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

TECHNICAL APPENDIX

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Models and Methodology

Energy Projection: GCAM-China

In this study, we use a China-focused version of GCAM, an integrated assessment model, called GCAM-China. 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 has previously been used to examine impacts of mitigation policies and technology deployment on greenhouse gas emissions (Clarke et al., 2008; Edmonds et al., 1997).

While the core version of GCAM disaggregates the global energy-economy system at 32 geopolitical regions, GCAM-China, a research branch of GCAM, further disaggregates the China region into 31 province-level 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.

Socioeconomic development, as well as energy demand, supply, and transformation are modeled at the provincial level in GCAM-China, and the model allows for electricity trade within grid regions. Renewable energy (such as solar and wind) and carbon storage resources are also provincial-specific, reflecting real-world constraints in resource availability. Moreover, GCAM-China takes in plant-level information for coal and nuclear power generation and tracks recent policy and infrastructure development for coal and nuclear power.

To model sectoral policies in GCAM-China under our NZ2050 scenarios, we used the following policies and parameters.

Table 1. Modeled Sectoral Policies in GCAM-China.

Sector	Action	Policy	Source of Policy or GCAM-integration Methodology
Buildings	Combined fossil phase-out	Phase-out of all fossil fuels in buildings by 2050	(The State Council, 2021a)
	Traditional biomass phase-out	Phase-out of traditional biomass from rural cooking and heating by 2025	(The State Council, 2021c, 2022b)
	Electrification	Reach nearly 100% electrification by 2050	(Q. Zhang et al., 2019)
	Increased energy efficiency	Green building code (Three Star/LEED) compliance and 2100 efficiency achieved in **2050**	(Gambhir et al., 2022; Yu et al., 2014, 2018)
Industry	Energy-efficiency improvement	1. Overall efficiency improvement of: **23% by 2035** 2. Increase efficiency of **cement** production **15% by 2035**, **25% by 2050** 3. Increase efficiency of **fertilizer** production **23% by 2035, 30% by 2050**	(Gambhir et al., 2022; International Energy Agency, 2021a; Ministry of Industry and Information Technology, 2021; Monteith & Menon, 2020)
	Coal phase-out	Decrease in coal usage starting in 2020 of 2.5 % / year (nearly full **phase-out by 2060**)	(CAEP & NRDC, 2021; J. Zhang & Wen, 2022)
	H_2 and electrification	Ambitious but achievable levels	Expert judgment
Transportation	Increased adoption of freight FCEV	Incentives for FCEV freight vehicles (trucks and buses)	(China Society of Automotive Engineers, 2020)
	Increased adoption of passenger BEV	All new passenger car sales in will be hybrid or all-electric vehicles in 2040	(WARC, 2020; Zhao et al., 2022)
	Enhanced fuel efficiency standards	Improve fuel efficiency standard improvements for passenger vehicles (exceed 75 grams of CO_2 per kilometer) by 2030	(Yang & Cui, 2022; Zhao et al., 2022)
	Shifting from SOV to low-carbon transit	Increased ridesharing by 2050 in provinces with significant urban populations by 25%	(Gambhir et al., 2022; Monteith & Menon, 2020; Project Drawdown, 2020)
		Increase use of public transportation in provinces with urban populations	(C40 Cities, 2021; Gambhir et al., 2022; Monteith & Menon, 2020)

Sector	Action	Policy	Source of Policy or GCAM-integration Methodology
Power	Coal phase-out	1. Phase-out of new coal power: Limit new coal power construction, then halt it after 2025 2. Retirement and reduced utilization of coal power plants older than **25 years**	(Lin, 2021; Schmollinger et al., 2021)
	Increase nuclear power	By 2050, installed capacity reaches **290 GW**	(World Nuclear Association, 2022; Xiao & Jiang, 2018)
	Increased hydropower	By 2030 an increase of 80 GW of hydro and **30 GW additional increase 2030-2050**	(International Energy Agency, 2023)
	Increased wind and solar	Increase total installed capacity of wind and solar power beyond the 1200 GW by 2030 target and achieve **5600 GW by 2050**	(UNFCCC, 2022)

Emissions Projection: DPEC Model

The DPEC was used to project future air pollutants emissions under global climate mitigation targets and China's local clean air policies. DPEC was developed by combining the integrated assessment model (GCAM-China) and the emissions projection model built based on emissions inventory (Multi-resolution Emission Inventory for China, MEIC). Based on the energy consumption projection from GCAM-China, the emissions projection model was used to project the future air pollutant emissions under the local clean air policies based on the evolution of future combustion / production technologies and control measures.

By using the DPEC model, the future energy consumption and air pollutant emissions can be quantified. The DPEC model was developed to project future air pollutant emissions by considering the pollution control policies, which includes two main models, the activity rate projection module and the emissions projection module (Tong et al., 2020). In the activity rate projection module, GCAM-China is used to provide standardized future energy demand and supply projection under different climate policy scenarios. In the emissions projection module, the sector-based technology turnover model was built to project future air pollutant emissions based on the evolution of future production technologies and control measures under local air pollution control policy scenarios.

Assumptions were made about what end-of-pipe control policies were incorporated in this analysis (Table 2).

Table 2. End-of-pipe Control Policy Assumptions for Guangdong and Shandong.

<table>
<tr><th>Emission source</th><th>2015</th><th>2016</th><th>2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029-2030</th><th>2031-2033</th><th>2034</th><th>2035</th><th>2036-2039</th><th>2040</th><th>2041-2044</th><th>2045</th><th>2046</th><th>2047</th><th>2048-2060</th></tr>
<tr><td>Coal-fired power plants</td><td>GB 13223 -2011</td><td colspan="3">achieving ultra-low standard</td><td colspan="11">achieved ultra-low emission standard</td><td colspan="2">achieving BAT control</td><td colspan="8">achieved BAT control [SO2-20;NOx30;PM-5]: removal efficiency of SO_2 99%; NOx>95%,de-PM devices update to WESP</td></tr>
<tr><td>Other thermal power plants</td><td colspan="3">GB 13223-2011</td><td colspan="3">achieving special limits</td><td colspan="4">achieved special limits</td><td colspan="3">achieving ultra-low emission</td><td colspan="5">achieved ultra-low emission standard</td><td colspan="3">achieving BAT control</td><td colspan="4">achieved BAT control</td></tr>
<tr><td>Coal-fired boilers (Heating and industrial)</td><td colspan="3">GB 13271-2014</td><td colspan="2">achieving limits</td><td>achieved limits</td><td colspan="3">achieving ultra-low standard</td><td colspan="8">achieved ultra-low emission standard</td><td colspan="4">achieving BAT control</td><td colspan="4">achieved BAT control</td></tr>
<tr><td>Iron and steel plants (Sinter/Coke/ Iron/Steel)</td><td colspan="3">standards</td><td colspan="2">special limits</td><td colspan="6">achieving ultra-low emission standard</td><td colspan="5">achieved ultra-low emission standard</td><td colspan="5">achieving BAT control of [SO2-35;NOx-50/100;PM-10]</td><td colspan="4">achieved BAT control: removal efficiency of SO2 >98%;NOx>93%,de-PM devices update to WESP</td></tr>
<tr><td>Nonferrous metal</td><td colspan="3">standards</td><td colspan="2">achieving special limits</td><td colspan="5">achieved special limits</td><td colspan="3">achieving ultra-low emission standard</td><td colspan="6">achieved ultra-low emission standard</td><td colspan="5">achieving BAT control</td><td>achieved BAT control</td></tr>
<tr><td>Cement plants</td><td colspan="3">GB 4915-2013</td><td colspan="2">achieving special limits</td><td colspan="3">achieved special limits</td><td colspan="3">achieving ultra-low emission standard</td><td colspan="8">achieved ultra-low emission standard</td><td colspan="3">achieving BAT control [SO2-35; NOx -50;PM-10]</td><td colspan="3">achieved BAT control: removal efficiency of SO_2>98%;NOx>95%,de -PM devices update to WESP</td></tr>
<tr><td>Flat glass</td><td colspan="3">GB 29495-2013</td><td colspan="2">achieving special limits</td><td colspan="5">achieved special limit</td><td colspan="3">achieving ultra-low emission standard</td><td colspan="7">achieved ultra-low emission standard</td><td colspan="3">achieving BAT control</td><td colspan="2">achieved BAT control</td></tr>
<tr><td>Bricklime and other industries</td><td colspan="3">standards</td><td colspan="2">achieving special limits</td><td colspan="5">achieved special limits</td><td colspan="4">achieving ultra-low emission standard</td><td colspan="6">achieved ultra-low emission standard</td><td colspan="4">achieving BAT control</td><td>achieved BAT control</td></tr>
<tr><td>Key VOCs-related industries</td><td colspan="3"></td><td colspan="3">improve LDAR</td><td colspan="7">further improve LDAR technology; install VOCs control facility in all VOC-related industries</td><td colspan="8">relative low emission levels</td><td colspan="4">Innovation of VOC control facilities</td></tr>
<tr><td>Light-duty gasoline vehicle</td><td colspan="2">China IV</td><td colspan="2">China V</td><td colspan="3">China IV a</td><td colspan="9">China IV b</td><td colspan="9">Assumed China VII</td></tr>
<tr><td>Heavy-duty gasoline vehicle</td><td colspan="5">China IV</td><td colspan="2">China V</td><td colspan="3">China VI a</td><td colspan="8">China VI b</td><td colspan="7">Assumed China VII</td></tr>
<tr><td>Light-duty diesel vehicle</td><td colspan="3">China IV</td><td colspan="4">China V</td><td colspan="2">China VI a</td><td colspan="8">China VI b</td><td colspan="8">Assumed China VII</td></tr>
</table>

Emission source	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029-2030	2031-2033	2034	2035	2036-2039	2040	2041-2044	2045	2046	2047	2048-2060
Heavy-duty diesel vehicle	China IV		China V				China VI a		China VI b												Assumed China VII				
All types of on-road vehicle*	phase out 20 million old vehicles			phase out 5.5 million old vehicles			phase out all the old vehicles																		
Off-road	China II	China III				China IV				China V										China VI a				China VI b	
Residential				cleaner coals and stoves			further reduce the ash and sulfur content in residential coal, and fully applied advanced stoves						relative low emission levels										Innovation of stoves and residential fuels		
Solvent use				lower the VOCs content			further improve the water-soluble solvent use; install VOC control facility in coating and painting industry							relative low emission levels									Innovation of solvent and VOC control facility		
Agriculture							enhance the intensive cultivation and graziery; promote the slow-release fertilizer							relative low emission levels									Innovation of cultivation and graziery		

Note:

BAT: best available pollution control technologies

*: Mobile fleet turnover policy

Air Quality Simulation: WRF-CMAQ Model

The WRF-CMAQ model was used to evaluate $PM_{2.5}$ concentrations under different scenarios. The Weather Research and Forecasting Model (WRF v3-9-1) 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.

Our simulation domain covers the entire Chinese mainland with a horizontal resolution of 36 km × 36 km. To better analyze the concentration variations at the provincial level in Guangdong and Shandong, the final simulation results were interpolated from the base year $PM_{2.5}$ concentration data (TAP) to obtain a 1 km $PM_{2.5}$ concentration data. In the WFR simulations, we used the reanalysis data from the National Center for Environmental Prediction Final Analysis (NCEP-FNL) as the initial and boundary conditions, and the meteorological parameters results were entered in the CMAQ model. Future changes in meteorology are not considered in this work, and meteorological conditions in 2020 are used in all simulations. Boundary conditions were provided by the global Goddard Earth Observing System (GEOS-Chem) simulations. A one-month rotation was applied in each simulation to reduce simulation uncertainty. It is a global 3-D model of atmospheric chemistry driven by meteorological input from the GEOS of the NASA Global Modeling and Assimilation Office (https://geoschem.github.io/).

Natural source emissions were also included in this study. Biogenic source emissions were calculated from the Model for Gaseous and Aerosol Emissions from Nature version 2-1 (MEGAN v 2-1). Open fire combustion emissions were obtained from the fourth generation Global Fire Emissions Database (GFED4). Future natural source emissions due to climate change are not considered in this work, and natural emissions in 2020 are fixed in all simulations.

Health Benefit Analysis: GBD 2019

In this work, the latest concentration-response functions developed in Global Burden of Disease (GBD, 2019) were used to estimate the $PM_{2.5}$ attributable deaths (Tong et al., 2020). In this work, we estimated deaths caused by ischemic heart disease (IHD), stroke (ischemic and hemorrhagic), chronic obstructive pulmonary disease (COPD), lung cancer and lower respiratory infection. Since we have obtained the spatial distribution of $PM_{2.5}$, we first estimate the $PM_{2.5}$ attributable deaths at 0.1°×0.1° grid level, and its function is as follows.

$$M_i = B \times P_i \times PS_j \times AF_j(C_i) \quad (1)$$

Where M_i is the premature mortality attributable to $PM_{2.5}$ exposure in grid *i*. *B* is the age-specific baseline mortality rate. GBD2019 provides the baseline mortality rate in the base year, and future premature mortality rates are calculated based on the changes in mortality rates in the World Population Prospects 2019 report (United Nations, 2019). P_i is the total population amount in grid *i*, PS_j is the proportion of population in the age group *j*. The gridded population data in 2020 were collected from the Gridded Population of the World fourth version (GPW v4) dataset and the gridded population data in 2030 and 2060 were obtained from Shared Socioeconomic Pathways (SSPs) database. The AF_i is an attributable fraction in grid *i* and it can be calculated as follows.

$$AF = \frac{RR-1}{RR} = 1 - \frac{1}{RR}, \quad (2)$$

$$RR(C) = \begin{cases} 1, & C \le tmrel \\ \dfrac{MRBRT(C)}{MRBRT(tmrel)}, & C > tmrel \end{cases} \quad (3)$$

Where *C* is the $PM_{2.5}$ concentration, *MRBRT* is the relative risk from fitting the MR-BRT splines curves and Institute for Health Metrics and Evaluation (IHME) provides the lookup table to use. *tmrel* is the theoretical minimum-risk exposure level and we use the 1000 samples of a uniform distribution from 2.4 to 5.9 mg/m^3 used in GBD 2019.

Then, the relative risk can be converted to attributable fraction (AF):

$$AF = \frac{RR-1}{RR} = 1 - \frac{1}{RR} \quad (2)$$

To estimate the $PM_{2.5}$-related mortality at regional and provincial level, we first estimate the $PM_{2.5}$-related deaths in the 0.1°×0.1° grid. Therefore, *B*, the age-specific baseline mortality rate, P_i, total population amount in grid *i*, PS_j, proportion of population in the age group *j*, and AF_i, attributable fraction in grid *i*, were multiplied to calculate the premature mortality attributable to $PM_{2.5}$ exposure, M_i.

$$M_i = B \times P_i \times PS_j \times AF_j(C_i) \quad (3)$$

For estimating the $PM_{2.5}$-related mortality, both population and baseline mortality are needed. The gridded population data in 2020 were collected from the GPW v4 dataset and the population data in 2030 and 2050 were obtained from SSPs database (O'Neill et al., 2016;Doxsey-Whitfield et al., 2015). GBD 2019 provided the age-specific baseline mortality rate for ischemic heart disease, stroke (ischemic and hemorrhagic), COPD, lung cancer and acute lower respiratory infection. For cardiovascular disease (CVD) cause (ischemic heart disease and stroke), we estimate separate curves for each 5-year age group in 2015. The baseline mortality rates in 2030 and 2060 are calculated based on the changes in premature mortality rates in the 2019 World Population Prospects.

Decompose drivers of variations in $PM_{2.5}$-related mortality

In this work, we decompose the drivers of variations in $PM_{2.5}$-attributable deaths in different periods. $PM_{2.5}$-attributable deaths is determined by the population size and distribution (*P*), population structure (*PS*), health care (*H*) and relative risks associated with $PM_{2.5}$ exposure (*AF*). So, we attribute the drivers of $PM_{2.5}$-attributable deaths to population change, population structure change, health care improvement and air quality improvement. The detailed decomposition method is described below.

$$\Delta M_P = Mean(\sum\nolimits_{th,tps,taf}(\sum\nolimits_i \sum\nolimits_j P_{tT} \times B_{th} \times PS_{tps} \times AF_{taf} - P_{t0} \times B_{th} \times PS_{tps} \times AF_{taf}))$$

$$\Delta M_{PS} = Mean(\sum\nolimits_{tp,th,taf}(\sum\nolimits_i \sum\nolimits_j PS_{tT} \times P_{tp} \times B_{th} \times AF_{taf} - PS_{t0} \times P_{tp} \times B_{th} \times AF_{taf}))$$

$$\Delta M_H = Mean(\sum\nolimits_{tp,tps,taf}(\sum\nolimits_i \sum\nolimits_j B_{tT} \times P_{tp} \times PS_{tps} \times AF_{taf} - B_{t0} \times P_{tp} \times PS_{tps} \times AF_{taf}))$$

$$\Delta M_{AF} = Mean(\sum\nolimits_{tp,tps,th}(\sum\nolimits_i \sum\nolimits_j AF_{tT} \times P_{tp} \times PS_{tps} \times B_{th} - AF_{t0} \times P_{tp} \times PS_{tps} \times B_{th}))$$

Where *i* and *j* represent the index of grid and population age group. *t0* and *tT* represent the start time and end time of decomposition changes. *th, tp, tps, taf* are time indicators, which all include *t0* and *tT*. ΔM_P, ΔM_{PS}, ΔM_H and ΔM_{AF}, respectively reflect impacts of population size and distribution change, population structure change, health care improvement and air quality improvement.

In this work, we decomposed the four drivers of variations in $PM_{2.5}$-related mortality during 2020-2050. The four drivers were changed one by one in order and the differences before and after each change are regarded as the contribution of each driver factor. Specifically, for each scenario, we first changed the population size and distribution (fixed in 2020 or projection in future), the population age structure (fixed in 2020 or projection in future),

$PM_{2.5}$ concentration (fixed in 2020 or projection in future), and health care (fixed in 2020 or projection in future) to obtain 16 results. Then the contribution of each driving factor can be considered as the difference between the future years and 2020. Finally, considering the difference under combinations of changes in other drivers, the mean value of those results is used as the final contribution of this driver factor.

Provincial Selection Methodology

Provincial Selection: To pinpoint differences in development, we ranked 30 provinces[1] in China (excluding Tibet, given limited data availability) on three key metrics: *fossil fuel dependency, air pollution, and economic development*. *Fossil fuel dependency* was measured using data from a multitude of sources: the share of employment in the mining industry (National Bureau of Statistics, 2020), share of fossil fuels in electricity (China Electricity Council, 2020), share of fossil fuels in final energy (GCAM-China output), and share of GDP contribution from the coal industry (Hao et al., 2019). *Air pollution* was measured using NO_2 concentration, O_3 concentration, $PM_{2.5}$ concentration, total air pollutants (Myllyvirta, 2020), and premature deaths (Yin et al., 2020). Finally, *economic development* was measured using GDP per capita and the share of tertiary industry (National Bureau of Statistics, 2020).

We ranked all 30 provinces on most to least fossil fuel dependency, most to least air pollution, and most to least economic development. From these rankings, we split select provinces into two key groups: Group 1, with higher dependency on fossil fuels, poor air quality and lower GDP per capita, and Group 2, with less dependence on fossil fuels, better air quality, and higher GDP per capita. From Group 1 and Group 2, we selected one province of interest. Shandong was selected from Group 1 for its larger air pollutant concentration as well as its large economy, higher emissions, and large population. Guangdong was selected from Group 2 for its low emissions and pollutant concentration, as well as its large population and economy. The large economies and populations of these two provinces have a substantial influence on China as a whole. Additionally, Guangdong and Shandong represent different development pathways, which allows for greater research and explanation into the diverse mitigation pathways needed to address net-zero and air quality goals across all provinces.

[1] This is based on the GCAM-China model, which disaggregates the China region into 31 sub-regions at the province level.

Air Pollutant Emissions Pathway Analysis

In addition to the large reductions in CO_2 emissions, we also observe strong decreases in the emissions of three air pollutants of importance to human health, NO_X, SO_2, 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 SO_2 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.

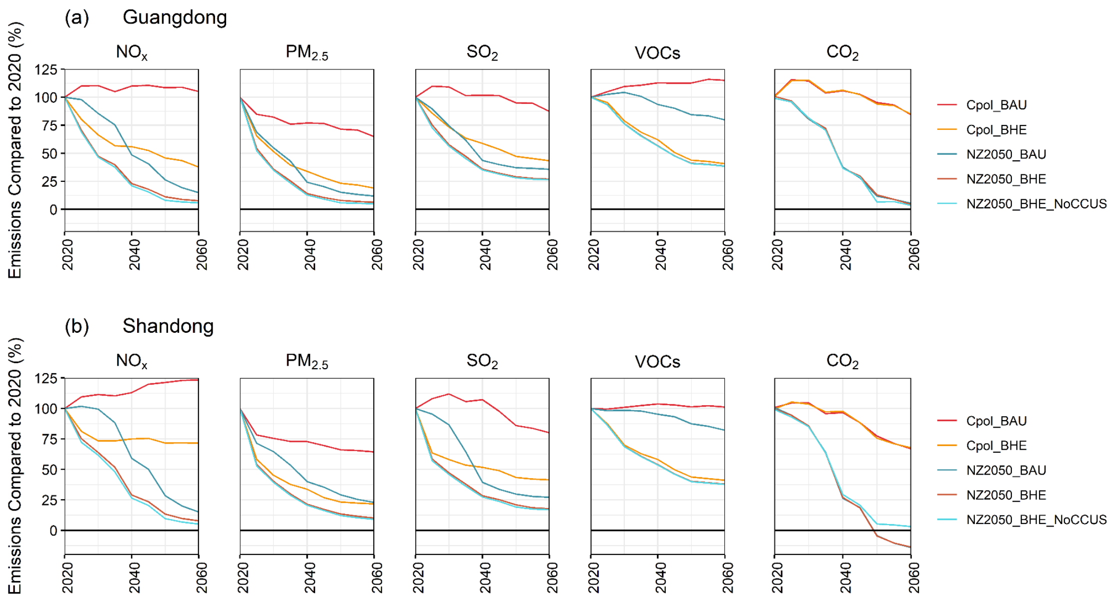

Figure 1. Emissions Projections of Air Pollutants and Carbon Dioxide Across Scenarios in Guangdong and Shandong.

Comparative Analysis Between Shandong and Guangdong

Table 3. Comparative Analysis Between Shandong and Guangdong.

Data of Year: 2021

A. Economy Situation/Structure	Guangdong	Shandong
Gross Domestic Products (GDP)(100 million yuan)	124369.7	83095.9
Energy Intensity by GDP (tce/10000 yuan)[2]	0.30	0.54
Population Density of Urban Area (persons/sq.km)	3819	1716
Urbanization Rate (%)	74.6	63.9
Area of Centralized Heating (10000 sq.m)	0	172859
Value-added of Industry above Designated Size by Sector (100 million yuan)	37306.5	27243.6
1. High-end manufacturing[3] (%)	53.7	25.4

[2] Data on value are calculated at current prices (2021), while indices are at constant prices. GDP and energy consumption data are from the 2022 China Statistical Yearbook.
[3] Industry classification referencing the OECD industry definitions and China Manufacturing 2025.

2. Light Industry[4] (%)	19.7	19.3
3. Resource Processing Industry (%)	27.1	55.5
B. Transportation[5]	**Guangdong**	**Shandong**
Passenger Turnover (million passenger-km)	235219	70560
Freight Turnover (million ton-km)	2838806	1200214
C. Energy Consumption by Sector (10000 tons of SCE) (%)[6]	**Guangdong**	**Shandong**
Total	36821.4	44611.1
1. Farming, Forestry, Animal, Husbandry and Fishery	711.81 (2.0%)	583.1 (1.3%)
2. Industry and Composition Ratios	20304.99 (56.5%)	34029.4 (76.3%)
Mining (%)	0.6	2.1
Manufacturing (%)	49.2	67.8
Production and Supply of Electricity, Gas and Water (%)	7.7	6.3
3. Construction	720.5 (2.0%)	535.3 (1.2%)
4. Transport, Storage, Postal and Telecommunication Services	3307.7 (9.2%)	2181.8 (4.9%)
5. Wholesale and Retail Trade and Catering Services	2096.3 (5.8%)	1073.3 (2.4%)
6. Residential Consumption	5884.5 (16.0%)	4595.1 (10.3%)
D. Energy Consumption/Production and Composition Ratios[7]	**Guangdong**	**Shandong**
Final Energy Consumption (10000 tons of SCE)	35955.6	44611.1
1. Coal (%)	5.2	63.0
2. Oil Product (%)	13.6	16.0
3. Electricity (%)	61.0	5.7
4. Others (%)	20.2	15.3
Final Energy Production (10000 tons of SCE)	8892.7	13030.9
1. Coal (%)	0	48.5

[4] The statistical criteria for light industry refer to the National Economic Industry Classification GB/T 4754-2017 and the Directory of Light Industry Classification.
[5] Passenger/freight turnover refers to the sum of the products of the volume of transported passengers/cargo multiplied by the transport distance.
[6] Data are from2022 Guangdong and Shandong Statistical Yearbook. The ratios are of total energy consumption.
[7] Data are from2022 Guangdong and Shandong Statistical Yearbook. The ratios are of total energy consumption.

2. Crude Oil (%)	28.0	24.2
3. Natural Gas (%)	18.1	0.5
4. Primary Electricity and Other Energy (%)	53.9	26.7
E. Power Generation (10^8 kw·h)[8] **and Composition Ratios**	6154	6196
1. Hydro Power Generation (%)	3.6	0.2
2. Fossil Power Generation (%)	72.9	85.0
3. Nuclear Power Generation (%)	20.2	2.5
4. Wind Power Generation (%)	2.2	6.6
5. Solar Power Generation (%)	1.7	5.0

Summary of Comparative Analysis on Guangdong and Shandong

The comparative analysis between Shandong and Guangdong provinces shows significant differences in various aspects such as industrial technology level, transportation, industrial structure, energy consumption structure, and power. Guangdong has a lower unit GDP energy consumption, indicating more efficient energy use and higher industrial technology level (Li & Li, 2010). Transportation demand is higher due to higher urbanization rate and population density (Chen et al., 2018), and the industrial structure is more focused on high-end manufacturing and high-tech industries. Energy consumption is more diversified and cleaner, and power (electricity) is more diversified, including ranking first in nuclear power generation. In contrast, Shandong still relies on traditional coal resources in many aspects, and its industrial and energy consumption structures are relatively monolithic. Power (electricity) is mainly generated by coal-fired power, and the differences in greenhouse gas and air pollutant emissions are significant between the two provinces. Here are some specific contents.

1. Economic Development. The energy intensity by GDP in Guangdong and Shandong is 0.30 and 0.54 tce/10000 yuan, respectively. A lower energy intensity indicates lower energy consumption per unit of GDP, which typically reflects higher production efficiency and cleaner, more efficient energy use. Thus, the data suggests that Guangdong is more energy-efficient than Shandong, and this also implies that Guangdong has a higher level of industrial technology (Li & Li, 2010).

[8] The data presented is derived from the 2022 China Energy Statistical Yearbook.

2. Industrial Structures. Shandong and Guangdong provinces have distinct industrial structures. Shandong's industrial sector is characterized by a higher proportion of traditional and heavy chemical industries, while Guangdong's is dominated by high-end manufacturing and high-tech industries. These differences in industrial structure can be attributed to factors such as geography, history, and culture, and have varying impacts on each province's economic development. The varying energy consumption and emission factors of different industries also result in significant differences in greenhouse gas and air pollutant emissions between the two provinces.

3. Energy Structure. When comparing the energy structures of Shandong and Guangdong provinces, several differences emerge in terms of industrial structure, resource types, and energy production structures. Shandong has a higher proportion of energy consumption in the manufacturing and mining industries, relying heavily on traditional coal resources, resulting in a relatively monolithic energy consumption structure. On the other hand, Guangdong has a higher proportion of energy consumption in transportation and residential sectors, and relies less on coal, using more natural gas and other energy sources in energy production. This is reflected in their energy production structures as well, with Guangdong having a more diversified energy structure, including a higher proportion of nuclear power generation, while Shandong's energy mix is dominated by fossil power, mainly coal-fired. These differences in industrial structure, resource types, and energy production structures can be attributed to variations in resource endowments, technological conditions, and policy orientations between the two provinces. Additionally, Guangdong's favorable technological conditions for electricity and other energy production, along with active government policy orientation in this field, contribute to its higher proportion of electricity and other energy production compared to Shandong.

4. Transportation. Compared with Shandong, Guangdong exhibits a higher energy consumption in the transportation sector. This can be attributed to two primary factors. Firstly, Guangdong boasts a greater degree of urbanization rate and population density, resulting in pronounced traffic congestion, which in turn increases the consumption of transportation energy. Secondly, as a pivotal transportation hub in southern China, Guangdong grapples with greater scale and heightened demand for transportation, evidenced by its amplified passenger and

freight turnover volumes. In contrast, Shandong's location in northern China fosters dispersed transportation demand and a relatively remote geographic position, consequently leading to a comparatively lower energy consumption in transportation.

Air Quality and Climate Policies in China

The following policies were reviewed to assess the policy framework in Guangdong and Shandong, relevant actors, sectors, and focus areas, with a specific focus on gap identification.

Table 4. Relevant Air Quality and Climate Policies Across China.

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
Cross-Sector Policies							
The 14[th] Five-Year Plan for the Comprehensive Work on Energy Conservation and Emissions Reduction (The State Council, 2022a)	"十四五"节能减排综合工作方案	2021-2025	National	All	VOCs, NO_x, NH_3-N	Air Quality, Climate	1. By 2025, the national energy consumption per unit of GDP will drop by 13.5% compared to 2020 2. Total energy consumption will be reasonably controlled, and the total emissions of chemical oxygen demand, ammonia nitrogen, nitrogen oxides and volatile organic compounds will drop by 8%, 8%, more than 10% and more than 10% respectively compared to 2020. 3. Energy conservation and emissions reduction policies and mechanisms are more sound, the efficiency of energy use in key industries and the level of control of major pollutant emissions basically reached the international advanced level, and the green transformation of economic and social development achieved significant results.
The 12[th] Five-Year Plan on Air Pollution Prevention and Control in Key Regions (Agency of Environmental Protection et al., 2012)	重点区域大气污染防治"十二五"规划	2012-2016	19 provinces targeted through various initiatives	All, with focus on Power, Industry, Transit	PM, SO_2, NO_x, VOCs	Air Quality	1. By 2015 reduce emissions of SO_2, NO_x, and industrial dust by 12%, 13%, and 10% respectively; comprehensively address VOCs emissions; reduce the concentration of SO_2 and PM_{10} by 10%, NO_2 by 7%, and $PM_{2.5}$ by 5%, compared to 2010. 2. Reduce the concentration of $PM_{2.5}$ in Beijing-Tianjin-Hebei area, Pearl River Delta, Yangtze River Delta by 6% compared to 2010.

[9] PM includes $PM_{2.5}$ and PM_{10}

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
Air Pollution Prevention and Control Action Plan (The State Council, 2013), Measures for the Assessment of the Implementation of the Air Pollution Prevention and Control Action Plan (Trial) (The State Council, 2014)	大气污染防治行动计划 (十条) 大气污染防治行动计划重点工作部门分工方案; 大气污染防治行动计划实施情况考核办法(试行)	2013-2017	Beijing-Tianjin-Hebei area, Pearl River Delta, Yangtze River Delta	All, with focus on Power, Industry, Transit	PM, SO_2, NO_x, VOCs	Air Quality	1. By 2017, decrease PM_{10} concentration in urban areas by 10% compared to 2012; resulting in annual increase in number of days with fairly good air quality 2. Concentrations of $PM_{2.5}$ in heavily polluted Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta regions must fall by around 25%, 20%, and 15% compared to 2012 level, respectively. 3. $PM_{2.5}$ annual concentrations in Beijing must be controlled below 60 mg/m3.
The 13th Five-Year Plan for Comprehensive Work on Energy Conservation and Emissions Reduction (International Energy Agency, 2021b)	"十三五"节能减排综合工作方案	2016-2020	National	All, with focus on Industry, Buildings, Transportation, Agriculture	SO_2, NO_x, VOCs, NH_3	Air Quality, Climate	1. By 2020, energy intensity will be reduced by 15% compared with 2015, and the total energy consumption will be capped within 5 billion tons of standard coal equivalent. 2. National total chemical oxygen demand, emissions of NH_3, SO_2, NO_x will be controlled below 20.01 million tons, 2.07 million tons, 15.80 million tons, 15.74 million tons, which are 10%, 10%, 15% and 15% lower than that in 2015, respectively.
Interim Provisions on the Administration of Pollution Discharge Permits (Agency of Environmental Protection, 2016); The Implementation Plan for the Permit System for Controlling Pollutant Discharge (The State Council, 2016b)	关于印发《排污许可证管理暂行规定》的通知; 国务院办公厅关于印发控制污染物排放许可制实施方案的通知	2016	National	Power, Industry	PM, SO_2, NO_x, VOCs, NH_3	Air Quality	1. Polluting entities must obtain a pollutant discharge permit for industrial emissions or the emissions of specified hazardous and toxic atmospheric pollutants. 2. Pollutant discharge permit is also required for entities manufacturing and operating coal-burning heat sources.

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
The 13th Five-Year Plan for the Ecological Environmental Protection (The State Council, 2016a)	"十三五"生态环境保护规划	2016-2020	National	All, with specific measures on Power, Industry, Transportation	PM, SO_2, NO_x	Air Quality	1. By 2020, for cities where the existing $PM_{2.5}$ standards have not been met, the urban concentration of $PM_{2.5}$ is targeted to decrease by at least 18% compared with 2015. 2. Annual number of days with fairly good air quality targeted to increase to at least 80%, and highly polluted days to decrease by at least 25% compared with 2015.
The Action Plan for Peaking Carbon Dioxide Emissions Before 2030 (The State Council, 2021a)	2030年前碳达峰行动方案	2021-2030	National	All, almost cover all the key economic sectors.	CO_2	Climate	1.By 2025, the proportion of non-fossil energy consumption will reach about 20%, energy consumption per unit of GDP will drop by 13.5% compared to 2020, and CO_2 emissions per unit of GDP will drop by 18% compared to 2020, laying a solid foundation for achieving carbon peaking. 2. By 2030, the proportion of non-fossil energy consumption will reach about 25%, CO_2 emissions per unit of GDP will drop by more than 65% compared to 2005, and the goal of carbon peaking by 2030 will be successfully achieved.
The 2020 Volatile Organic Compound Treatment Plan (Ministry of Ecology and Environment, 2020)	2020年挥发性有机物治理攻坚方案	2020	National, with key regions	All	PM, VOCs, O_3	Air Quality	Effectively enhance VOCs management capacity, achieve a significant reduction in VOCs emissions, and effectively curb O3 pollution in summer. the key regions, the junction areas of Jiangsu, Anhui, Shandong and Henan and other O_3 pollution prevention task heavy areas of the city June to September the average number of good days increased by about 11 days, to promote the 13th FYP to determine the provinces (autonomous regions and municipalities) the number of good days ratio binding targets fully completed.

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
The Plan for Improving the Dual Control System of Energy Consumption Intensity and Total Volume (National Development and Reform Commission, 2021)	国家发展改革委关于印发《完善能源消费强度和总量双控制度方案》的通知	2016-2030	National	All	N/A	Climate	1. By 2025, the dual control system of energy consumption will be more complete, the allocation of energy resources will be more reasonable, and the utilization efficiency will be greatly improved. 2. By 2030, the dual control system for energy consumption will be further improved, the intensity of energy consumption will continue to drop significantly, the total energy consumption will be reasonably controlled, and the energy structure will be more optimized. 3. By 2035, the optimal allocation of energy resources and the overall conservation system will be more mature and finalized, which will strongly support the achievement of the goal of steady and steady reduction of carbon emissions after reaching the peak.
Opinions on Further Prevention and Control of Pollution (The State Council, 2021b)	中共中央国务院关于深入打好污染防治攻坚战的意见	2021-2035	National	All	PM, CO_2, SO_2, NO_x, VOCs, NH_3	Air Quality, Climate	1. By 2025, the ecological environment will continue to improve, total emissions of major pollutants will continue to decline, carbon dioxide emissions per unit of GDP will drop by 18% compared to 2020, fine particulate matter ($PM_{2.5}$) concentration in cities at the prefecture level and above will drop by 10%, the ratio of good air quality days will reach 87.5%, heavy polluted weather will be basically eliminated, and the ratio of heavily polluted days nationwide will be limited to less than 1%. The ratio of heavy polluted weather is basically eliminated, and the ratio of heavy and above polluted days is controlled within 1%. By 2025, the total ammonia emissions from large scale farms in Beijing, Tianjin, Hebei and surrounding areas will drop by 5% compared to 2020. 2. By 2035, a green production and lifestyle will be widely formed, carbon emissions will be steadily reduced after reaching the peak, the ecological environment will be fundamentally improved, and the goal of building a beautiful China will be basically achieved.

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
The 13th Five-Year Plan for the Prevention and Control of Volatile Organic Compounds Pollution (Agency of Environmental Protection et al., 2017)	"十三五"挥发性有机物污染防治工作方案	2017-2020	National, with key regions	All, with focus on Industry, Transportation, Agriculture, and Buildings	VOCs	Air Quality	By 2020, reduce total VOCs emissions by 10% compared to 2015 level
Measures for the Management of Air Pollution Prevention and Control Funds (Ministry of Finance, 2021)	大气污染防治资金管理办法	2021-2025	National	All	PM, O_3, VOCs, NO_x	Air Quality	Support the implement of the Recommendations on comprehensively strengthening ecological and environmental protection and resolutely fighting for pollution prevention and control
Three-Year Action Plan for Making China's Skies Blue Again (The State Council, 2018b)	打赢蓝天保卫战三年行动计划	2018-2020	Beijing-Tianjin-Hebei and surrounding areas	All, with focus on Power, Industry, Transit	PM, SO_2, NO_x, VOCs, NH_3	Air Quality	1. Targets for reducing sulfur dioxide (SO_2) and nitrogen oxides by 2020, both to decrease by at least 15% compared with 2015. 2. For cities where the existing $PM_{2.5}$ standards have not been met, the urban concentration of $PM_{2.5}$ decreases by at least 18% compared with 2015. The annual number of days with fairly good air quality increases to at least 80%, and highly polluted days decreases by at least 25% compared with 2015. 3. Explicit mention of reduction in emissions of pollutants "in coordination with" a reduction in emissions of greenhouse gases (integrating the management of air pollution and climate change)
Shandong Province's Action Plan for Making China's Skies Blue Again (2021-2025) (Department of Ecology and Environment of Shandong Province, 2021)	山东省深入打好蓝天保卫战行动计划（2021—2025年）	2021-2025	Shandong Province	All, with focus on Power, Industry, Transit	PM, O_3, VOCs, NO_x	Air Quality	By 2025, the province's annual average $PM_{2.5}$ concentration will reach 38 micrograms per cubic meter, O_3 concentration will remain stable, the proportion of good air quality days will reach 72.5%, and the proportion of heavily polluted days and above will not exceed 0.8%.

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
Special Action Plan for Intensified Treatment of Volatile Organic Compounds in Summer and Autumn of 2020 in Shandong Province (People's Government of Shandong Province, 2020)	山东省2020年夏秋季挥发性有机物强化治理专项行动方案	2020	Shandong Province	Industry	PM, NO_x, SO_2	Air Quality	By the end of 2020, the province's industrial furnace air pollution comprehensive management system is basically established, the level of equipment and pollution management significantly improved, monitoring and control system is more sound, the pollutants are fully and stably meet the standard emissions, industrial industries sulfur dioxide, nitrogen oxides, particulate matter and other pollutant emissions further decline, iron and steel, building materials and other key industries to effectively control the total amount of carbon dioxide emissions, to promote continuous improvement in ambient air quality and industrial quality development.
Shandong Province's Implementation Recommendations on Comprehensively Strengthening Protection for Ecological Environment and Against Pollution (People's Government of Shandong Province, 2018b)	山东省关于全面加强生态环境保护坚决打好污染防治攻坚战的实施意见	2018-2020	Shandong Province	All	PM, SO_2, NO_x, NH_3-N, CO_2	Air Quality, Climate	By 2020, the province's average concentration of fine particulate matter ($PM_{2.5}$) strives to reduce 35% compared to 2015, and the average proportion of days with good air quality in cities with districts reached 62%. Total emissions of sulfur dioxide, nitrogen oxides, chemical oxygen demand and ammonia nitrogen decreased by 27%, 27%, 11.7% and 13.4% or more, respectively, compared to 2015. CO_2 emissions per unit of gross regional product decreased by 20.5%. compared to 2015

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
Shandong Province's Plan for Making China's Skies Blue Again (2013-2020) and Three-year Plan for Protection Against Pollution (2018-2020) (People's Government of Shandong Province, 2018a)	山东省打赢蓝天保卫战作战方案暨2013—2020年大气污染防治规划三期行动计划（2018 —2020年）	2018-2020	Shandong Province	All	PM, SO_2, NO_x, O_3	Air Quality	1. By 2020, the province's total emissions of sulfur dioxide and nitrogen oxides, respectively, more than 27% lower than in 2015, the province's annual average $PM_{2.5}$ concentration to ensure the completion of the improvement targets set by the State, and strive to improve 35% over 2015, ozone concentration rising trend year by year has been significantly curbed. 2. The addition of two or more municipalities with districts to meet the national secondary standards for air quality. 3. The province's excellent air quality rate of no less than 62%, and the ratio of heavily polluted days and above reduced by more than 50% compared to 2015. 4. The annual average concentration of $PM_{2.5}$ in the cities set up with districts strives to eliminate high values greater than 60μg/m3. 5. 7 transmission channel cities air quality indicators strive to meet national requirements.
Guangdong Province's Action Plan of for Making China's Skies Blue Again (2018-2020) (People's Government of Guangdong Province, 2018)	广东省打赢蓝天保卫战实施方(2018—2020年)	2018-2020	Guangdong Province	All	PM, SO_2, NO_x, VOCs	Air Quality	1. By 2020, the province's proportion of good air quality days (AQI compliance rate) to 92.5%, the average annual concentration of fine particulate matter ($PM_{2.5}$) is controlled at 33 micrograms per cubic meter or less, the basic elimination of heavy polluted weather, the annual evaluation of the six basic indicators of air quality in cities at or above all levels to meet the national secondary standards, Shenzhen strive to reduce the average annual concentration of $PM_{2.5}$ to 25 micrograms per cubic meter or less. 2. Implementation of multi-pollutant synergistic emissions reduction, by 2020, the province's sulfur dioxide (SO_2,), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) and other major pollutants emissions decreased by 5.4%, 3% and 18% respectively compared to 2015

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
Guangdong Province Issued the 2018 Energy Saving and Emissions Reduction Work Promotion Plan (China Clean Development Mechanism Fund, 2018)	广东省印发2018年节能减排工作推进方案	2018	Guangdong Province	All	VOCs,	Air Quality, Climate	In 2018, the province's energy consumption per unit of GDP fell by 3.2% compared to 2017, total energy consumption was controlled within 335.42 million tons of standard coal, and emissions of major pollutants completed the target tasks set by the state.
The 14th Five-Year Plan for Mitigating Climate Change of Guangdong Province (Department of Ecology and Environment of Guangdong Province, 2022)	广东省应对气候变化"十四五"专项规划	2022-2025	Guangdong Province	All	PM, CO_2, SO_2, NO_x, VOCs	Climate	The total amount and intensity of carbon emissions were effectively controlled. The province's carbon peak action is in full swing, and by 2025 carbon dioxide emissions per unit of GDP will drop by 20.5% compared to 2020, with carbon intensity levels continuing to be at the forefront of the country
Guangdong Province's Action Plan for Continuously Improving Air Quality (2021-2025) (Draft for Comments) (People's Government of Guangdong Province, 2021)	广东省环境空气质量持续改善行动计划（2021-2025 年）	2021-2025	Guangdong Province	All	PM, SO_2, NO_x, VOCs, O_3	Air Quality	1. By 2025, the proportion of good air quality days (AQI compliance rate) in the province will reach more than 95%, the annual average concentration of $PM_{2.5}$ will be controlled below 22 μg/m3, the rising trend of O_3 will be effectively controlled, the number of days with O_3 as the primary pollutant exceeding the standard will be reduced, and heavy polluted weather will be basically eliminated. Guangzhou and Foshan City, the annual average value of nitrogen dioxide (NO_2) is controlled at less than 30 micrograms / cubic meter. 2. By 2025, the completion of the national emissions reduction targets for nitrogen oxides (NO_x) and volatile organic compounds (VOCs).
Industry-Specific Policies							

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
Industrial Green Development Plan (Ministry of Industry and Information Technology, 2016)	工业绿色发展规划	2016-2020	National	Industry	SO_2, NO_x, VOCs	Air Quality, Climate	All-encompassing plan to: improve energy efficiency, reduce pollution and emissions substantially, enhance the comprehensive utilization of resources, cut GHG emissions, improve technical supporting capability, accelerate the construction of a green manufacturing system, push forward green and coordinated industrial development, implement the mode of “green manufacturing + Internet”, enhance the basic capability for green development, boost green and open industrial development.
Notice of the Ministry of Science and Technology on Issuing the "Implementation Plan for the Green Development Special Action of the National High-tech Zone" (Ministry of Science and Technology, 2021)	科技部关于印发《国家高新区绿色发展专项行动实施方案》的通知	2021-2025	National, with focus on high-tech zone	All, with focus on high-tech industry	CO_2	Climate	1. The first to achieve the United Nations 2030 Agenda for Sustainable Development, near-zero industrial wastewater emissions, carbon peaking, and modernization of the park's green development governance within the national high-tech zones, and some high-tech zones are the first to achieve carbon neutrality. 2. The average annual reduction rate of carbon dioxide emissions per unit of industrial added value will be more than 4%, and some high-tech zones will achieve carbon peaking. Three main tasks: 1. Promote energy conservation and emission reduction in national high-tech zones, optimize the green ecological environment. Reduce the amount of pollutants in the park and lower the consumption of fossil energy in the park, construct a new model of green development. 2. Guide national high-tech zones to strengthen the supply of green technologies, build a green technology innovation system. Enhance research and development of green technologies, establish a green technology standard and service system, and implement pilot demonstrations of green manufacturing. 3. Support the development of green industries in national high-tech zones, establish a green industrial system.

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
Notice on Issuing the "Guidelines for Governance of Key Industries Involving Volatile Organic Compounds (VOCs) in Guangdong Province" (Department of Ecology and Environment of Guangdong Province, 2021a)	广东省涉VOCs重点行业治理指引	2021-2035	Guangdong Province	Focus on 12 key industries of VOCs emissions	VOCs, PM, O_3	Air Quality	Each policy task requirements based on whether it is "mandatory" divided into "requirements" and "recommended" two categories. Encourage enterprises to meet the basic control requirements on the basis of the implementation of the "recommended" control requirements to further improve the comprehensive management of VOCs and reduce VOCs emissions.
The Implementation Plan for Comprehensive Control of Air Pollution in Industrial Furnaces and Kilns in Shandong Province (Department of Ecology and Environment of Shandong Province, 2020)	山东省工业炉窑大气污染综合治理实施方案	2018-2020	Shandong Province	Industry, with focus on industrial furnace	SO_2, NO_x, PM, CO_2	Air Quality	By the end of 2020, the province's industrial furnace air pollution comprehensive management system is basically established, the level of equipment and pollution management significantly improved, monitoring and control system is more sound, the pollutants are fully and stably meet the standard emissions, industrial industries sulfur dioxide, nitrogen oxides, particulate matter and other pollutant emissions further decline, iron and steel, building materials and other key industries to effectively control the total amount of carbon dioxide emissions, to promote continuous improvement in ambient air quality and industrial quality development
Notice of the Department of Ecology and Environment of Guangdong Province on the Key Work of Comprehensive Renovation of Industrial Furnaces and Boilers in 2021 (Department of Ecology and Environment of Guangdong Province, 2021b)	广东省生态环境厅关于2021年工业炉窑、锅炉综合整治重点工作的通知	2021	Guangdong Province	Industry, with focus on industrial kilns, boilers	PM, VOCs	Air Quality	Complete more than 70% of industrial furnace enterprises involved in comprehensive remediation work
Power-Specific Policies							

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
Recommendations on Comprehensively Strengthening Protection for Ecological Environment and Against Pollution (The State Council, 2018a)	关于全面加强生态环境保护坚决打好污染防治攻坚战的意见	2018	National	Power	Smoke dust, SO_2, NO_x	Air Quality	By 2020, all coal-fired power plants eligible for transformation complete ultra-low emissions transformation; high-polluting coal-fired power plants that are not eligible in key areas are gradually retired
The 14th Five-Year Plan for Energy Development of Shandong Province (People's Government of Shandong Province, 2021)	山东省能源发展"十四五"规划	2021-2025	Shandong Province	Power	N/A	Climate	1. By 2025, Coal power generation, clean energy generation, and out-of-province power accounted for The proportion of electricity consumption of the whole society is optimized from 68:15:17 to 60:20:20. The proportion of coal consumption decreases to within 60%, and the proportion of non-fossil energy consumption increases to about 13%. The proportion of renewable energy power increased to about 19%. 2.By 2035, clean energy will become the main energy supply, fossil energy basically The main purpose is to achieve clean and efficient use of fossil energy.
Transportation-Specific Policies							
Notice of the State Council on Issuing the Development Plan for Energy-Saving and New Energy Automobile Industry (2012-2020) (The State Council, 2012)	国务院关于印发节能与新能源汽车产业发展规划(2012—2020年)的通知	2012-2020	National	Transportation	N/A	Air Quality, Climate	1. Fuel consumption for new passenger vehicles: by 2015, standard vehicles <6.9 L/ 100 km, energy efficient vehicles <5.0 L/100km; by 2020, standard vehicles <5 L/ 100 km, energy efficient vehicles <4.5 L/100km 2. National fuel consumption standards established for various types of vehicles by 2016 3. Total production and sales of electric vehicles and plug-in hybrid vehicles reached 500,000 by 2015 and 5 million by 2020; production capacity reached 2 million per year. Fuel cell vehicle and automotive hydrogen energy industries advance with international standards.

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
Technical Guidance for Motor Vehicle Pollution Prevention and Control (He & Li, 2018; Ministry of Ecology and Environment, 2017)	机动车污染防治技术政策	2017	National	Transportation	PM, NO_x, CO, THC, CO_2, NH_4	Air Quality, Climate	1. Gradually tighten emissions limits for CO, THC, NO_x and PM. Enhance the control of unconventional pollutants from motor vehicles. 2. National emissions standards set by The Ministry of Ecology and Environment, should be adopted for new motor vehicles. Encourage localities to implement more strict vehicle emissions standards and fuel standards that national standards.
Limits and Measurement Methods for Emissions from Light-duty Vehicles (Ministry of Ecology and Environment, 2016)	轻型汽车污染物排放限值及测量方法GB 18352.6–2016	2020	National	Transportation	PM, NO_x, CO, THC, NMHC	Air Quality	Light-duty vehicles sold and registered in China are required to comply with this standard effective July 1, 2020. The China 6 standard for light-duty vehicles is similar to the EU No 715/2007, No 692/2008 standard, and United Nation Global Technical Regulation No.15, Worldwide Harmonized Light Vehicles Test Procedure, with some deviations.
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)	乘用车企业平均燃料消耗量与新能源汽车积分并行管理办法	2018	National	Transportation	N/A	Climate	Auto companies producing or importing over 30,000 non-NEV passenger cars per year will be required to earn NEV credits equal to a set percentage of their non-NEV sales in China starting in 2019. The required annual NEV credit percentage is 10% in 2019 and will increase to 12% in 2020.
Buildings-Specific Policies							
Assessment Standard for Green Buildings (Ministry of Housing and Urban-Rural Development, 2006, 2014, 2019)	绿色建筑评价标准	2006, 2014, 2019	National	Buildings	NH_3, CH_2O, C_6H_6, VOCs	Air quality	1. Develop indoor air quality standards 2. Controls on materials used for civil construction projects

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
Standard for Indoor Environmental Pollution Control of Civil Building Engineering (Ministry of Housing and Urban-Rural Development, 2018, 2020)	民用建筑工程室内环境污染控制标准	2018, 2020	National	Buildings		Air Quality	1. Reduce energy consumption 2. Increase energy efficiency 3. Facilitate the low-carbon green development of the civil buildings
Guidelines for the Prevention and Control of Construction Dust on Housing Construction Sites in Shandong Province (Housing and Urban-Rural Construction Department of Shandong Province, 2020)	山东省房屋建筑工地施工扬尘防治导则	2018-2020	Shandong Province	Buildings	PM	Air Quality	Further strengthen the construction of housing construction site dust management, accelerate the standardization of dust prevention and control, effective control of construction dust pollution, enhance the province's housing construction site civilized construction and green construction management level.
2021 Work Plan for Special Control of Dust on Construction Sites in Jiangsu Province (Housing and Urban-Rural Construction Department of Jiangsu Province, 2021)	2021年江苏省建筑工地扬尘专项治理工作方案	2021	Jiangsu Province	Buildings	PM	Air Quality	Solidly carry out special treatment of construction site dust, to further implement the main responsibility of the parties involved in the construction and government supervision, and continue to strengthen dust management "six percent" requirements; vigorously promote the construction of green and intelligent sites, improve the level of information on site dust management, to achieve video surveillance and dust monitoring equipment online above the scale of construction sites "two full coverage", and networking with local authorities; promote the site dust control differentiated management, do a good job of classification and control, the implementation of the exemption policy for emergency control of heavy pollution weather, and improve the refinement of civilized construction management of construction sites across the province.

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
Hebei Province's Measures for the Prevention and Control of Construction Dust Pollution in 2021 (Sinadichan, 2021)	河北省2021年建筑施工扬尘污染防治工作方案	2021	Hebei Province	Buildings	PM	Air Quality	Implement the main responsibility of enterprises, strengthen supervision and enforcement, improve the level of civilized construction management, improve the construction of dust pollution prevention and long-term mechanism, focusing on strengthening housing construction, municipal infrastructure construction and building demolition site construction dust control, the province's counties and urban planning and construction sites within the scope of construction sites to fully implement the "Hebei Province dust pollution prevention measures.
Action Plan for Promoting the Production and Application of Green Building Materials (Ministry of Housing and Urban-Rural Development, 2015)	促进绿色建材生产和应用行动方案	2015-2025	National	Buildings	NO_x, PM	Air Quality, Climate	Increase the use and number of green building materials. Decrease energy intensity of buildings materials 8% compared to 2015 values. Particular focus on NO_x and dust, which should decrease by 8% compared with 2015 values. Increase green building materials by 30% in new buildings, 50% in green buildings, 70% in pilot projects, and 80% in renovation projects

Policy	Policy (Chinese)	Year	Region	Sector	Gases[9]	Policy Type	Policy Targets
The 14th Five-Year Plan for Building Energy Efficiency and Green Building Development of Guangdong Province (Housing and Urban-Rural Construction Department of Guangdong Province, 2022)	广东省建筑节能与绿色建筑发展"十四五"规划	2022-2025	Guangdong Province	Buildings		Climate	By 2025, the energy-saving and green transformation of existing buildings will be completed over 30 million square meters, 3 million square meters of ultra-low energy and near-zero energy buildings with Lingnan characteristics will be constructed, 2 million kilowatts of solar photovoltaic capacity will be added, the replacement rate of renewable energy in urban buildings will reach 8%, the energy consumption structure of buildings will be gradually optimized, and the proportion of electricity consumption in building energy consumption will exceed 80%. Develop star-rated green buildings, promote the Pearl River Delta region to become a new highland for green building development, and the proportion of star-rated green buildings in new green buildings in cities and towns in the province exceeds 30%, including more than 45% in nine cities in the Pearl River Delta in the Guangdong-Hong Kong-Macao Bay Area, the proportion of assembled buildings in new buildings in urban areas reached 30%, the bulk cement rate reached more than 75%, ready-mixed concrete enterprises to achieve full compliance with green production, new wall materials in new buildings in urban areas are fully applied, the proportion of green building materials applications increased significantly.

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