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# Economic Impacts from $PM_{2.5}$ Pollution-Related Health Effects: A Case Study in Shanghai

Rui Wu,[†,§,#] Hancheng Dai,*[,‡] Yong Geng,*[,§,∥] Yang Xie,[⊥,∇] Toshihiko Masui,[⊥] Zhiqing Liu,[§] and Yiying Qian[§]

[†]Key Lab on Pollution Ecology and Environmental Engineering, Institute of Applied Ecology, Chinese Academy of Sciences, No. 72 Wenhua Road, Shenyang 110016, China

[‡]College of Environmental Sciences and Engineering, Peking University, No. 5 Yiheyuan Road, Beijing 100871, China

[§]School of Environmental Science and Engineering and [∥]China Institute for Urban Governance, Shanghai Jiao Tong University, No. 800 Dongchuan Road, Minhang, Shanghai 200240, China

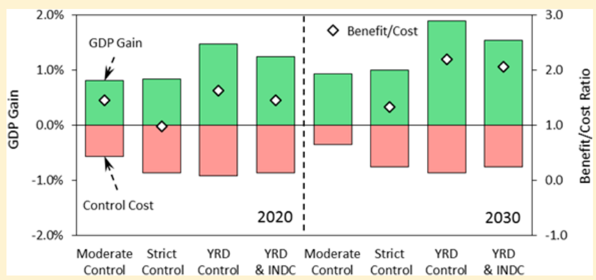
[⊥]Social and Environmental Systems Division, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba City, Ibaraki 305-8506, Japan

[#]University of Chinese Academy of Sciences, No. 19A Yuquan Road, Beijing 100049, China

[∇]Department of Social Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

Supporting Information

**ABSTRACT:** $PM_{2.5}$ pollution-related diseases cause additional medical expenses and work time loss, leading to macroeconomic impact in high $PM_{2.5}$ concentration areas. Previous economic impact assessments of air pollution focused on benefits from environmental regulations while ignoring climate policies. In this study, we examine the health and economic impacts from $PM_{2.5}$ pollution under various air pollution control strategies and climate policies scenarios in the megacity of Shanghai. The estimation adopts an integrated model combining a Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, exposure-response functions (ERFs), and a computable general equilibrium (CGE) model. The results show that without control measures, Shanghai's mortality caused by $PM_{2.5}$ pollution are estimated to be 192 400 cases in 2030 and the work time loss to be 72.1 h/cap annually. The corresponding GDP values and welfare losses would be approximately 2.26% and 3.14%, respectively. With an estimated control cost of 0.76% of local GDP, Shanghai would gain approximately 1.01% of local GDP through local air pollution control measures and climate policies. Furthermore, the application of multiregional integrated control strategies in neighboring provinces would be the most effective in reducing $PM_{2.5}$ concentration in Shanghai, leading to only 0.34% of GDP loss. At the sectoral level, labor-intensive sectors suffer more output loss from $PM_{2.5}$ pollution. Sectors with the highest control costs include power generation, iron and steel, and transport. The results indicate that the combination of multiregional integrated air pollution control strategies and climate policies would be cost-beneficial for Shanghai.




## 1. INTRODUCTION

One of the side effects of China's rapid industrialization and urbanization is severe ambient air pollution. Ambient particulate matter pollution ranks fourth out of 67 risk factors after high blood pressure, tobacco exposure, and diet low in fruits in China (second highest in the G20).[1] A total of 83% of the Chinese population live in areas exceeding the WHO Level 1 interim target of an annual average of 35 $\mu g/m^3$ $PM_{2.5}$ (fine particulate matter $\leq 2.5$ $\mu m$ in aerodynamic diameter), leading to serious health concerns.[2−5] $PM_{2.5}$ pollution is associated with a broad spectrum of acute and chronic health effects, including cardiopulmonary diseases, lung cancer, tracheal cancer, and bronchial cancer.[6] Many efforts were made to understand the linkages between exposure to outdoor air pollution and mortality or morbidity in developed countries[7−9] and China.[10−12] Outdoor air pollution, mostly $PM_{2.5}$, results in 3.0−3.7 million premature deaths annually worldwide, predominantly in China and India.[13−15]

As a result of the adverse health effects, outdoor air pollution leads to economic costs, particularly additional health expenditure, work time loss, and labor productivity loss. Previous studies adopted various approaches to quantify the values of economic loss related to air pollution.[16] For instance, one study in the United States found that ozone levels well below federal air-quality standards have a significant impact on the productivity of agricultural workers.[17] Also, a natural experiment conducted in Mexico City indicates that 19.7%

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decline in $SO_2$ led to a 1.3 h (or 3.5%) increase in work hours per week.[18] In China, the economic impact of air pollution accounts for 0.72−6.94% of regional GDP according to different studies at both the city and the province levels.[19−23] Outdoor air pollution cost more than \$5 trillion in welfare losses globally in 2013[24] and cost \$1.7 trillion in OECD countries, \$1.4 trillion in China, and \$0.5 trillion in India in 2010.[25] Based on the literature review, most of the assessments adopt econometric methods, such as willingness to pay (WTP), value of a statistical life (VSL), human capital approach (HCA), and cost of illness (COI). Compared with these methods, the computable general equilibrium (CGE) model could capture the full range of interaction and feedback effects between different agents in the economic system, which is a more-systematic method of measuring the economic impact of air pollution. Based on the OECD's CGE model ENV-Linkages,[26] the global economic losses of outdoor air pollution are projected to increase to 1% of global GDP by 2060, and such losses would be especially large in China (−2.6%).[27] Matus et al.[28] estimated that marginal welfare impact to the Chinese economy caused by air pollution increased 4-fold between 1975 and 2005 by using a CGE model named EPPA. Xie et al.[29] further projected that $PM_{2.5}$ pollution would lead to 2% GDP loss in China in 2030. Other similar studies focused on the United States[30] and the European Union.[31−33]

Because greenhouse gases (GHG) and air pollutants are emitted from common sources, GHG mitigation policies can bring co-benefits to the improvement of both air quality and human health. Several studies analyzed the ancillary health benefits of GHG mitigation.[34−38] For instance, Thompson et al.[39] found that health-related benefits from air quality improvements can offset 26−1050% of the cost of the United State's carbon policies. Östblom and Samakovlis[40] simulated health benefits from achieving the Swedish carbon dioxide target. Matus[41] estimated an increase of \$2.4 billion in China's GDP in 2010 resulting from air quality improvement due to climate policies. Recently, China submitted its formal commitment to the Paris Agreement that pledged to peak carbon emissions around 2030. China has also nationally determined to lower $CO_2$ emissions per unit of GDP by 60% to 65% from the 2005 level by 2030 in its Intended Nationally Determined Contributions (INDC). To achieve these targets, Chinese government will implement a series of climate policies. Thus, the corresponding health and economic benefits of these policies should be necessarily evaluated.

In general, previous studies quantified adverse health effects and economic consequences of air pollution but were limited to part of the whole chain of air pollution. Few studies examined the effectiveness of environmental regulations on public health and economic development as well as climate policies. In addition, studies valuing regional economic benefits from air pollution control seldom evaluated multiregional integrated control effects. Actually, at the city level, air quality is significantly affected by atmospheric transport from nearby regions. In this regard, it is necessary to model the whole chain of air pollution, from the economic aspect and energy driving forces over air pollutant emissions and air quality to health and economic impacts. Such a measure can help quantify the integrated impacts of different policy disturbances and compare their costs and benefits.

A pair of key research questions are expected to be answered in this study. The first one is what the health and economic impacts from $PM_{2.5}$ pollution-related health effects are under different scenarios with combinations of various air pollution control strategies and climate policies by 2030 in a megacity of Shanghai. The second question is what the effects of multiregional integrated air pollution control strategies implemented in Yangtze River Delta (YRD) region (including Shanghai, Jiangsu, and Zhejiang) are.

## 2. METHODOLOGY

**2.1. Integrated Health and Economic Model.** This study applies an integrated model developed on the basis of combining a provincial level health and economic model[29] and a Shanghai CGE model.[42] As shown in Figure 1, the integrated

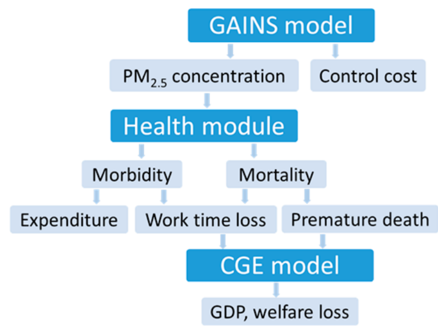


**Figure 1.** Research framework.

model combines a Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, a health impact module, and a CGE model. The GAINS model estimates future air pollutants emissions using data on energy consumption, industrial production, and proposed environmental regulations (under different scenarios) and emission factors originating from peer reviewed literatures and measurement campaigns. The GAINS model includes all key emission sources and considers up to about 2000 sector-fuel-technology combinations. Based on the emission inventory, the GAINS model outputs annual $PM_{2.5}$ concentration derived from an atmospheric dispersion model named TM5 model. Health impacts of $PM_{2.5}$ pollution including the morbidity of six symptoms, chronic mortality, and work-loss day (WLD) are calculated in the health module using both linear and nonlinear exposure-response functions (ERFs) from refs 11 and 43−45. In addition to health end points and work time loss, the health module quantifies medical expenditure due to $PM_{2.5}$ pollution.[29] Next, work time loss and premature death are inputs as disturbance variables to the CGE model so that macroeconomic impacts can be simulated (see a more-detailed description in the Supporting Information).

**2.2. Scenarios Setting.** A total of seven scenarios are set in this study, including BaU_base, INDC_base, BaU0, INDC1, INDC2, BaU3, and INDC3 scenarios. Table 1 lists the key assumptions of these scenarios. The labels BaU ("business as usual") and INDC represent the social and economic assumptions, including GDP, energy pathways, and emission limitations. In the scenarios labeled with BaU, the annual GDP growth rate of Shanghai is set as 10.0% during 2007−2020 and 3.7% during 2020−2030, and there is no carbon intensity limit. In contrast, scenarios labeled with INDC are used for estimating the co-benefits of INDC targets in air pollution reduction, in which $CO_2$ emissions per unit of GDP of Shanghai would decrease by 65% over 2007−2030. As a result of carbon emissions limitation, GDP growth rates and energy


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**Table 1. Key Assumptions of Seven Scenarios**

| scenario | GDP growth rates | $CO_2$/GDP decrease rates | health impact | control strategy | Jiangsu and Zhejiang control |
|---|---|---|---|---|---|
| BaU_base | 10.0% during 2007−2020 and 3.7% during 2020−2030 | no constraints | ignored | no control | no |
| BaU0 | | | not ignored | no control | no |
| BaU3 | | | not ignored | strict control | yes |
| INDC_base | 9.4% during 2007−2020 and 3.6% during 2020−2030 | 44% during 2007−2020 and 64% during 2007−2030 | ignored | no control | no |
| INDC1 | | | not ignored | moderate control | no |
| INDC2 | | | not ignored | strict control | no |
| INDC3 | | | not ignored | strict control | yes |

consumption under INDC scenarios are slightly lower than those under BaU scenarios.

The BaU_base and INDC_base scenarios are reference scenarios. They assume that the health impacts from $PM_{2.5}$ pollution are ignored, i.e., there is no morbidity, premature death, health expenditure, or work time loss from $PM_{2.5}$ pollution. Both scenarios simulate an ideal situation that does not exist but can be used to evaluate the negative macroeconomic impacts of pollution as a reference.

The other five scenarios consider the health impacts caused by $PM_{2.5}$ pollution. The BaU0 scenario assumes that no air pollution control measures are applied in the GAINS model. The INDC1 scenario assumes that Shanghai would adopt moderate control measures of which penetration rates in 2020 and 2030 remain the same as in 2010. The INDC2 scenario assumes the same control measures adopted in 2010 would last until 2020, but the stricter control measures would be adopted in 2020 and 2030. Furthermore, the BaU3 and INDC3 scenarios assume that not only Shanghai but also Jiangsu and Zhejiang, the other two neighboring provinces in YRD, would adopt the strict emission control measures.

## 3. RESULTS

### 3.1. Air Pollutant Emissions and $PM_{2.5}$ Concentration.

Figure 2 illustrates that implementation of emission control measures could substantially reduce $PM_{2.5}$, $SO_2$, and $NO_x$ emissions, especially $PM_{2.5}$ (reduced by over 90%). The $PM_{2.5}$, $SO_2$, and $NO_x$ emissions under the INDC1 scenario in 2030 would be 0.17, 0.57, and 0.71 Mt, respectively. When the strict control strategy is implemented under the INDC2 scenario, the three pollutants emissions will further decrease by 39−61%, namely approximately 0.07 Mt ($PM_{2.5}$), 0.28 Mt ($SO_2$), and 0.43 Mt ($NO_x$). $PM_{2.5}$ emissions will be lower in 2030 than in 2020 under all scenarios. Unlike $PM_{2.5}$, the other two pollutants emissions will decrease only under strict control scenarios during 2020−2030. Therefore, if the control measures are not strengthened or adjusted, emissions of $SO_2$ and $NO_x$ are likely to rebound along with economic development.

In terms of sectoral emissions, iron and steel and power generation appear to be the top two contributors to $PM_{2.5}$ emissions in Shanghai, accounting for about 50% and 31% in the BaU0 scenario in 2030, respectively. Under the INDC1 scenario, the shares of these two sectors would decrease to approximately 28% and 12%, respectively. Hence, those large iron and steel plants and power plants would be the key emission control targets. Similarly, in terms of $SO_2$, a large share of emissions is from power generation (35%) under the uncontrolled scenario. In contrast, with control measures, the share is estimated to be 3%, and the "other" manufacture sector accounts for 38% under the INDC1 scenario. As a port city, about 36% of Shanghai's $NO_x$ emissions will be from waterway under the BaU0 scenario in 2030. Other key $NO_x$ emission sectors include power generation (16%) and cars (13%). Under the INDC1 scenario, transport, other manufacture and power generation sectors account for approximately 45%, 22%, and 9% of total $NO_x$ emission, respectively.

Figure 2d shows that without any control, $PM_{2.5}$ concentration of Shanghai will far exceed the WHO Level 1 interim target of 35 $\mu g/m^3$ under the BaU0 scenario in 2020 and 2030. However, the emission control strategy can significantly decrease the $PM_{2.5}$ concentration to approximately 182.9 $\mu g/m^3$ (INDC1), 170.1 $\mu g/m^3$ (INDC2), 73.2 $\mu g/m^3$ (BaU3), and 71.7 $\mu g/m^3$ (INDC3) in 2030. Furthermore, different levels of


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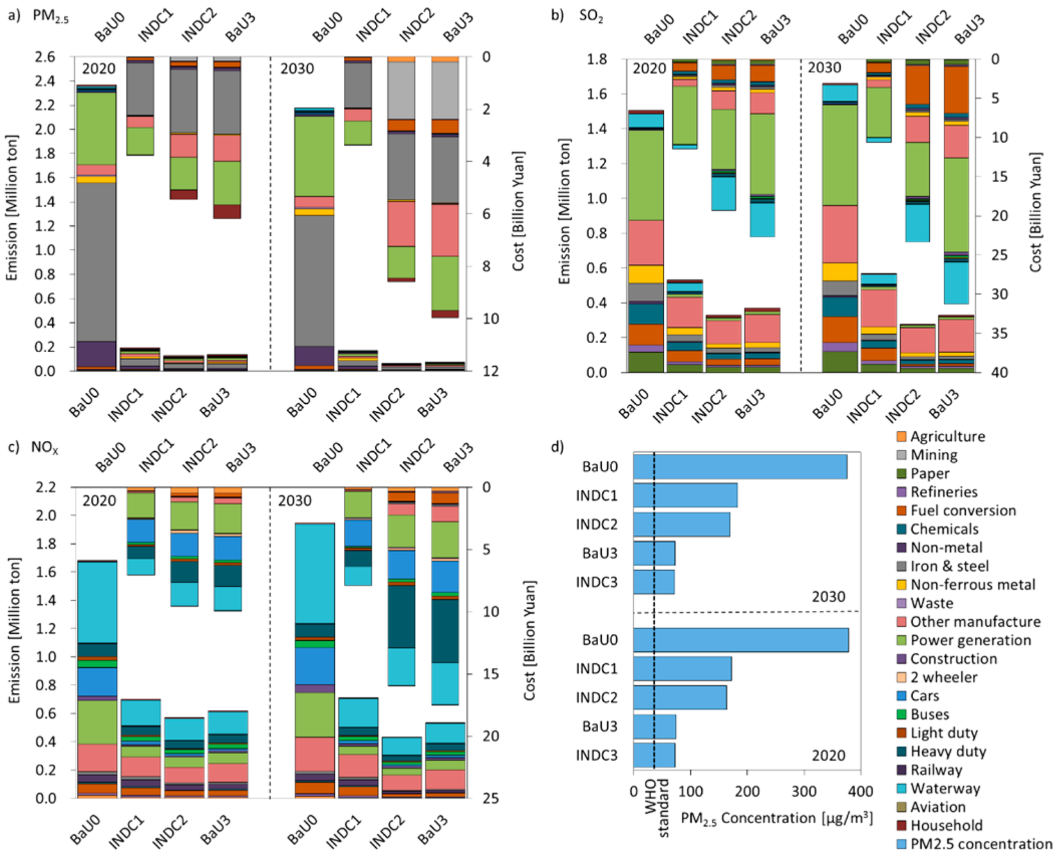


**Figure 2.** Annual $PM_{2.5}$ (a), $SO_2$ (b), and $NO_x$ (c) emissions and control costs (2007 constant price) and $PM_{2.5}$ concentrations (d) in 2020 and 2030 in Shanghai (emissions and control costs under the INDC3 scenario are not plotted because they are the same as those under the INDC2 scenario).

the air pollution control measures adopted only in Shanghai have limited effects on local $PM_{2.5}$ concentration reduction if the neighboring regions do not apply any control measures at all. Such results suggest that air quality in Shanghai is heavily influenced by the surrounding areas through atmospheric transport of pollutants. The high $PM_{2.5}$ concentrations in neighboring Jiangsu and Zhejiang provinces can offset the local efforts on emission control. Therefore, it is critical to adopt the control strategy in the entire YRD region to significantly reduce $PM_{2.5}$ pollution in Shanghai. In addition, climate policies could also improve air quality. With the same air pollution control measures but a smaller energy and transport activity, the $PM_{2.5}$ concentration could be 1.5 $\mu g/m^3$ lower under the INDC3 scenario than under the BaU3 scenario.

**3.2. Health Impacts.** Many studies confirm that long-term exposure to high $PM_{2.5}$ polluted air may induce higher morbidity and mortality of respiratory, cardiovascular and cerebrovascular diseases.[7−9] Figure 3a shows that annual mortality is estimated to be 192 400 (95% CI: 14 400−384 900) cases under the BaU0 scenario in 2030, but its uncertainty is large. Relative to the uncontrolled scenario, local emission control combined with climate policies could avoid approximately 101 500 and 108 200 premature deaths under the INDC1 and INDC2 scenarios. Multiregional integrated control could avoid around 159 200 cases under the BaU3 scenario, indicating that it is the most-effective control strategy. Moreover, $PM_{2.5}$ pollution could also induce additional morbidity. Annual morbidity of $PM_{2.5}$-pollution-related diseases is extremely high under the BaU0 scenario, with a figure of a total 0.31 (95% confidence interval, CI: 0.26−0.37) cases per capita in 2030. Upper respiratory infection is the dominating morbidity end point, followed by asthma and chronic bronchitis. The morbidity is projected to be 0.24 (upper respiratory infections), 0.04 (asthma), and 0.02 (chronic bronchitis) cases per capita under the BaU0 scenario, and these three diseases account for 97% of total morbidity. Implementation of emission control strategy could reduce half of the morbidity under the INDC1 and INDC2 scenarios. Likewise, multiregional integrated control could further reduce the morbidity to approximately 0.05 (95% CI: 0.05−0.06) cases per capita under the BaU3 scenario. The morbidity and mortality will both decrease slightly with the application of climate policies in INDC3 from the BaU3 level.

The additional morbidity and mortality lead to heavier economic burdens on the residents. Annual expenditure on $PM_{2.5}$-pollution-related diseases is projected to be 282 (95% CI: 147−386) yuan per capita or in total 5.2 (95% CI: 2.7−7.1) billion yuan in 2030 under the BaU0 scenario (Figure 3b). The top diseases with the most expenditure are respiratory hospital admission, upper respiratory infection, cerebrovascular hospital admission, and cardiovascular hospital admission. Among all the expenditures, hospital admission expenditure would be the highest, and such an expenditure would increase significantly from 2020 to 2030 under all the scenarios. The expenditure would decrease substantially if implementing emission control measures in Shanghai. Under the local control scenarios, the expenditure on $PM_{2.5}$-pollution-related diseases is equivalent to 45% of the BaU0 scenario in 2030. Furthermore, the


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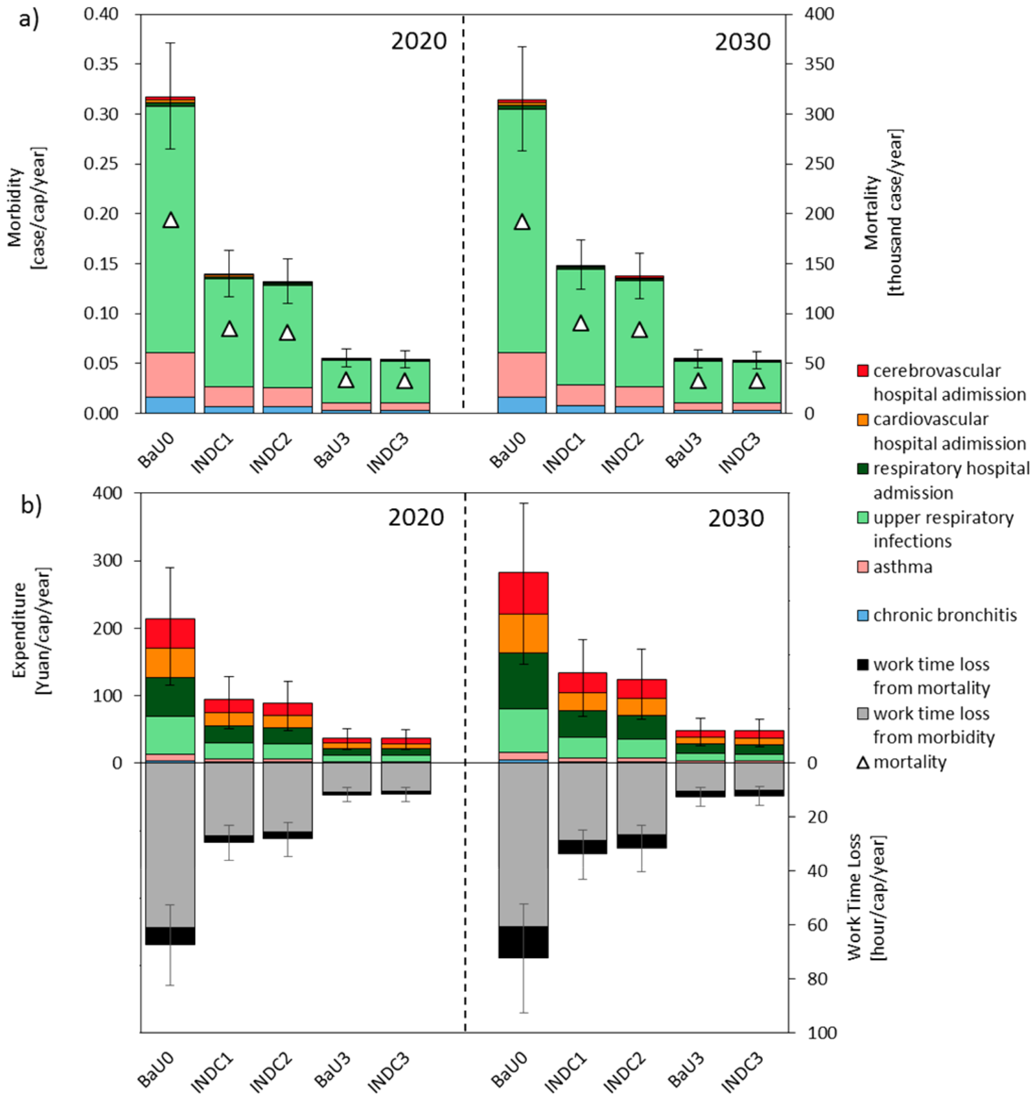


**Figure 3.** Annual morbidity and chronic mortality (a) and expenditure and work time loss (b) in 2020 and 2030. Error bars of morbidity, expenditure, and work time loss are acquired from the 95% confidence interval of exposure−response functions.

multiregional integrated control measures could considerably decrease the health expenditure to 49 (95% CI: 25−67) yuan per capita under the BaU3 scenario, equivalent to 17% of the BaU0 scenario in 2030. In other words, multiregional integrated control measures could avoid in a total 4.3 billion yuan expenditure in 2030.

A work-loss day is defined as a day when a person aged 15−64 stays off work or school because of illness. In this study, work-time loss is divided into two parts: that from morbidity and that from cumulative mortality. Work time loss from morbidity accounts for about 90%, and that from mortality accounts for about 10%. From per capita point of view, the annual work time loss in Shanghai is estimated to be over 60 h due to $PM_{2.5}$ pollution under the uncontrolled scenarios (Figure 3b). Under the local control scenarios, annual work time loss will be reduced to 28.1−33.7 h. Such a figure would decrease to 11.5 (95% CI: 8.9−14.1) and 12.2 h (95% CI: 8.8−15.7) under the INDC3 scenario in 2020 and 2030, respectively.

**3.3. Macroeconomic Impacts.** Additional expenditure and work time loss caused by $PM_{2.5}$-pollution-related diseases will lead to macroeconomic impacts. Table 2 shows that GDP and

**Table 2. GDP and Welfare Losses in 2030 (Lower and Upper Values of 95% Confidence Interval of Exposure−Response Functions)**

| | GDP losses (%) | | | welfare losses (%) | | |
|---|---|---|---|---|---|---|
| scenario | lower | medium | upper | lower | medium | upper |
| BAU0 | 1.60 | 2.26 | 2.95 | 2.18 | 3.14 | 4.15 |
| INDC1 | 0.70 | 0.95 | 1.22 | 0.78 | 1.07 | 1.37 |
| INDC2 | 0.65 | 0.89 | 1.14 | 0.72 | 0.99 | 1.28 |
| BAU3 | 0.27 | 0.37 | 0.48 | 0.37 | 0.51 | 0.65 |
| INDC3 | 0.25 | 0.34 | 0.44 | 0.28 | 0.38 | 0.50 |

welfare loss in 2030 will be high under the BaU0 scenario, with losses of 2.26% and 3.14%, respectively. The GDP and welfare loss would decrease to 0.95% and 1.07% with air pollutants emission control under the INDC1 scenario and even to 0.89% and 0.99% with strict control under the INDC2 scenario. Under the INDC3 scenario, the GDP and welfare loss could be only 0.34% and 0.38%, respectively, which are the lowest among all the scenarios. The multiregional integrated control in YRD could reduce more than half of GDP loss from local control in Shanghai, equivalent to 34.8 billion yuan. If GHG


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mitigation policies are not implemented simultaneously, the GDP and welfare loss would be 0.37% and 0.51% under the BaU3 scenario, respectively, higher than under the INDC3 scenario. Thus, climate policies could reduce the economic loss, especially residents' welfare, although its health benefit is limited. Compared with Kan and Chen's[19] estimated 1.03% of GDP loss of Shanghai in 2001, the GDP losses under pollution control scenarios in 2030 are lower in this study. Furthermore, sectoral outputs will also be affected. Especially, those labor-intensive sectors may suffer from more output losses, e.g., agriculture, food, textile, and service sectors, with leading output loss rates of 1.41%, 0.65%, 0.75%, and 0.57%, respectively (see more details in Table S2).

However, the reduced GDP loss would be achieved at the expense of control measures. The GAINS model estimates the control costs for all the scenarios, and the results show that the total costs would be 22.3 billion yuan under the INDC1 scenario (0.56% of GDP) and 34.3 billion yuan under the INDC2 scenario (0.86% of GDP) in 2020 (Figure 2a–c). The control costs will decrease slightly during 2020–2030 under the INDC1 scenario but will increase substantially under the INDC2 scenario. However, their proportion of the overall GDP will both decrease to 0.35% (INDC1) and 0.76% (INDC2) in 2030. If not combined with climate policies, the control measures will cost the highest under the BaU3 scenario but cannot achieve the lowest emissions. In general, the costs of $SO_2$ control measures are the highest among the three pollutants, although the emission reduction rate of $PM_{2.5}$ is the highest. Sectors with large amounts of air pollutant emissions under the uncontrolled scenarios will correspondingly spend more on emission control. Consequently, the sectors with the highest control costs are projected to be power generation (for $PM_{2.5}$, $SO_2$, and $NO_x$), iron and steel (for $PM_{2.5}$), and transport (for $NO_x$).

Figure 4 compares the costs and benefits of air pollution control and reveals that in general, the benefits would be higher

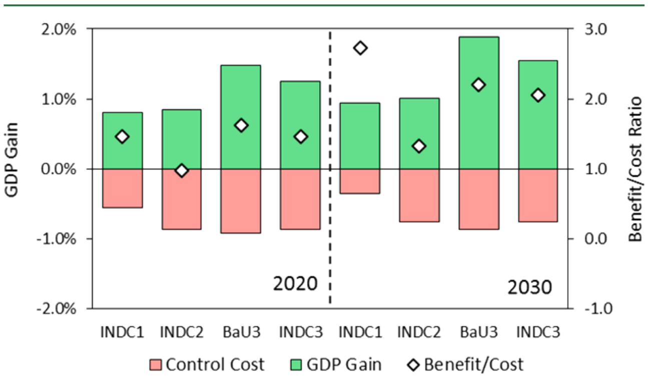


**Figure 4.** Costs and benefits of air pollution control measures in 2020 and 2030.

than the costs except for the year of 2020 under the INDC2 scenario. With a control cost of 0.76% of GDP, Shanghai would gain 1.01% of GDP through strict control measures under the INDC2 scenario in 2030. The benefit-to-cost ratio under the INDC1 scenario is 2.7, more than twice of that under the INDC2 scenario, which means that the marginal utility of control measures will be reduced. Furthermore, with almost the same control costs under the INDC2 scenario, multiregional integrated control in YRD could achieve more GDP gains, with a benefit-to-cost ratio of 2.1 under the INDC3 scenario in 2030. The benefit-to-cost ratio under the INDC3 scenario will be slightly lower than that under the BaU3 scenario because GDP will suffer some losses from climate policies. It is noteworthy that the benefit-to-cost ratios will increase during the period of 2020–2030 under all the scenarios, indicating increasing net benefits gained by applying air pollution control measures in Shanghai.

## 4. DISCUSSION

**4.1. Policy Implications.** Labor-intensive sectors, such as agriculture, food, textile, and service sectors, suffer more output losses from $PM_{2.5}$ pollution. It implies that enterprises in these sectors should pay more attention to workers' health, e.g., administering regular medical examinations.

This study shows a substantial $PM_{2.5}$ concentration decrease and economic benefits in Shanghai when implementing multiregional air pollution control strategies. This means that Shanghai, Jiangsu, and Zhejiang should closely collaborate to control air pollution so that the benefits can be maximized. Currently, there are some ongoing collaboration activities among Shanghai, Jiangsu, and Zhejiang. For instance, the YRD region established a joint air pollution warning center in Shanghai for sharing monitoring data. When one city in YRD holds high-level national or international events such as the G20 Summit in Hangzhou in 2016, the whole YRD region will take the same control measures, e.g., temporarily shutting down polluting factories. In addition, the region has adopted strict ship diesel emission standards in certain ports and plans to expand it to all sea and inland water areas in YRD in the future. The collaborative action in the next phase should move to implement progressive unifying emission standards for all factories and vehicles in the region.

Climate policies could reduce macroeconomic loss caused by air pollution control measures in Shanghai. In particular, reducing the use of fossil fuels in the total energy consumption and developing renewable energy can both reduce $CO_2$ and air pollutant emissions. Shanghai should import more hydropower from other provinces, promote electric or hybrid vehicles, and encourage the application of wind power, solar power, and geothermal power.

**4.2. Sensitivity Analysis.** Uncertainty could be classified into three aspects within our research framework. The first aspect is uncertainty of future economic development and

**Table 3. Sensitivity Analysis of Future GDP under the INDC2 Scenario in 2030**

| | range | | | range | |
|---|---|---|---|---|---|
| | upper | lower | | upper | lower |
| $PM_{2.5}$ emission | 4.40% | −3.60% | morbidity | 0.25% | −0.19% |
| $SO_2$ emission | 2.40% | −2.10% | mortality | 0.25% | −0.19% |
| $NO_x$ emission | 7.40% | −6.20% | GDP loss | −10.10% | −4.80% |
| $PM_{2.5}$ concentration | 0.20% | −0.20% | welfare loss | −19.40% | 31.40% |


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energy consumption in the CGE model. The second aspect is estimation of future air pollutant emissions and $PM_{2.5}$ concentration, which is related to both technology selection and the source-receptor matrix in the GAINS model. The third aspect is related to ERFs used in the health model. We analyzed the uncertainty related to the first aspect by adding two additional scenarios with high and low economic development and energy consumption in the CGE model, and this information is fed into the GAINS model. Speeding up annual GDP growth rates from 7.2% to 7.5% or slowing down to 6.9%, i.e., 10.1% higher or 8.4% lower of GDP in 2030 will lead to emissions, concentration, health, and economic changes (Table 3). Under the INDC2 scenario, GDP and welfare losses are more-sensitive to GDP changes than $PM_{2.5}$ concentration and health impacts. Regarding the second aspect, we have two levels of control technology penetration, so it is partly addressed. Regarding calculation of $PM_{2.5}$ concentration, we described how it is calculated in the Supporting Information. In terms of uncertainty of ERFs, the error bars in Figure 3 show 95% CI of ERFs and morbidity ranges between −17% and 17%, morbidity between −93% and 100%, expenditure between −48% and 37% and work time loss between −27% and 29% in 2030. This indicates that chronic mortality caused by ambient air pollution is sensitive to ERFs. Nonetheless, only 10% of work-time loss results from mortality so that the sensitive variable mortality is not likely to considerably influence the economic results. Table 2 shows that GDP and welfare losses range between −26% and 32%, corresponding to 95% CI of ERFs.

**4.3. Limitations.** The valuation of morbidity in this study only considers the costs from work-time loss but does not include the costs from performing at less than full capacity due to less-serious restrictions on normal activity. In terms of work-time loss, this study ignores the time spent on taking care of family and others with health problem from $PM_{2.5}$ pollution. Future epidemiological studies can add such surveys of the general population. In addition, without considering the direct health and economic benefits from GHG mitigation, the benefit-to-cost ratios of the INDC pathway may be under-estimated.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b00026.

GAINS-China model, the health module, and a detailed description of CGE model. Tables showing exposure-response functions and GDP loss, welfare loss, and sectoral output loss rate relative to reference scenarios in 2030. (PDF)

## ■ AUTHOR INFORMATION

### Corresponding Authors

*Phone: +86-10-62764974; fax: +86-10-62764974; e-mail: dai.hancheng@pku.edu.cn.

*Phone: +86-21-54748019; fax: +86-21-54740825; e-mail: ygeng@sjtu.edu.cn.

### ORCID

Rui Wu: 0000-0002-5389-1199

Hancheng Dai: 0000-0003-4251-4707

Yong Geng: 0000-0002-2284-1375

### Notes

The authors declare no competing financial interest.

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