van Harmelen, T., van Horssen, A., & Ramirez, A. (2011). Carbon Dioxide Capture and Air Quality. In Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality. IntechOpen.

National Bureau of Statistics. (2020). *2020 China Statistical Yearbook*. https://www.yearbookchina.com/navibooklist-n3020013033-1.html

Nilsson, A., Smit, S., & Kuramochi, T. (2021). *Non-State and Subnational Climate Action in China*. https://newclimate.org/sites/default/files/2022/01/NewClimate_ChinaNSA_Jan22.pdf

People's Government of Shandong Province. (2021). *Ecological Environment Status Bulletin of Shandong Province in 2020*. http://www.shandong.gov.cn/art/2021/6/4/art_97560_416343.html

Scovronick, N., Budolfson, M., Dennig, F., Errickson, F., Fleurbaey, M., Peng, W., Socolow, R. H., Spears, D., & Wagner, F. (2019). The Impact of Human Health Co-Benefits on Evaluations of Global Climate Policy. *Nature Communications*, *10*(1), Article 1. https://doi.org/10.1038/s41467-019-09499-x

Shan, Y., Huang, Q., Guan, D., & Hubacek, K. (2020). China CO_2 Emission Accounts 2016–2017. *Scientific Data*, *7*(1), Article 1. https://doi.org/10.1038/s41597-020-0393-y

United Nations. (2021). China Headed Towards Carbon Neutrality by 2060; President Xi Jinping Vows to Halt New Coal Plants Abroad. *UN News*. https://news.un.org/en/story/2021/09/1100642

Wang, P., Lin, C.-K., Wang, Y., Liu, D., Song, D., & Wu, T. (2021). Location-Specific Co-Benefits of Carbon Emissions Reduction from Coal-Fired Power Plants in China. *Nature Communications*, *12*(1), Article 1. https://doi.org/10.1038/s41467-021-27252-1

World Health Organization. (2021). *WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. https://www.who.int/publications-detail-redirect/9789240034228

Xing, J., Lu, X., Wang, S., Wang, T., Ding, D., Yu, S., Shindell, D., Ou, Y., Morawska, L., Li, S., Ren, L., Zhang, Y., Loughlin, D., Zheng, H., Zhao, B., Liu, S., Smith, K. R., & Hao, J. (2020). The Quest for Improved Air Quality May Push China to Continue Its CO_2 Reduction Beyond the Paris Commitment. *Proceedings of the National Academy of Sciences*, *117*(47), 29535–29542. https://doi.org/10.1073/pnas.2013297117

Yamineva, Y., & Liu, Z. (2019). Cleaning the Air, Protecting the Climate: Policy, Legal and Institutional Nexus to Reduce Black Carbon Emissions in China. *Environmental Science & Policy*, *95*, 1–10. https://doi.org/10.1016/j.envsci.2019.01.016