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Emission mitigation pathways to achieve PM_{2.5} Interim target III of the World Health Organization in the Pearl River Delta in 2035

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ABSTRACT :

By participating in the construction of China's Guangdong-Hong Kong-Macao Greater Bay Area (GBA) and as the core zone of the GBA, the region (PRD) aims to have the ambient air quality basically reaching the level of the world-class bay areas by 2035. In this study, we developed three scenario strategies (Moderate Scenario (S_M), Intensified Scenario (S_I) and Radical Scenario (S_R)) for the PRD in 2035 taking the average annual $PM_{2.5}$ concentrations in the PRD reaching the world health organization interim target 3 (WHO-III, $15\mu g/m^3$) as the constraint standard. Under each scenario, we formulated the structural adjustment and end-of-pipe control measures to predict the development of industry, transportation and energy in the PRD in 2035. The results show that the total emissions of SO_2 , NO_x , PM (Particulate Matters) and NMVOCs (Non-methane Volatile Organic Compounds) were 152, 511, 205 and 382kt in the S_M scenario, respectively, and were 114, 436, 177 and 325kt in the S_I scenario, respectively, while they are 77, 344, 143 and 269kt in the S_R scenario, respectively. We also consider the emission reduction of pollutants outside the PRD. In this study, the S_M , S_I and S_R scenarios were combined with different national scenario inventories (DPEC) in 2035 and the WRF-CMAQ model was used to simulate these scenarios. The simulation results show that annual average concentrations of $PM_{2.5}$ in the PRD under the S_M -DPEC1, S_I -DPEC2 and S_R -DPEC3 scenarios were expected to reach 15.1, 14.6 and $14.8\mu g/m^3$, respectively, which just meet the WHO-III standard. In the process of achieving WHO-III target in the future, the government and policy makers can match the most suitable scenario in the study by referring to the actual decline of air pollutant emissions in the main contributing regions outside the PRD under each scenario, so as to obtain the best feasible control strategy in the PRD.

Keywords : Pearl River Delta, $PM_{2.5}$, WHO-III, Scenario study, Structural adjustment, CMAQ

Graphic abstract

1 Introduction

The Pearl River Delta (PRD) region is located in the core area of Guangdong province with the largest population in China, accounting for less than 31% of the land area of Guangdong province, but it gathers 53% of the population and 80% of the total economy (SBG, 2018). The PRD, together with Beijing-Tianjin-Hebei (BTH) region and Yangtze River Delta (YRD), is one of China's three major urban agglomerations and an important engine of China's economic development. With the rapid process of urbanization and industrialization in recent years, the PRD and other rapidly developing regions in China are facing increasing atmospheric environmental pressure, and air pollution occurs frequently in cities and even in the whole region (Lin et al., 2018). In consideration of human health and sustainable development, it is necessary to gradually abandon the previous extensive development model and take adequate pollution control measures to improve ambient air quality.

In 2013, the State Council of China (SCC) promulgated the toughest-ever *Air Pollution Prevention and Control Action Plan from 2013 to 2017* (Action Plan), which was considered the most stringent and ambitious air pollution plan to date. Under the guidance of "Action Plan", the national air pollutant emissions have decreased significantly (Zheng et al, 2018), and the estimated national population-weighted annual mean $PM_{2.5}$ concentrations decreased from 61.8 to 42.0 $\mu g/m^3$ (Zhang et. al, 2019). After the completion of the "Action Plan", more action plans, such as the *Three-Year Action Plan for Winning the Blue Sky Defense Battle from 2018 to 2020* and *Comprehensive Air Quality Improvement Action Plan (2021-2025)*, have been released to further improve the atmospheric environment.

In the process of continuous air pollution controls in Guangdong province, the air quality has been significantly improved (Zhang et al., 2020). After the completion of the "Action Plan" in 2017, the annual average concentration of $PM_{2.5}$ in the PRD was 34 $\mu g/m^3$, which has reached the WHO-I target (35 $\mu g/m^3$). Then, the SCC unveiled the *Outline Development Plan for the Guangdong-Hong*

Kong-Macao Greater Bay Area (GBA) (SCC, 2019) to build the PRD, Hong Kong and Macao into a world-class Bay area comparable to the New York Bay area, Los Angeles Bay area and Tokyo Bay Area by 2035. The industrial, transportation and energy structures in the GBA will be comprehensively optimized and improved. In addition, ecological environment construction is one of the main components of the overall construction framework in the GBA and the atmospheric environment in the region will reach the current international first-class Bay area level in 2035. It is noteworthy that the PRD, as the main body of the GBA, is facing the phenomenon of decreases of end-of-pipe control potentials and marginal benefits of pollution controls and greater difficulties in achieving the lower $PM_{2.5}$ concentration target. Therefore, the strategic study for the PRD to achieve the air quality improvement goal in 2035 is valuable and necessary for policy making.

Many studies have focused on the assessment of environmental benefits generated by existing policies so far (Geng et al., 2021. Zhang et. al., 2019. Zhang et. al., 2020. Wang et. al., 2016). The air quality in the PRD has improved significantly in recent years (Yan et al., 2020), in which the structural adjustments of industry, transportation and energy have played a key role and can provide some reference for the formulations of pollution control strategies in the future. Huang et al. (2018) studied the main sources of $PM_{2.5}$ in the PRD and found that industrial emissions accounted for the largest contribution. Wang et al. (2016) analyzed the main sources of pollutants in the PRD in recent years and believed that the improvements of $PM_{2.5}$ in Guangzhou, Foshan and Shenzhen from 2004 to 2015 were mainly due to the emission reduction of mobile sources and that controlling the scale of coal-fired power plants also plays a certain role in reducing $PM_{2.5}$ emissions in Guangzhou and Dongguan. Lu et al. (2016) analyzed the source of $PM_{2.5}$ in the PRD, and found that the contribution of regional transport to the PRD could not be ignored. Some studies have also made some scenario assumptions for achieving future air quality improvement (Cai et al., 2018, Zhao et al., 2013). Feng et al. (2018) predicted the policy scenarios of urban air pollution controls in 2020 with 2017 as the base year, but the scenarios only considered the controls of local pollution sources and did not consider the impacts of outside transport changes. Hu et al. (2016) focused on the

development scenarios of the power industry at the national level, and the setting of the scenarios was not constrained by the achievements of air quality target. Tong et al. (2019) considered the scenario settings outside the study area when studying and developing the future scenarios of the BTH area, but only provided a scenario that could meet the standard, and did not pay attention to the uncertainty of future air quality changes outside the study area, in which the control of outside pollutants in the study area was not the same as the scenario settings, leading to less reference value of the studied compliance scenarios.

In this study, the air pollution control strategies were studied with the realization of WHO-III target of $PM_{2.5}$ annual average concentration in the PRD in 2035 as the constraint by taking 2017 as the base year. First, based on the development trends and adjustment policies of energy, industrial and transportation structures in the PRD, this study forecasts the development scenarios of energy, industry and transportation in the PRD in 2035, formulates pollutant control strategies, and estimates the emissions of main pollutants. Secondly, this study considers the impact of regional transport on the realization of the target path as well as the prediction scenarios outside the PRD. Thirdly, this study considers the impact of the uncertainties of air quality change outside the PRD in the long term in the future. In order to reduce the impacts of this uncertainty on the practicability of the results, we have developed three PRD emission reduction scenarios of “Moderate Scenario (S_M)”, “Intensified Scenario (S_I)” and “Radical Scenario (S_R)” based on the reduction intensities required in the PRD region. The scenarios with different emission reduction intensities are also selected outside the PRD under each scenario. The three combined scenarios can make the PRD meet the target of WHO-III. In the process of achieving future goals, the government and policy makers can match the most suitable scenario by referring to the actual changes of air pollutant emissions outside the PRD, and then get the best feasible control strategy of the PRD.

2 Material and methods

2.1 Overview

Based on the predictions of the development of industry, transportation, energy structures and the end-of-pipe control measures of pollution sources in the PRD, this study designed three future development scenarios (Moderate Scenario (S_M), Intensified Scenario (S_I) and Radical Scenario (S_R)) and estimated the anthropogenic source emissions in the PRD under the scenarios. The emission inventory from the Dynamic Project model for Emissions in China Version 2.0 (DPEC v2.0) will be used for the regions of outside the PRD (Cheng et al. 2021). S_M , S_I and S_R are corresponding to ambitious-pollution-1.5°C-goals (DPEC1), ambitious-pollution-Neutral-goals (DPEC2) and ambitious-pollution-2°C-goals (DPEC3) in the 2035 scenario inventories of DPEC (see Table S1), respectively (S_M -DPEC1, S_I -DPEC2, S_R -DPEC3). In terms of emission reductions in the PRD region, S_R is stronger than S_I , and S_I is stronger than S_M . While in terms of emission reductions outside the PRD region, DPEC1 was stronger than DPEC2, and DPEC2 was stronger than DPEC3. The air quality model was used to carry out scenario simulations by formulating the internal scenarios of the PRD, and then the simulations were carried out again by adjustments of the emission reduction intensities of the PRD in each scenario according to the simulation results to make the average annual concentration of $PM_{2.5}$ in the PRD in the three scenarios just reach the WHO-III target (i.e. $14.5\mu g/m^3 \leq PM_{2.5} < 15.5\mu g/m^3$). The three sets of scenarios after reaching the WHO-III target can be used as a reference for the future implementation path (see Fig. S1).

2.2 Air Quality Simulations

2.2.1 Air quality model

The chemical transport model, Model-3/CMAQ version 5.0.2 (<https://www.epa.gov/cmaq>), was used in this study. As shown in Fig. S2, the CMAQ model used the triple nested grid of

Lambert projection for simulations with the grid resolutions of $27\text{km} \times 27\text{km}$ (d01), $9\text{km} \times 9\text{km}$ (d02), and $3\text{km} \times 3\text{km}$ (d03) from outside to inside. The PRD is located in the center of the innermost simulation domain (d03). The vertical direction of the model adopted the sigma coordinate system with a total of 14 layers. CB-05 was used as the gas phase chemical mechanism, and AERO6 was used for aerosol chemistry (Yarwood et al., 2005). The meteorological driving data were obtained by the mesoscale meteorological prediction model WRF V3.9.0.1 (Skamarock et al., 2008). The microphysical scheme was Morrison-2moment (Morrison et al., 2008). The boundary layer and near surface schemes were ACM2 (Pleim et al, 2007) and Pleim-Xiu (Pleim et al, 2001), respectively. The input data of the WRF used the 6-hour global meteorological reanalysis data (FNL) released by the National Center for environmental prediction (NCEP) of the United States which were assimilated by the radiosonde and ground station observation data in the corresponding periods. All of the CMAQ simulations used the meteorological data in 2017.

2.2.2 Emission inventory

Based on the current data of population, industrial developments and motor vehicle ownerships in the PRD in 2017 and referring to the existing localized emission factors in Guangdong province (Zhong et al, 2018), a high-resolution anthropogenic air pollutant emission inventory of the PRD in 2017 is prepared. The emission inventory includes emissions of industrial combustion, power, industrial processes, solvent usages, NMVOCs storages, on-road, non-road, anthropogenic dust, residents, agriculture and biomass burning.

For the benchmark scenario simulations, the above inventory was used for the PRD region in the innermost layer (d03), and the anthropogenic emission inventory of MEICv1.3 (Multi-resolution Emission Inventory) in 2017 with the resolution of $0.25^\circ \times 0.25^\circ$ was used for other regions (Zheng et al, 2018). New emission inventory will be transformed to the model-ready format by SMOKE model. When simulating each prediction scenario in 2035, the innermost (d03) PRD region used the

2035 scenario inventory prepared in this study, and other regions used the anthropogenic emission scenarios of DPEC in 2035. MEIC and DPEC data are available at <http://meicmodel.org/>. The biogenic emission sources used in the simulations were prepared by Model of Emissions of Gases and Aerosols from Nature (MEGAN) version 2.10 (Guenther et al, 2012). The emission sources for sea salt and windblown dust are calculated by the CMAQ model online.

2.3 Forecasting methods of future scenario developments for the PRD

2.3.1 Overview

The elastic coefficient and multiple linear regression methods were applied to predict the main development parameters of industry, transportation and energy in the PRD in 2035. The required historical data were mainly from the Guangdong statistical yearbook over the years.

2.3.2 Coefficient of elasticity method

By analyzing the development and change law of economic activities and the relationship with demand parameters, the change laws of demand parameters can be obtained relatively accurately, which can be used to predict the demand parameters. In this study, the elasticity coefficient method was used to predict total energy consumption (see Table S2), industrial product outputs and industrial added values (see Fig. S4), and motor vehicle ownerships (see Section 3.1.1.3). (Harel et al, 1991; Liu et al, 2018). For example, the motor vehicle ownerships can be predicted as follows:

$$P_k = P_{2017}(1 + \alpha_k)^{k-2017} \quad (k \in [2018, 2035]) \quad (1)$$

$$\alpha_k = \varepsilon \times \beta_k \quad (2)$$

$$\varepsilon = \frac{1}{13} \sum_{k=2005}^{2017} \frac{\alpha_k}{\beta_k} \quad (3)$$

where k is the year, P_k is the number of motor vehicles in the region in year k , P_{2017} represents the number of motor vehicles in the region in 2017, α_k is the annual growth rate of motor vehicle ownership, ε is the elasticity coefficient calculated from the historical data from 2005 to 2017 (a total of 13 years), and β_k is the annual GDP growth rate of the region in k years

2.3.3 Multiple Linear Regression

The multiple linear regression method was used to predict passenger and freight volumes in transportation demands (see Fig. S5) in this study (Liu et al., 2014). By selecting the main economic and social development variables, the linear regression model between random variables and general variables through stepwise regression can be obtained as follows:

$$Y = \theta_0 + \theta_1 x_1 + \theta_2 x_2 + \cdots + \theta_n x_n \quad (4)$$

where θ is the regression coefficient, Y is passenger volume or freight volume (unit: T), and x_n is the main economic and social development parameter with GDP per capita, population, urbanization rate and product output of bulk goods (such as cement output) as variables.

3 Results

3.1 Pollution Control Scenarios in the PRD

As described in section 2.1, the PPD scenarios S_M , S_I and S_R were combined with DPEC1, DPEC2 and DPEC3, respectively, in simulation. After several simulation tests, the average annual concentration of $PM_{2.5}$ in the PRD just reached the WHO-III target in S_M -DPEC1, S_I -DPEC2 and S_R -DPEC3. For energy, industry and transportation, the structure adjustment measures are different in S_M , S_I and S_R . The pollution control measures for the PRD were recorded as follows.

3.1.1 Structural adjustment strategies

3.1.1.1 Energy structure adjustments

As shown in Table S2, the total energy consumption in the PRD was 236.0 million TSC (Tons of Standard Coal) in 2017, including 133.0 million TSC for the power consumption. In the power consumption, the total amounts of import power, coal-fired power generation, gas-fired power generation, nuclear power generation and new energy power generation (e.g. wind power and photovoltaic) were 64.5, 40.2, 11.3, 11.7, and 5.2 million TSC, respectively. Under the S_M scenario,

the total energy demand in the PRD will increase to 434.1 million TSC in 2035, including 251.6 million TSC for the power consumption. In the power consumption, the total amounts of import power, coal-fired power generation, gas-fired power generation, nuclear power generation and new energy power generation (e.g. wind power and photovoltaic) were 138.8, 30.4, 51.0, 23.5 and 7.8 million TSC, respectively. Under the S_I scenario, the adjustment of energy structure will be strengthened based on the S_M scenario. In 2035, the total energy demand of the PRD will be about 375.1 million TSC, of which the total power consumption will be 233.6 million TSC. In the power consumption, the total amounts of import power, coal-fired power generation, gas-fired power generation, nuclear power generation and new energy power generation (e.g. wind power and photovoltaic) were 119.5, 11.7, 71.0, 23.5 and 7.8 million TSC, respectively. Under the S_R scenario, the adjustment of energy structures will be further strengthened on the basis of S_I scenario. In 2035, the total energy demand in the PRD will increase to 310.9 million TSC. The total power consumption is 213.7 million TSC. In the power consumption, the total amounts of import power, coal-fired power generation, gas-fired power generation, nuclear power generation and new energy power generation (e.g. wind power and photovoltaic) were 112.1, 11.7, 56.0, 23.5 and 10.4 million TSC, respectively.

3.1.1.2 Industrial structure adjustments

As the core of economic development in South China, the PRD has a high degree of industrial agglomeration, including a large number of industries with high pollution and energy consumptions (such as ceramics, cement and steel). In 2017, the total industrial energy demand in the PRD was 113.8 million TSC, including 19.7, 14.2, 7.4, and 72.6 million TSC for coal, oil, gas and electricity, respectively. The adjustment of industrial structures should become one of the main measures for the control of air pollutants in the future. It is proposed in the plan (2018-2035) for building a

modern industrial system in the GBA that the modern industrial system in the GBA will be fully completed and become an important advanced manufacturing and modern service industry base in the world by 2035. Compared with the development status of the PRD, by 2035, the proportions of production capacity of emerging industries (including pharmaceutical manufacturing, equipment manufacturing and automobile manufacturing etc.) will continue to expand, and the existing traditional high pollution industries (including textile, non-metallic mineral products, papermaking etc.) will be reduced. Under this background, the industrial structure adjustment scenarios of the PRD were designed below.

As shown in Fig. S4, the production capacity of major industries has increased to varying degrees, and the growth rate of emerging industries is more significant under the S_M scenario with reference to the long-term development plans of major industries in the PRD but except papermaking and steel. Table S2 shows that the total demand for industrial energy has increased to 235.8 million TSC, including 18.7 million TSC for coal, 21.4 million TSC for oil, 10.7 million TSC for gas and 185.0 million TSC for electricity. Under the S_I scenario, the production capacity of most traditional industries such as non-metal mineral products, papermaking, metal products and plastic products has decreased significantly, and the transformation to emerging industries has been accelerated as a whole. The total demand for industrial energy increased to 204.5 million TSC, including 9.8 million TSC for coal, 19.5 million TSC for fuel oil, 7.8 million TSC for gas and 167.4 million TSC for power. Under the S_R scenario, some traditional industries, such as textile, steel, metal products and plastics, were phased out completely, and the growth of emerging industries has been further accelerated. The total demand for industrial energy increased to 157.0 million TSC, including 3.7 million TSC for coal, 17.9 million TSC for fuel oil, 5.8 million TSC for gas and 129.6

million TSC for power.

3.1.1.3 Traffic Structure Adjustments

The passenger and freight traffic volumes in the PRD are large and growing rapidly. It is mainly highway transportation with great rooms for improvement in the transportation structures. For example, in 2017, the freight volume in the PRD was 2.79 billion tons, of which road, water, railway, pipeline and air transportations accounted for 68.6%, 28.4%, 2.2%, 0.7% and 0.1%, respectively. The average daily motorized travel volume in the city was about 71 million passengers, of which car, bus, rail transit, motorcycle and taxi travels accounted for 42.6%, 23.2%, 17.4%, 11.5% and 5.3%, respectively, and the motorized travel rate of public transport was about 45.0%. The intercity passenger traffic volume was 1.04 billion passengers, of which road, railway, air and water transportations accounted for 61.5%, 24.3%, 12.4% and 1.8%, respectively. The number of motor vehicles was 18.73 million (SBG, 2018). It is predicted that by 2035, the number of motor vehicles was 32.19 million, and the freight and passenger volumes in the PRD will reach 5.5 and 2.3 billion passengers, respectively, with about 110 million passengers for the motorized travels. On this basis, the traffic structure adjustment scenarios of the PRD were designed below.

As shown in Fig. S5, in the S_M scenario, in terms of freight structure, highway, waterway, railway, pipeline and air transportations accounted for 58.6%, 35.0%, 5.0%, 1.3% and 0.2%, respectively. For the intercity passenger transport structure, highway, railway, air and waterway transportations accounted for 44.8%, 40.0%, 14.0% and 1.3%, respectively. For the motorized travel structure of urban residents, car, bus, rail transit, motorcycle and taxi travels accounted for 35.0%, 25.0%, 30.0%, 5.0% and 5.0%, respectively, and the motorized travel rate of public transport increased to 60.0%. Under the S_I scenario, the adjustment of traffic structure will be strengthened based on the S_M scenario. For the freight structure, highway, waterway, railway, pipeline and air transportations accounted for 55.6%, 36.0%, 7.0%, 1.3% and 0.1%, respectively. For the intercity

passenger transportation structure, highway, railway, air and waterway transportations accounted for 41.8%, 45.0%, 12.0% and 1.2%, respectively. For the motorized travel structure of urban residents, car, bus, rail transit, motorcycle and taxi travels accounted for 31.0%, 27.0%, 35.0%, 3.0% and 4.0%, respectively, and the motorized travel rate of public transportation increased to 66.0%. Under the S_R scenario, the adjustment of traffic structure will be further strengthened on the basis of the S_I scenario. For the freight structure, highway, waterway, railway, pipeline and air transportations accounted for 51.6%, 38.0%, 9.0%, 1.3% and 0.1%, respectively. For the intercity passenger transport structure, highway, railway, air and waterway transportations accounted for 38.0%, 50.0%, 11.0% and 1.0%, respectively. For the motorized travel structure of urban residents, car, bus, rail transit, motorcycle and taxi travels accounted for 25.0%, 30.0%, 40.0%, 2.0% and 3.0%, respectively, and the motorized travel rate of public transportation increased to 73.0%.

3.1.2 End-of-pipe control measures

3.1.2.1 Power

The amount of pollutants produced in the power plant is large, and the corresponding treatment standards are also relatively strict. Efficiencies of emission control measures were estimated. As shown in Table S3, all power plants (including enterprise owned power plants) in the PRD will meet the ultra-low emission standards for power plants (GB13223-2011) (MEE, 2012). Power plants with the small scale (no more than 300MW), old technology or unable to carry out “ultra-low” emission retrofit will be phased out. In order to meet the ultra-low emission requirements, coal-fired power plants need to adopt the flue gas desulfurization with removal efficiency not less than 95% (e.g. the high-efficiency seawater desulfurization method and limestone-gypsum method), the flue gas denitration with removal efficiency not less than 80% (e.g. low- NO_x combustion technology with selective catalytic reduction) and soot treatment processes with removal efficiency not less than 99%

(e.g. wet electrostatic precipitators with fabric filters). The gas-fired power plant shall adopt the flue gas denitration (such as low-NO_x combustion technology, selective catalytic reduction) with removal efficiency not less than 80%. End-of-pipe control measures for power plants are the same under the different scenarios.

3.1.2.2 Industry

As shown in Table S3, the industrial end-of-pipe control measures are strengthened through boilers, kilns and VOCs emission control. Efficiencies of emission control measures were estimated. End-of-pipe control measures for industry are the same under the different scenarios.

Industrial boilers. All coal-fired boilers below 10 t/h scale were phased out or converted to gas-fired boilers or electric boilers, and control measures for the rest of coal-fired boilers are strengthened. The coal-fired boilers adopted the flow gas desulfurization (such as limestone gypsum method) with a removal efficiency of not less than 90%, the flow gas denitration (such as low-NO_x combustion technology + selective catalytic reduction) with a removal efficiency of not less than 70% and the soot treatment process (such as fabric filters) with a removal efficiency of not less than 95%. The gas-fired boilers adopted the flow gas denitration (such as low-NO_x combustion technology + selective catalytic reduction) with the treatment efficiency not less than 70%.

Industrial kilns. The iron and steel industries adopted the flow gas desulfurization (such as high-efficiency seawater desulfurization method) with a removal efficiency of not less than 95%, the flow gas desulfurization (such as low-NO_x combustion technology + selective catalytic reduction) with a removal efficiency of not less than 80% and the soot treatment process (such as wet electrostatic precipitators + fabric filters) with a removal efficiency of not less than 99%. The

cement and glass manufacturing industries adopted the flow gas desulfurization (such as limestone-gypsum method) with a removal efficiency of not less than 90%, the flow gas desulfurization (such as low- NO_x combustion technology + selective catalytic reduction) with a removal efficiency of not less than 70% and the smoke and dust treatment process (such as fabric filters) with a removal efficiency of not less than 95%. Other kilns adopted more efficient removal equipment, and the average removal efficiencies of SO_2 , NO_x and PM reached more than 80%, 60% and 85%, respectively.

Strengthen the emission controls of industrial VOCs. Oil refining adopted Leak Detections and Repair Programs (LDAR), and Covers on Oil and Water Separators (COWS) to reduce oil and gas leakages and emissions by more than 90%. The chemical industry adopted high-efficiency end-of-pipe control technologies (such as Regenerative Thermal Oxidizer (RTO), Regenerative Catalytic Oxidation (RCO) or Photocatalytic Oxidation with Active Carbon Adsorption (PO+ACA), and the comprehensive VOCs removal efficiency was not less than 70%. Other industries (including furniture, electronic products, plastic products, and automobile manufactures, etc.) adopted RTO / RCO or PO+ACA and other efficient end-of-pipe control measures to promote the substitution of low volatile solvent raw material, and the comprehensive VOCs removal efficiency was not less than 65%. Small and polluting factories would be phased out.

3.1.2.3 Transportation

Use clean energy. As shown in Table S4, road transport emissions were reduced by increasing the electrification rate of motor vehicles and reducing the proportion of gasoline and diesel vehicles for the intercity transportation. The emissions of waterway transportation were reduced by using all

shore power during berthing and adding LNG powered ships. Air transportation emissions were by switching some aircrafts to biological aviation kerosene. The emissions of railway transportation were reduced by realizing the electrification of all railway locomotives. In terms of urban transportation, it was mainly to realize the electrification of buses and taxis, and significantly increase the proportion of electrification of private cars to achieve emission reductions. All gasoline and diesel vehicles meet the emission standards: In 2035, all gasoline and diesel vehicles still in use will meet the "China 6b" emission standard (Limits and measurement methods for emissions from light-duty vehicles (CHINA 6) (GB 18352.6—2016) and Limits and measurement methods for emissions from diesel fueled heavy-duty vehicles (CHINA VI) (GB 17691—2018)). Gasoline vehicles and diesel vehicles that fail to meet the "China 6b" emission standard will be eliminated.

3.2 Emission reductions under the three scenarios in the PRD

As shown in Fig. 1, the total SO₂, NO_x, PM, and NMVOCs emissions in 2017 for the PRD region were 258, 838, 445 and 707kt, respectively. SO₂ emissions were mainly from industrial process (31%), power (26%) and non-road mobile sources (26%). NO_x emissions were mainly from road mobile (32%), non-road mobile (28%) and power sources (16%). PM emissions were mainly from industrial process (34%), man-made dust (30%) and power sources (13%). NMVOCs emissions were mainly from solvent use (51%), industrial process (22%) and road mobile sources (8%).

Fig. 1 and 2 present the sectoral emission estimates for SO₂, NO_x, PM and NMVOCs from 2017 to 2035. Under the S_M scenario, the total emissions of SO₂, NO_x, PM and NMVOCs in the PRD were 152, 511, 205 and 382kt, respectively, which decreased by 106, 327, 240 and 325kt, respectively, relative to the baseline scenario. Among them, SO₂ emission reductions were mainly from industrial process (42kt) and non-road mobile sources (26kt); NO_x emission reductions were

mainly from road mobile (121kt) and non-road mobile sources (80kt); PM emission reductions were mainly from industrial process (100kt) and dust sources (66kt); the emission reductions of NMVOCs were mainly from solvent use (173kt) and industrial process sources (75kt). Under the S_I scenario, the total emissions of SO_2 , NO_x , PM and NMVOCs in the PRD were 114, 436, 177 and 325kt, respectively, which decreased by 145, 402, 268 and 382kt, respectively, relative to the baseline scenario. Among them, SO_2 emission reductions were mainly from industrial process (48kt) and power sources (38kt); NO_x emission reductions were mainly from road mobile (144kt) and non-road mobile sources (104kt); PM emission reductions were mainly from industrial process (110kt) and dust sources (66kt); The emission reductions of NMVOCs were mainly from solvent use (207kt) and industrial process sources (86kt). Under the S_R scenario, the total emissions of SO_2 , NO_x , PM and NMVOCs in the PRD were 77, 344, 143 and 269kt, respectively, which decreased by 181, 494, 302 and 439kt, respectively, relative to the baseline scenario. Among them, SO_2 emission reductions were mainly from industrial process (61kt) and power sources (51kt); NO_x emission reductions were mainly from road mobile (161kt) and non-road mobile sources (122kt); PM emission reductions were mainly from industrial process (127kt) and dust sources (66kt); The emission reductions of NMVOCs were mainly from solvent use (233kt) and industrial process sources (101kt).

In Fig. 3, the expected growths of major pollutant emissions by 2035 in each scenario were estimated, including the expected increases of power generation, industrial development, transportation, and the emission reductions caused by structural adjustment and end-of-pipe control measures. The expected emission increases of power generation were brought by the growth of power consumption demands while maintaining the existing power generation structure and end-of-pipe control measures. Similarly, the expected emission growths of transportation were brought by the growth of transportation demands while maintaining the existing transportation structure and end-of-pipe control measures. The expected emission increases of industrial development were the emission growth under the condition that the industrial structure under the S_M

scenario and end-of-pipe control measures under baseline year remained unchanged.

Under the S_M scenario, the increase of power demands increased the emissions of SO_2 , NO_x , PM and NMVOCs by about 60, 120, 52 and 24kt, respectively. Industrial developments increased the emissions of SO_2 , NO_x , PM and NMVOCs by about 12, 18, 26 and 368kt, respectively. The increases of traffic volume were expected to increase the emissions of SO_2 , NO_x , PM and NMVOCs by about 71, 533, 36 and 72kt, respectively. Through the energy structure adjustment, SO_2 , NO_x , PM and NMVOCs emissions were reduced by 76, 104, 66 and 26kt, respectively. Through the adjustment of transportation structure, SO_2 , NO_x , PM and NMVOCs emissions were reduced by 10, 152, 10 and 21kt, respectively. SO_2 , NO_x , PM and NMVOCs emissions were reduced by 162kt, 742kt, 278kt and 744kt respectively through the end-of-pipe controls. Since the S_M scenario was currently taken as the basic scenario for industrial development, the adjustment of industrial structure would not produce emission changes.

Under the S_I scenario, considering the changes of power demands (see Table S2), the increase of power demands increased the emissions of SO_2 , NO_x , PM and NMVOCs by about 51, 102, 44 and 20kt, respectively. The emission changes caused by industrial developments and the growth of transportation volumes were the same as that in the S_M scenario. The contributions of the structural adjustment to pollutant emission reductions increased. Through the energy structure adjustment, SO_2 , NO_x , PM and NMVOCs emissions were reduced by about 98, 138, 85 and 32kt, respectively. Through the industrial structure adjustment, SO_2 , NO_x and PM emissions were reduced by 53, 68 and 97kt, respectively, while the NMVOCs emissions were increased by about 38kt. Through the adjustment of transportation structure, SO_2 , NO_x , PM and NMVOCs emissions were reduced by about 15, 197, 13 and 27kt, respectively. Through the end-of-pipe controls, SO_2 , NO_x , PM and NMVOCs emissions were reduced by about 112, 653, 179 and 822kt, respectively.

In the S_R scenario, the changes of power demands were also considered. At this time, the increases of power demands increased the emissions of SO_2 , NO_x , PM and NMVOCs by about 41, 82, 35 and 16kt, respectively. The emission changes caused by industrial developments and the

growth of transportation volumes were the same as that in the S_M scenario. Under this scenario, the contributions of the structural adjustment to pollutant emission reductions continued to increase. Through the energy structure adjustment, SO_2 , NO_x , PM and NMVOCs emissions were reduced by about 98, 148, 85 and 35kt, respectively. Through the industrial structure adjustment, SO_2 , NO_x and PM emissions were reduced by 108, 110 and 195kt, respectively, while NMVOCs emissions were increased by about 101kt. Through the adjustment of transportation structure, SO_2 , NO_x , PM and NMVOCs emissions were reduced by about 22, 258, 17 and 35kt, respectively. Through the end-of-pipe controls, SO_2 , NO_x , PM and NMVOCs emissions were reduced by about 76, 611, 102 and 927kt, respectively.

3.3 Scenario simulation results

As shown in Fig. 4, the simulation results show that the current S_M -DPEC1, S_I -DPEC2 and S_R -DPEC3 scenarios can make the annual average concentrations of $PM_{2.5}$ in the PRD meet the WHO-III target requirements. Under the S_M -DPEC1 scenario, the annual average concentrations of $PM_{2.5}$ in cities in the PRD were from $13.5 \mu g/m^3$ (Huizhou) $\sim 17.1 \mu g/m^3$ (Foshan) with the average value of $15.1 \mu g/m^3$. Under the S_I -DPEC2 scenario, the annual average concentrations of $PM_{2.5}$ in cities in the PRD were from $12.9 \mu g/m^3$ (Huizhou) $\sim 16.4 \mu g/m^3$ (Jiangmen) with the average value of $14.6 \mu g/m^3$. Under the S_R -DPEC3 scenario, the annual average concentrations of $PM_{2.5}$ in cities in the PRD were from $13.6 \mu g/m^3$ (Huizhou) $\sim 15.9 \mu g/m^3$ (Guangzhou) with the average value of $14.8 \mu g/m^3$.

4 Discussions

4.1 Application of the results

The choice of the final realization scenario. Considering the changes of external emissions, the annual average concentrations of $PM_{2.5}$ in the PRD can meet the WHO-III target requirements

under the scenarios of S_M -DPEC1, S_I -DPEC2 and S_R -DPEC3. Therefore, the three groups of comprehensive strategies can be used as a reference for the annual average concentrations of $PM_{2.5}$ in the PRD to reach the WHO-III target. There was a certain uncertainty in the long-term changes of emissions outside the PRD in the future, which will have impacts on the strength of measures that must be taken to achieve the established target in the PRD. In the process of achieving WHO-III target in the future, the government and policy makers will match the most suitable scenario in the study by referring to the actual declines of air pollutant emissions in the main contributing regions outside the PRD, so as to obtain the best feasible control strategy in the PRD under the corresponding scenario.

Guidance for other regions. The emission control strategies in these scenarios in this study were formulated by predictions of developments in the future based on current situations. Apart from reference to the PRD, these emission control measures could offer some general references to studies in the regions with air pollution, such as BTH and YRD. In addition, we recommend that other regions consider emission changes outside the study areas when developing long-term mitigation scenarios by the methodology like this paper.

4.2 Simulation result evaluation and error correction

The corresponding hourly $PM_{2.5}$ concentrations in the 56 state-controlled monitoring stations in 9 cities in the PRD from the benchmark scenario simulations in 2017 were extracted to compare with the observations to evaluate the model performance. The surface $PM_{2.5}$ observation data used in this study was obtained from <https://quotsoft.net/air/>. In 2017, the annual mean values of $PM_{2.5}$ observed in cities in the PRD were from $28 \mu g/m^3 \sim 41 \mu g/m^3$ with an average of $34.4 \mu g/m^3$, and the simulated annual mean values were from $27 \mu g/m^3 \sim 40 \mu g/m^3$ with an average of $34.0 \mu g/m^3$. The normalized mean bias was about - 1.3%. Since the annual average concentration data of $PM_{2.5}$ were mainly used in this study, the simulation results of the current model on the annual average concentrations of $PM_{2.5}$ in the PRD were generally good.

Because there is a certain error between the model simulations and the actual observations, the

scenario simulation results should be corrected by the observed concentrations and the benchmark scenario simulations to eliminate the simulation errors before application. The calculation formula of simulation error eliminations was as follows:

$$C_{i,j} = O_{i,j} \times \frac{Ms_{i,j}}{Mb_{i,j}} \quad (5)$$

where O represents the pollutant monitoring value, Mb represents the simulation value of the benchmark scenario, Ms represents the simulation value of the reduction scenario, C represents the predicted value of the pollutant concentration under the reduction scenario after error eliminations, i , j represent different cities and simulated days, respectively.

5 Conclusions

In this study, three sets of scenario strategies (i.e. S_M , S_I and S_R) for the PRD to achieve the WHO-III goal in 2035 are formulated by taking 2017 as the base year and $PM_{2.5}$ as the constraint. For the PRD, the total SO_2 , NO_x , PM , and $NM VOCs$ emissions in 2017 were estimated to be 258, 838, 445, and 707kt, respectively. Under various scenarios, the developments of industries, transportation and energy in the PRD in 2035 were predicted, and structural adjustments and the end-of-pipe control measures were formulated. The emission increments brought by future developments and the emission reductions brought by structural adjustments and end-of-pipe control measures were estimated. In terms of emission reductions in the PRD, S_R was stronger than S_I , and S_I was stronger than S_M . Under the S_M scenario, the total emissions of SO_2 , NO_x , PM and $NM VOCs$ were 152, 511, 205 and 382kt, respectively. Under the S_I scenario, the total emissions of SO_2 , NO_x , PM and $NM VOCs$ in the PRD were 114, 436, 177 and 325kt, respectively. Under the S_R scenario, the total emissions of SO_2 , NO_x , PM and $NM VOCs$ in the PRD were 77, 344, 143 and 269kt, respectively.

This paper emphasizes that the impacts of regional transport should be considered when formulating the long-term air quality target compliance strategies. Pollutant emission reductions

outside the simulation area shall also be considered simultaneously. In this study, on the basis of developing the internal scenarios of the PRD, the three groups of scenarios were simulated with the different national 2035 scenario inventories. The simulation results show that the annual average concentrations of $\text{PM}_{2.5}$ under the S_M , S_I and S_R scenarios were expected to reach $15.1 \mu\text{g}/\text{m}^3$, $14.6 \mu\text{g}/\text{m}^3$ and $14.8 \mu\text{g}/\text{m}^3$, respectively, all of which just reach the WHO-III target value. In the process of achieving WHO-III target in the future, the government and policy makers can match the most suitable scenario in the study by referring to the actual declines of air pollutant emissions in the main contributing regions outside the PRD, so as to obtain the best feasible control strategy in the PRD under the corresponding scenario.

Supplementary materials.

Supplementary information is available online.

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Fig. 1. Sectoral emissions of major air pollutants for the baseline year 2017 and three scenarios in 2035 in the PRD region.

Fig.2. Sectoral emission reductions of major air pollutants under the three scenarios in 2035 in the PRD region.

Fig. 3. New emission forecasts and contributions of measures to reduce emissions under each scenario

Fig. 4. Simulating results of PM_{2.5} annual average concentrations under the scenarios S_M-DPEC1, S_I-DPEC2 and S_R-DPEC3. (a~c) Spatial distributions of PM_{2.5} annual average concentrations in the PRD region. (d~f) PM_{2.5} annual average concentration ranges in the cities of the PRD region.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

HIGHLIGHTS

- Three sets of scenarios for achieving the WHO-III target of PM_{2.5} annual average concentration in the PRD in 2035 were developed.
- The emission control scenarios of the PRD based on the developments and adjustments of energy, industrial, transportation structures, and end-of-pipe control strategies were formulated.
- The WRF-CMAQ model was used to simulate and predict the strategic scenarios in 2035.
- Combined with external emission reduction scenarios, the three scenarios can make the annual average concentration of PM_{2.5} in the PRD reach the WHO-III target.
- In the future, the most appropriate path can be selected among the three groups of strategies in combination with the external emission reductions in the PRD.