LETTER

Co-benefits of deep carbon reduction on air quality and health improvement in Sichuan Province of China

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Abstract

Facing the dual challenges of air pollution and climate change, China has set ambitious goals and made decisive efforts to reduce its carbon emission and win the ‘Battle for Blue Sky’. However, how the low-carbon transition and air quality targets could be simultaneously achieved at the sub-national levels remains unclear. The questions arise whether province-level climate change mitigation strategies could help ease the air pollution and close the air quality gap, and how these co-benefits can be compared with the cost of the green transition. Here, using an integrated modeling framework, we combined with local air pollutant emission inventories and issued policy documents to quantitatively evaluated the current situation and targets of the air quality and health co-benefits of deep carbon mitigation in Sichuan, a fast-developing inland province in China. We found that by 2035, without system-wide energy transformation induced by carbon mitigation policies, the improvement in air quality in Sichuan Province might be limited, even under stringent end-of-pipe emission control measures. On the contrary, the co-benefits of low-carbon policies would be significant. On top of stringent end-of-pipe controls, the implementation of carbon mitigation policy in line with China’s enhanced climate target could further reduce the average PM$_{2.5}$ concentration in Sichuan by as much as 2.8 μg m$^{-3}$, or the population-weighted PM$_{2.5}$ concentration by 5.9 μg m$^{-3}$ in 2035. The monetized health co-benefits in Sichuan Province would amount to 23 billion USD under the stringent carbon mitigation scenario, exceeding 1.7 billion USD of the mitigation cost by 2035. The results indicate that significant air quality and health benefits could both be achieved from carbon mitigation at the provincial level. Both air-pollution or carbon-reduction oriented policies would be important for improving environmental quality and public health.

1. Introduction

Climate change and air pollution have become two of the most imminent environmental challenges for China [1–6]. With substantial CO$_2$ emissions and the health burden induced by air pollution [7–14], China has also made continuous efforts to tackle these two problems, attempting to find better synergistic solutions [15–19]. By 2019, China has achieved the climate targets for 2020 in its Nationally Determined Contribution (NDC) in advance, realizing a 48.1% reduction in carbon intensity and a 15.3% share of non-fossil fuels in the total primary energy consumption [20, 21]. In terms of air pollution, after implementing the unprecedentedly intensive Action Plan on Air Pollution Control and Prevention [22] followed by a series of policies and actions since 2013, emissions of primary pollutants and the severity of PM$_{2.5}$ pollution have both reduced substantially [19, 23–26]. With the current achievement, China has set more ambitious targets to pursue deep climate mitigation and better air quality [15]. China started a new three-year action plan for cleaner air (often quoted as ‘Battle for Blue Sky’) [27] in 2018, and more recently, the country has
updated its NDC target, stressing reaching an emission peak before 2030 and aiming at carbon neutrality before 2060 [28, 29].

Literature has revealed the potential pathways, opportunities, and challenges in China’s transition toward green development. Jiang et al [30] analyzed the 1.5 °C scenario for China using the Integrated energy and environment Policy Assessment model for China. They found that to achieve the deep mitigation target, China’s fossil-based energy system needs rapid transition to zero-emission energy, and the carbon capture and storage technology needs to play an important role. Using the Global Change Assessment Model to assess different energy system transition scenarios, Zhou et al [31] found that China’s CO2 emissions should peak as earlier as 2025 or 2020 to achieve the 2 °C or 1.5 °C targets. Tong et al [32] have identified effective sectoral emission control policies to alleviate anthropogenic pollutant emissions in China under different socioeconomic and climate change scenarios, pointing out that active air pollution control policies are critical for achieving near-team pollution reductions.

At the same time, many studies have revealed the potential synergies between climate change mitigation and air pollution control. On either the global or national scale, by promoting the industrial upgrade and improving the energy consumption structure, carbon mitigation policies could play an important role in improving local air quality, bringing significant co-benefits and becoming an important supplement for air pollution control policies [33–38]. For China, many co-benefit studies are conducted at the national level or focus on a specific policy, which offers broad insights into China’s mitigation pathways while the regional resolution is relatively coarse. Peng et al [39] found that the electrification of final energy demand combined with coal-to-electrification transition could simultaneously curb the emissions of CO2 and air pollution, avoiding 55.0–69.0 thousand deaths per year by 2030. A recent study by Cheng et al [40] investigated the air quality improvement pathways in China under current and future mitigation efforts towards carbon neutrality, and highlighted the importance of ambitious climate mitigation strategies in China’s post-2030 air quality improvement.

As significant regional heterogeneity exists in China, cost-effective mitigation pathways for different provinces could be completely different. Therefore, more specific regional research looking into the possible co-benefits of and synergies between policies is needed for China’s provinces to achieve multiple environmental targets. Literature has also reported the synergies between energy transition and air pollution control policy in China at the sub-national level. A few systematic studies have explored the magnitude and variation of health co-benefits across multiple cities or provinces in China. For example, Li et al [41] revealed that industry and power would be the key sectors in terms of air pollution control, and the increased air pollution control cost induced by stricter control strategies could be eased by low-carbon policies in the long run. Li et al [42] found that the air quality co-benefits of carbon pricing in China for a scenario with 4% emission intensity reductions per year could reach US$1.6–53.7 billion for different provinces, and whether the monetized health co-benefits could partially or fully offset the policy costs would depend on the choice of mortality valuation parameter. Xing et al [43] stressed the gap between China’s climate change mitigation efforts with its NDC target in terms of achieving deep mitigation of air pollution. Ramaswami et al [44] evaluated the effects of mitigation policies in 637 cities in the Chinese mainland and found significant heterogeneity in health co-benefits. Besides, studies [44–52] have also evaluated the co-benefits of climate change mitigation on air quality and human health for one province or city, especially for the eastern developed regions (e.g. Beijing, Shanghai, Tianjin, and Shandong). The common conclusions are that the air quality co-benefits could help avoid as large as tens to hundreds of thousand annual premature deaths, depending on the strength and coverage of low-carbon transition policy as well as the underlying population number and baseline mortality rates.

Current studies have demonstrated the importance of low carbon transition in the medium-to-long run, and provided insights on effective regional air pollution control. However, only a few studies [43, 53] have conducted cost-benefit analysis for provincial climate mitigation pathways in China or Chinese provinces, which might impact the ambition of regional climate policies. More importantly, most existing studies applied partial equilibrium models or energy system optimization models to generate the energy pathways [15, 37, 43]. More detailed analysis on the evolution of the energy system that interacts with the regional economic growth and economic competitiveness are still lacking, and could provide better cost-benefit insights for local policy-makers.

In this study, we use a computable general equilibrium (CGE) model to investigate the combined effects of climate change mitigation and air pollution control policies, as well as the cost-benefit of climate policy in a Chinese province-Sichuan. As a fast-developing province in recent years, Sichuan performs better in economic growth than most central or western provinces in China, with 83.75 million population and total GDP accounting for more than 20% of western China in 2019 [54]. Although the carbon intensity has been continually decreasing since early 2000, Sichuan’s CO2 emissions are still the third-highest in China’s western provinces, reaching 309 MtCO2 or 3.1% of national total CO2 emissions in 2017 [10]. Additionally, sitting in the Sichuan Basin in southwestern China, Sichuan has suffered from severe air pollution due to the combined effects
of high air pollutant emissions and special geographical conditions [55–59], and is facing great challenges in distinguishing and implementing effective air pollution control policies. According to the bulletin issued by the Department of Ecology and Environment of Sichuan Province [60], there is still about half of the cities with annual average PM$_{2.5}$ concentration exceeding the National Ambient Air Quality Standard (NAAQS) (35 µg m$^{-3}$), although haze pollution in Sichuan has already been greatly alleviated. Under this situation, finding a coordinated way to reduce carbon emissions while combating air pollution is crucial for Sichuan’s sustainable development. In particular, with abundant water resources and great potential in hydroelectricity, Sichuan has the particular advantage to become a pioneer in reaching carbon emission peak by promoting clean electricity and energy efficiency improvement, realizing the green transition and simultaneously improving the air quality.

For the Sichuan Province, the literature has constructed carbon emission inventories or carbon footprints [61–63] in this region and has also revealed the spatial-temporal variability and source contribution of its air pollution [56, 57, 64, 65]. However, there is still a lack of knowledge for the pathways, costs, and benefits of mid-to-long-term low carbon transition and air pollution control in Sichuan Province. Only several national studies [42, 49] with provincial resolution have reported the health co-benefits of CO$_2$ reduction or costs of pollution reduction in Sichuan, and they found that the cost-effectiveness in Sichuan is not very outstanding compared with other provinces. To our knowledge, few have discussed the synergies between carbon mitigation and air pollution control policies in Sichuan at a sector-wise scale in the mid-to-long run. Therefore, how Sichuan could achieve the CO$_2$ emission peaking goal under the national pledge framework, and to what extent Sichuan could coordinate the climate and air quality targets cost-effectively, both of which remain to be investigated.

Here, using an integrated modeling framework which includes an energy-economy model (IMED|CGE), the GAINS (Greenhouse Gas-Air Pollution Interactions and Synergies) model, and a health impact assessment model (IMED|HEL), we examine the impacts of both climate policy and air pollution control policy on air pollutant and carbon emissions, PM$_{2.5}$ pollution and public health in 2020–2035 in Sichuan Province. For climate policy, we focus on the deep mitigation scenario in line with China’s recently updated NDC, which is also corresponding to the global 1.5 degree target [66]. This is in accord with the short-to-medium term mitigation targets for provinces in China, and the target year 2035 corresponds to the ‘Beautiful China 2035’ goal, which aims to achieve fundamental improvement in environmental quality. We mainly address the following three questions: (a) what is the maximum potential of air pollution mitigation through end-of-pipe control measures in Sichuan Province? (b) What are the air quality and public health co-benefits of ambitious climate change mitigation policies in line with China’s updated climate goals, on top of the end-of-pipe control measures? (c) How are the monetized health co-benefits compared with the cost of carbon policies? Our findings provide policy implications for coordinated achievement of air pollution control and low carbon development, supporting a harmonized, cost-effective sustainable transition in the sub-national region.

2. Method

2.1. Overview of the integrated modeling framework

In this study, the macroeconomic model IMED|CGE (Integrated Model of Energy, Environment and Economy for Sustainable Development|Computable General Equilibrium), GAINS (Greenhouse Gas-Air Pollution Interactions and Synergies) model, and the health impact assessment model IMED|HEL (Integrated Model of Energy, Environment and Economy for Sustainable Development|Health) are coupled to quantitatively evaluate the effects of carbon emission reduction policy and air pollution control policy in Sichuan Province. The overall framework is shown in figure 1.

We investigate different carbon policy and air pollution control pathways for Sichuan from the base year 2015 to the target year 2035, by which China would have reached the CO$_2$ emission peak at the national level, and achieved the environmental protection target ‘Beautiful China 2035’ [67, 68]. After drawing up the scenario framework that includes both carbon policy and end-of-pipe air pollution control policies, we evaluate the levels of air pollutant emissions and PM$_{2.5}$ pollution under different scenarios using the GAINS model. We then assess the health impacts and the monetized losses in each scenario using the IMED|HEL model, and analyze the effects of air pollution control and carbon mitigation policies. Finally, we compare the mitigation costs under low carbon scenarios with the avoided PM$_{2.5}$-related economic losses to evaluate the low carbon policy’s cost-benefit ratio. All economic costs and benefits presented in the studies are in constant price (2017 USD). More detailed methods are described in the appendix.

2.2. IMED|CGE model

The IMED|CGE model is a multi-sector, multi-region economic model. As a recursive-dynamic CGE model, it can simulate the dynamic economic growth, sectoral output, employment, and many other economic elements under specific intervention under the equilibrium market conditions. The model includes
Figure 1. Integrated modeling framework for studying mitigation co-benefits.

several modules that interact with each other: a production module, a trading module for both domestic and foreign markets, a residents’ expenditure module as well as a government module. By linking and harmonizing the social accounting matrix (SAM) data with the energy balance table and emission inventories, the model can also investigate the dynamics of energy system evolution and the trends of air pollutants and greenhouse gas emissions. The unique advantages of applying a CGE model in the co-benefit study include its ability to capture the dynamic evolution of the energy system [69–72], which is largely affected by industry upgrading under carbon emission constraints, and the corresponding mitigation costs that occurred for the whole system (e.g. GDP losses, consumption losses).

The IMED|CGE model is flexible in region classification and the sector divisions, and has been applied in a wide range of studies to analyze the impacts of low-carbon transition and air pollution control strategies at global, national and provincial scales [73, 74]. In this study, we use the IMED|CGE model with 25 aggregated economic sectors to analyze different climate policy scenarios for Sichuan Province. The base year of modeling is 2017 and the target year is 2035. The national carbon budgets under scenarios with climate targets are downscaled to obtain reasonable carbon mitigation pathways for Sichuan Province.

2.3. GAINS model

The GAINS model is a comprehensive energy-technology and air quality model developed by IIASA, which covers more than 160 countries or regions. The model has highly integrated modules, including technology module, cost module, emission module, and air quality module, which make it advantageous in analyzing the technical cost, emission pathways, as well as air quality implications of the green transition. This model has been widely used in exploring cost-effective multi-sectoral pollution control strategies under specific carbon or air quality targets [73, 75–78].

In this study, we use the GAINS-China version and focus on the Sichuan region to analyze the impacts of low-carbon and air-quality-control policies on pollutant emissions and PM$_{2.5}$ concentration. Activity data from climate policy scenario results modeled by IMED|CGE, and end-of-pipe technology mix projections under different air pollution control scenarios, are combined in the GAINS-China model to estimate pollutant emissions and PM$_{2.5}$ concentration under each scenario. To avoid inconsistency between statistics and the GAINS model, we modified...
the built-in energy activity data for the base year in the GAINS model according to the energy balance table of Sichuan Province in 2017 before coupling the IMED|CGE and GAINS-China model. The sectoral mapping between the IMED|CGE and GAINS model and more information on the adjustment of base year energy data is provided in the appendix.

Besides, one of the important advantages of the GAINS model is its systematic and fast calculation of the cost of emission control. Therefore, similar to the literature [33, 41], we also extract the total costs of end-of-pipe control from the GAINS-China model results to analyze the decreased pollution control costs under climate change mitigation scenario from reduced use of fossil energy, and further calculate the total economic benefit of climate change mitigation by adding this avoided control cost with monetized health benefits obtained with the IMED|HEL model.

2.4. IMED|HEL model
The IMED|HEL model is a health impact assessment model that can evaluate the disease burden and the induced economic losses attributable to air pollution or climate change. This model has been widely used in studies to analyze the health implications of air pollution control policies at global, national, or local scales, as well as the health co-benefits under climate change mitigation policies [11, 53, 79, 80]. The IMED|HEL model, instead of the built-in health impact assessment module in the GAINS-China model, is used in our study as it can conduct a more comprehensive health and economic impact assessment of the PM$_{2.5}$ pollution, and allows for a more flexible choice of exposure–response functions (ERFs) and the gridded socioeconomic data used in the assessment. The input data for this model include exposure or concentration level of air pollution, the exposed population, and the updated ERFs from epidemiologic studies. Available choices of ERFs include the log-linear form function [81], the integrated exposure–response (IER) function [82], and the Global Exposure Mortality Model (GEMM) [83]; these enable uncertainty analysis of the health co-benefit in terms of ERFs. In this study, the IMED|HEL model quantifies the relative risk of PM$_{2.5}$-related morbidity or mortality for each 0.5°grid in Sichuan, and estimates total excess morbidity, mortality, and work loss in Sichuan Province under each scenario. The monetization module in this model then assesses the corresponding economic losses induced by the disease burden, and the avoided economic losses under carbon mitigation scenarios are further compared with the costs of carbon mitigation.

2.5. Scenario setting
We set up a two-dimensional scenario framework with four scenarios for comprehensively investigating the impacts of carbon mitigation policies and air pollution policies in Sichuan Province, with a focus on energy-related and industrial process-related air pollutant emissions and induced disease burden. We use this scenario framework to analyze the whole system costs, benefits and co-benefits of mitigation policies, hoping to shed light on cost-effective provincial green transition pathways.

The first dimension is carbon mitigation scenarios, including two scenarios: a baseline scenario (BaU) versus a low-carbon development scenario (1.5 degree). The BaU scenario depicts the full attainment of China’s initial submitted version of NDC, aiming at a 60%–65% CO$_2$ emission intensity reduction by 2030 compared with 2005. The reason of using an emission trend closer to ‘current policy’ instead of ‘no policy’ as BaU scenario is that China has a great possibility to realize the unconditional NDC targets [84], and it would be more meaningful and straightforward for policy-makers to analyze the co-benefits of more ambitious targets. Then we introduce the 1.5 degree scenario depicting a mitigation pathway compatible with the global 1.5 degree climate target and China’s recently enhanced NDC targets [29]. The results of energy and sectoral output under the 1.5 degree scenario are compared with the baseline (BaU) scenario to uncover the changes in driving forces of pollutant emissions.

The second dimension is the levels of end-of-pipe air pollution control measures. We consider three different scenarios, i.e. reference case with emission control levels fixed at the 2015 level (REF), levels of controls following current legislation trend (CLE), and level of controls that realize maximum feasible reduction (MFR). Based on these two dimensions, we draw up a total of four scenarios to investigate the effects of end-of-pipe control and the air quality co-benefits of carbon mitigation (table 1). A detailed introduction, including the storylines, underlying assumptions for each scenario, and how the scenarios are used in this study, can be found in the appendix.

2.6. Data
The SAM used to build the IMED|CGE model is adjusted from the 2017 input–output tables of China and Sichuan, which are taken from China’s Statistical Yearbook [85] and Sichuan Provincial Bureau of Statistics [86]. Future population estimates for Sichuan Province, as well as gridded population data for health impact assessment, are from the provincial projections results under the ‘Middle of the Road’ shared-socioeconomic pathway in the literature [87]. The energy balance table for Sichuan Province is from China Energy Statistical Yearbook [88]. The energy and activity projections in the GAINS model have been modified upon the baseline built-in projections in the GAINS model, according to the energy balance table and CGE results. The built-in projections are from the WEO2016_CPS_CLE scenario data in the GAINS model database. Emission inventories
for calibrating $\text{CO}_2$ and air pollutants emissions in the base year are derived from our own emission inventory. Parameters for health impact monetization, including the value of a statistical life and disease expenditure per case, are estimated using the baseline data or regression model reported in the literature \[89, 90\]. All economic costs and benefits presented in this study are in constant price (2017 USD).

### 3. Results

#### 3.1. Evolution of energy consumption under climate change mitigation scenarios

Implementing stronger carbon mitigation policies would reshape the post-2020 energy system in Sichuan Province to a great extent (figure 2). The peak year of primary energy consumption would arrive in 2020 under the 1.5 degree scenario, 10 years ahead of that under the BaU scenario, and the peak volume would be significantly lower (figure 2(a)). Under the BaU scenario, final energy consumption increases from 97 Mtoe in 2017 to 157 Mtoe in 2035; while under the 1.5 degree scenario, the increase would be moderate and electricity would dominate the final energy demand (accounting for about 50%). While the consumption of coal, oil, gas and coke will decrease by 58%, 31%, 0.9% and 64% by 2035 compared with 2017, electricity demand will triple, from 16 Mtoe in 2017 to 66 Mtoe in 2035.

From the sectoral perspective, the low-carbon transition toward carbon neutrality in the power sector will significantly reduce the share of fossil fuels in Sichuan’s primary energy, which compares well with previous studies focusing on China \[40, 66, 91\]. The use of fossil energy in power generation will peak at 23 Mtoe in 2031 under the BaU scenario, of which coal, gas, oil and coke accounted for 85%, 10%, 4.8%, and 0.3%, respectively (figure 2(c)). However, in the 1.5 degree scenario, fossil energy consumption will reach its peak in 2024 at 18 Mtoe, of which coal accounts for the largest share (73%), and gas, oil and coke accounted for 19%, 7.8% and 0.7%, respectively. The substantial reductions in the use of fossil fuels are also driven by the growth in energy efficiency, as well as by demand reductions.

#### 3.2. Carbon dioxide and air pollutant emissions

Strict carbon budgets in the 1.5 degree scenario would lead to substantial and earlier $\text{CO}_2$ emission reduction (figure 3(b)). In the baseline scenario (BaU), Sichuan’s carbon emissions maintain a growing trend from 2017 to 2030, then decline from 2030 to 2035. While in the 1.5 degree scenario, carbon emissions in Sichuan would peak around 2020 in advance. In the baseline scenario, carbon emissions would increase by about 73 Mt (+24%) in 2025, 87 Mt (+28%) in 2030 and 57 Mt (+19%) in 2035 compared with 2017. In the 1.5 degree scenario, carbon emissions would decrease significantly from the 2017 level by about 19 Mt (−6.0%) in 2025, 76 Mt (−25%) in 2030, and 129 Mt (−42%) in 2035.

Implementing deep carbon mitigation policy and end-of-pipe control measures can reduce pollutant emissions with varying degrees (figure 3(b)). Under scenarios without carbon constraints, the end-of-pipe control measures in the BaU_CLE and BaU_MFR scenarios would help reduce emissions of all air pollutants in the next 20 years. Under the BaU_CLE scenario, the emission of $\text{SO}_2$ would increase by 50 kt (5.6%), and the emissions of NOx, VOCs, NH3 and PM$_{2.5}$ would reduce by 190 kt (22%), 385 kt (42%), 79 kt (8.7%) and 240 kt (40%) in 2035 compared with the 2015 level. By realizing maximum levels of end-of-pipe controls (BaU_MFR), emissions of all primary pollutants would further decrease. In 2035, the emissions of $\text{SO}_2$ would increase by 50 kt (5.5%), and the emissions of NOx, VOCs, NH3 and PM$_{2.5}$ would reduce by 230 kt (27%), 427 kt (46%), 102 kt (11%) and 329 kt (55%) compared with 2015 (figure 3(a)).

Differences in driving forces and intense policy for emissions of different air pollutants lead to divergent reduction rates in the future. The end-of-pipe control measures can significantly reduce the $\text{SO}_2$, NOx, VOCs and PM$_{2.5}$ emissions from the agricultural sector by 86%–100% respectively in 2035.

### Table 1. Scenario settings.

| Scenarios                      | Air pollution control policies                      | Carbon mitigation policies                      |
|-------------------------------|----------------------------------------------------|-------------------------------------------------|
| Air pollution policies        |                                                    | • Carbon emission reduction in 2015–2030 in line with China’s NDC targets |
| (end-of-pipe control)         |                                                    | • Carbon emissions peak in 2030                |
| BaU_REF                       | End-of-pipe control strategies fixed at 2015 level |                                                    |
| BaU_CLE                       | Stronger end-of-pipe control measures under stated air quality policies and targets |                                                    |
| BaU_MFR                       | Stringent end-of-pipe controls to achieve maximum feasible emission reduction |                                                    |
| Carbon mitigation policies    | 1.5deg_MFR                                        | • Deep mitigation in line with the 1.5 degree climate target |
|                               | Stringent end-of-pipe controls to achieve maximum feasible emission reduction (same with BaU_MFR) |                                                    |
Figure 2. Energy consumption in Sichuan Province from 2017 to 2035: (a) primary energy; (b) final energy; (c) energy balance table without import and export. The unit is millions of tonnes of oil equivalent.

Figure 3. Carbon dioxide and air pollutant emissions: (a) air pollutant emissions by sectors; (b) CO$_2$ and air pollutant emissions; (c) co-reduction rate under 1.5deg-MFR scenario.

under the MFR scenario, which is because Sichuan Province has basically eliminated the open burning of straw of the agricultural sector in 2020. However, according to emission inventory of Sichuan Province, agricultural sources of NH$_3$ emissions, mainly the use of ammonia fertilizer and livestock breeding reduction, are relatively hard to abate, limiting the reductions of NH$_3$ emissions in the future. The increase in electricity demand in Sichuan Province due to economic development will lead to a slight
increase in SO$_2$ emissions from 2015 to 2030, about 75% under the BaU_REF scenario, and the end-of-pipe emission reduction potential of the power and heating plants is low, with only 3.1% decline in 2030, which is related to the implementation of the ‘Ultra-Low Emissions of Electricity’ target, and SO$_2$ emissions from the power and heating plants have been far lower than those of industrial sources in 2015. Moreover, Sichuan Province has formulated a series of end-of-pipe removal rate targets for VOCs for sectors including petrochemical, pharmaceutical, automobile manufacturing, which lead to a 24% reduction of VOCs emission in 2035.

Deep climate mitigation policies could bring further air pollutant emission reductions on top of strict end-of-pipe control. Under the 1.5deg_MFR scenarios, it is expected that the emissions of all air pollutants would further decline in the next 20 years (figure 3(b)). Compared with the 2015 level, the low-carbon policy in the 1.5deg_MFR scenario would lead to reductions of SO$_2$, NO$_x$, VOCs, NH$_3$ and PM$_{2.5}$ emissions by 370 kt (41%), 465 kt (54%), 478 kt (52%), 109 kt (12%) and 374 kt (63%) in 2035.

Under the 1.5 degree scenario, significant drops in pollutant emissions could be expected owing to the shift in structures of energy production and final energy demand. In Sichuan Province, it is estimated that the proportion of renewable energy power generation will further increase by 2035, so emissions from the power sector will be significantly reduced. Total emissions of primary PM$_{2.5}$ will drop by 21%, 42% and 35%, respectively in 2035 compared with the BaU scenario, while co-benefits of reductions in VOCs and NH$_3$ emissions are smaller. Considering that VOCs and NH$_3$ are also important precursors of secondary PM$_{2.5}$ pollution, future clean air plans might still need to pay more attention to end-of-pipe controls for non-methane VOCs and NH$_3$.

For different years and different air pollutants, moving from the previous NDC target to 1.5 degree features varied reduction rates relative to CO$_2$ emission abatement. Figure 3(c) compares the reduction rates of CO$_2$ and different air pollutants under the 1.5deg_MFR scenario in 2025 and 2035. Greater emission reduction co-benefits could be expected in 2035, and for NO$_x$, SO$_2$ and primary PM$_{2.5}$, which are pollutants more closely related to fossil fuel combustion targeted by the climate policy. In 2025, the reduction rates of the carbon and air pollutants under the 1.5 degree scenario would range between $\sim$24% (carbon reduction) and $\sim$43% (PM$_{2.5}$ reduction), the range would be $\sim$51% and $\sim$55% in 2035, respectively. Among all pollutants, carbon dioxide and NO$_x$, SO$_2$, PM$_{2.5}$ have a greater co-emission reduction space, which can reduce emissions by 47%, 45%, and 55%, respectively in 2035; the space for NH$_3$ and VOC is smaller, at 17% and 31%.

3.3. PM$_{2.5}$ pollution mitigation

Sichuan Province has suffered from relatively severe PM$_{2.5}$ pollution as it sits in the Sichuan Basin, which favors local circulation and pollution transmission [92], and the pollution is especially severe in the eastern part, where located the Chengdu Plain urban cluster that gathers 60% of the population and 60% of the industrial activity of Sichuan Province [93, 94]. Under mitigation policies, the PM$_{2.5}$ concentration in Sichuan Province would decline significantly from 2015 to 2030, especially in the more polluted region. Among the scenarios, BaU_REF is a counterfactual scenario in which we assume that there are additional carbon mitigation policies but not end-of-pipe control measures after 2015. As a result, the PM$_{2.5}$ concentration would be 35 $\mu$g m$^{-3}$ in 2025 and 32 $\mu$g m$^{-3}$ in 2035 (figure 4(b)); PM$_{2.5}$ concentration in the central and eastern part would still be above China’s air quality standard (figure 4(a)). Implementing pollutant control measures would lead to different extents of improvements in PM$_{2.5}$ concentration, while the strengthened carbon mitigation policy could bring more significant air quality improvements in a larger region (figure 4(a)). When end-of-pipe control levels following the current trend (BaU_CLE) are implemented, the PM$_{2.5}$ concentration would be reduced by 1.3 $\mu$g m$^{-3}$ in 2025 and 1.7 $\mu$g m$^{-3}$ in 2035; when the maximum potential of end-of-control measures is realized (BaU_MFR), it would be reduced by 2.5 $\mu$g m$^{-3}$ in 2025 and 2.6 $\mu$g m$^{-3}$ in 2035, which reflects the increasingly limited effects of end-of-pipe control measures. When a deeper carbon mitigation policy (1.5deg_MFR) is implemented, the concentration of PM$_{2.5}$ would be further reduced by 4.5 $\mu$g m$^{-3}$ in 2025 and 5.4 $\mu$g m$^{-3}$ in 2035. Consequently, the regional average concentration would be lower than 35 $\mu$g m$^{-3}$, meeting China’s air quality level II standard.

However, from the perspective of population-weighted concentration, which better takes into account the actual exposure of people, the results show that there is still a gap from the air quality guideline (AQG) level recommended by the World Health Organization (WHO) and the ‘Beautiful China’ target (figure 4(b)). Due to the high industrial density and high population density in southeastern parts of Sichuan Province, population-weighted PM$_{2.5}$ concentration in 2035 still exceeds the national standard, reaching 64 $\mu$g m$^{-3}$ under the conventional policy scenario. Even if the most ambitious end-of-pipe control is implemented, the population-weighted PM$_{2.5}$ concentration could only drop slightly to 58 $\mu$g m$^{-3}$. As the improvement potential depletes from the conventional end-of-pipe measures, climate policy plays a more important role. The PM$_{2.5}$ concentration in 2030 would be further reduced to 52 $\mu$g m$^{-3}$ under the 1.5deg_MFR scenario. This also indicated that further efforts in air
pollution mitigation are urgently needed. Further air pollution control measures should take into account the spatial distribution of concentration and population, as well as regional coordination in pollution control, as the pollution transported by the surrounding provinces could also be substantial, which is not assessed in our study as we focus on benefits from local mitigation policies.

3.4. Health impacts
With significant air quality co-benefits, achieving low-carbon transition in Sichuan following China’s 2060 carbon neutrality target could substantially reduce the disease burden attributable to air pollution. We estimated premature deaths from five diseases caused by PM$_{2.5}$ in Sichuan Province in different scenarios based on the GEMM ERF [83], including ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease, lung cancer and lower respiratory infection (figure 5(b)). Among the causes, IHD leads to most PM$_{2.5}$-related premature mortality, followed by stroke. Results show that large numbers of PM$_{2.5}$-related premature deaths could be avoided by implementing more stringent end-of-pipe controls, as well as by deep carbon mitigation in the long term. In the baseline scenario (BaU_REF), premature deaths related to PM$_{2.5}$ would be approximately 150 (95% confidence interval, CI95: 100–190) thousand in 2025, and would be reduced to 140 (CI95: 99–180) thousand in 2035. The implementation of end-of-pipe control policies (BaU_CLE and BaU_MFR) can avoid 4500 and 7200 premature deaths in 2035, respectively; when deep climate change mitigation is achieved (1.5deg_MFR), the avoided excess mortality could be as many as 14 000 in 2035, accounting for 10% of the total mortality in the baseline scenario. The projected increase in premature mortality under reduced population-weighted PM$_{2.5}$ concentration in the future is mainly driven by the growth and aging of the population (see more detailed analysis in Appendix). This indicates that efforts to reduce air pollution are indispensable and crucial to protect public health, particularly in the context of the future rapidly aging population and increased population vulnerabilities to air pollution.

Carbon emission mitigation could also help further reduce the incidence of diseases caused by PM$_{2.5}$ exposure, including chronic bronchitis, asthma, upper respiratory, respiratory hospital admission, cardiac hospital admission, and cerebrovascular hospital admission (figure 5(a)). Under the baseline scenario (BaU_REF), the per capita incidence risk would decrease, from $5.4 \times 10^{-8}$ (CI95: 0.3E-8–2.1E-8) in 2015 to $4.7 \times 10^{-8}$ (CI95: 0.3E-8–1.8E-8) in 2035. With the combination of stringent end-of-pipe controls and climate policy (1.5deg-MFR), the reduction
of PM$_{2.5}$-related disease risks could be $1.1 \times 10^{-8}$ in 2035 (23%).

Avoided work loss days in Sichuan could also be expected under mitigation scenarios. By avoiding disease cases and premature mortality, pollution alleviation could reduce labor loss, contributing to both improvements in social benefits and economic development. In the baseline scenario (BaU_REF), the number of labor days lost related to PM$_{2.5}$ would decrease from 109 million days in 2025 to 97 million days in 2035 (figure 5(c)). Stringent carbon mitigation and end-of-pipe control policies would further contribute to reducing the work loss, and the maximum avoided labor loss time can reach 20 million days in 2035, equivalent to 5 h of labor time loss per year per capita.

### 3.5. Monetized health co-benefits

The monetized health benefits from both mitigation policies could be substantial. The avoided outpatient and hospitalization expenditure from PM$_{2.5}$-related disease would increase over time under mitigation scenarios (figure 6). The expenditure on diseases caused by PM$_{2.5}$ shows an overall downward trend from 2015 to 2035, consistent with the results of primary pollutant emissions and PM$_{2.5}$ concentration (figure 6(a)). Under the 1.5deg_MFR scenarios, the disease expenditure of Sichuan Province would account for 0.12‰ of GDP of the year by 2025 and 0.068‰ by 2035 (figure 6(b)); compared with the BaU_MFR scenario, avoided disease expenditure would amount to 20 million USD in 2025 and 23 million USD in 2035, respectively, which means that carbon mitigation policies would avoid substantial costs of disease expenditure and reduce the household expenditure burden.

The value of life losses induced by PM$_{2.5}$ pollution could be effectively avoided by carbon mitigation. Under the baseline scenario (BaU_REF), the loss of life value in Sichuan Province would decrease over...
time, reaching 170 billion and 230 billion USD (constant price in 2017) in 2025 and 2035, respectively. This loss in 2035 would be twice that of the 2015 level. When the carbon mitigation policies (1.5deg_MFR) are implemented, the proportion of life value losses as of GDP would be significantly lower, decreasing to 16% by 2035 (figure 6(b)). Compared with the baseline scenario, the loss of life value would be reduced by 12 billion USD in 2025 and 23 billion USD in 2035 (figure 6(a)).

3.6. Cost-benefit analysis of carbon mitigation

We compared the costs of 1.5 degree mitigation relative to BaU from the IMED|CGE model, which are indicated in consumption loss, with the monetized health co-benefits and avoidable end-of-pipe control costs. This frames a cost-benefit analysis for deep carbon mitigation policy in Sichuan (figure 7). The consumption loss indicator in this study is the change of household consumption in the carbon mitigation scenario compared with the baseline scenario, indicating the changes in the level of household welfare. The health co-benefits from the IMED|HEL model include the avoided value of statistical life and disease expenditures; the emission control costs are extracted from the GAINS-China model, covering all pollutants and are discounted with a 4% discount rate.

Results show that only considering the population health improvement, the co-benefits could fully cover the cost of carbon mitigation, and the net benefit would increase over time in the 1.5deg_MFR scenario (figure 7). The total pollutant control costs in Sichuan Province would be approximately US$23 million per year in 2020, and continued to increase by 32 folders to US$766 million in 2035, due to growing activity levels and stricter control measures. The avoided control costs from low-carbon energy and industrial transition would be smaller than the monetized health co-benefits, but it would not be negligible. The consumption loss from deeper mitigation will be US$3.1 billion in 2025 and increase to US$3.9 billion in 2030. Decreased carbon mitigation cost in 2035 is mainly due to the increase in services demand from the residential sector, which may be driven by the industrial structure adjustment under the 1.5 degree target. The net benefits of carbon mitigation would be 9.0 billion USD in 2025, 16 billion USD in 2030 and 22 billion USD in 2035.

The cost of avoidable emission control of carbon mitigation scenario will not offset consumption losses and are far lower than the health benefits. For
example, the avoidable emission control cost will be US$770 million in 2035, consumption loss will be US$1.7 billion, while the health benefits will reach US$23 billion. This conclusion is consistent with previous studies \cite{41} that reducing air pollution control costs will not offset the incremental CO$_2$ mitigation costs associated with deep decarbonization; therefore, health co-benefits would be important. At the same time, the reduced control cost is also not negligible as this is a market impact and the order of magnitude is comparable with the cost of climate change mitigation.

3.7. Uncertainties in health impact assessment

Previous studies have shown that the choice of ERFs may lead to great uncertainties in the assessment of PM$_{2.5}$-related health impacts \cite{95–98}, so we used three different ERFs to estimate the avoidable PM$_{2.5}$-related premature deaths in Sichuan Province under different scenarios and analyzed the potential uncertainties (figure \ref{fig8}).

In Sichuan Province, the health benefits of avoiding premature deaths estimated with different ERFs would be between 8.0% and 20% in 2035. The premature deaths estimated using the non-linear IER function are lower than those estimated using the log-linear or GEMM function (figure \ref{fig8}). In 2015, according to the IER function, the PM$_{2.5}$-related premature deaths in Sichuan Province was 98 (95% CI: 46–133) thousand; the premature deaths under the BaU_MFR and 1.5deg_MFR scenarios would decrease by 3.9 thousand (3.9%) and 7.9 thousand (8.0%) deaths by 2035 compared with BaU_REF scenario. Based on the GEMM function, we estimate that PM$_{2.5}$-related premature deaths will be 140 (95% CI: 100–180) thousand in 2015; by 2035, the premature deaths under the BaU_MFR and 1.5deg_MFR scenarios would decrease to 7.2 thousand (5.0%) and 14.5 thousand (10.0%) deaths, respectively. An important finding is that even if switching to the IER function, which is the default choice of quantifying health impact in the GAINS-China model, the qualitative implication is robust that health co-benefits from deep climate change mitigation would be much higher than the mitigation costs: the avoidable health losses calculated by the IER equation in 2035 would be 11 billion USD, and the total cost would only be 1.7 billion USD. This is consistent with previous studies \cite{75,99} that pointing out the uncertainties in health impact assessment might impact the results for cost-benefit ratios, but will not induce a decisive impact on the qualitative results.

4. Discussion

4.1. Comparison with other studies

Previously, most provincial-level studies focus on NDC and 2 degree scenarios instead of the 1.5 degree scenario. Still, we try to compare the physical and monetized health co-benefits of carbon mitigation with other studies (table \ref{tab2}). The estimations of this study are higher than others in terms of both
Figure 8. The co-benefits on avoided premature deaths in Sichuan Province between 1.5deg_MFR and BaU_REF scenario using three different ERFs: ‘linear’ indicating the log-linear function with parameters from [81], non-linear GEMM and non-linear IER. The unit is million deaths.

Table 2. Comparison of the health benefits of carbon mitigation in 2030 with other studies.

| National level | Provincial level |
|----------------|------------------|
| **Avoidable premature deaths** | Shanghai: 108 200 [53] |
| 102 730–167 425 [100] | Different provinces: 248–10 383 [42] |
| 19 962 [101] | Sichuan: 7690–14 170 ^a |
| 18 402–162 217 [102] | Guangdong: 4691 [101] |
| 94 000–160 000 [42] | Shaanxi: 3181 [101] |
| 95 200 [103] | Xinjiang: 1175 [101] |
| 170 000 [99] | Gansu: 3610 [101] |

| **Monetized health co-benefits** | Different provinces: 1.6–53.7 billion USD [42] |
| 90.0 billion USD [100] | Sichuan: 15.9 billion USD ^a |
| 2.72–9.45 billion USD [101] | Northwest region: 1.03–4.87 billion USD [101] |
| 619 billion RMB [102] | |
| 790.7 billion USD [42] | |
| 406 billion USD [99] | |

| **Avoided health damages per capita** | Sichuan: 47.0–78.4 USD ^a |
| | Sichuan: about 200 USD [42] |
| | Different provinces: about 180–820 USD [42] |

^a This study.

Avoidable premature deaths and monetized health co-benefits. The main reason for the difference could be the stricter carbon mitigation assumption in this study that leads to greater health benefits. The per capita avoidable health damages for Sichuan in this study are lower than Li et al [42], which may be due to the choice of the value of statistical life parameters in this study as well as the different carbon mitigation scenario designs.

The estimations for national- or provincial-level co-benefits differ in terms of the avoidable premature deaths and monetized health co-benefits, although they generally agree with each other in terms of the order of magnitude of the physical and monetized health co-benefits. Apart from scenario design and policy assumption, the differences could also be attributable to modeling mechanisms, parameter settings, and ERFs. Among these factors, the uncertainties from health impact assessment, especially due to the choice of ERFs that have been continuously updated, would be crucial and widely discussed in previous studies [95–98]. Therefore, more detailed uncertainty analysis and reporting would be necessary for future researches for better comparison among studies.

The emission source inventory is an important basic data for environmental air quality management. Although the national-level inventory established by domestic scholars obtains the air pollutant emissions of Sichuan Province, these inventories are based on the ‘top-down’ method to calculate the total emission, which is difficult to accurately interpret the
pollution discharge characteristics of the region. Taking the MEIC inventory [104] for example, we classify and compare the emission inventory in this study based on the MEIC inventory system (appendix table S8 (available online at stacks.iop.org/ERL/16/095011/ mmedia)). It can be found that the MEIC inventory overestimated the SO\textsubscript{2}, NO\textsubscript{x} and VOCs emissions of Sichuan Province in 2015, especially in the industrial sector by 324.1 kt, 112.7 kt and 214.4 kt, respectively. Among the PM\textsubscript{2.5} emissions, the MEIC inventory overestimates the the residential sector emissions by 193.8 kt, and does not take into account non-point emissions such as fugitive dust.

4.2. Limitation
It should be noted that our research has some limitations in data, models and other aspects. For instance, we set the carbon mitigation policies for Sichuan with the assumption that Sichuan province adopts the same reduction rates of carbon intensity or per capita emission as China’s national level, and has yet to consider possible individualized carbon reduction pathways. Since current policies generally target only as far as 5 years ahead, our study has a certain degree of uncertainty regarding policy extrapolation. The uncertainty in emission and PM\textsubscript{2.5} concentration estimation is also not assessed in the GAINS model, which is also a caveat that needs to be noted. Besides, in the CGE model, the results of mitigation costs in terms of total GDP losses could be significantly affected by assumptions on international and interprovincial trade, especially for the two-region model that could have a more detailed depiction for local features but with more aggregated trade volume analysis. Therefore, our study investigates the costs of carbon mitigation policies on the welfare of the whole society with the ‘consumption loss’ indicator, which could make the results more stable and higher than the baseline scenario in some provinces, because carbon constraints would change local industrial structure to indirectly stimulate household consumption [42], which can also explain the consumption losses in 2035 is lower than those in 2030 in this study.

4.3. Policy implications
Our study on Sichuan’s coordinative green transition pathway might be instructive for the policy-making not only in this province, but also in other Chinese provinces, especially the regions in pursuit of both fast and high-quality development. After implementing existing air pollution control policies, the remaining emission reduction space of the end-of-pipe emission control measures might be limited, making it harder to alleviate air pollution and reach more stringent air quality standards. This has become a shared problem for many Chinese cities and provinces. At the same time, there is an increasingly stronger willingness to promote low-carbon transition and structural changes from both the Chinese government and local stakeholders. Therefore, whether provinces can earn the double dividend of air pollution reduction and gains in public health and economy through low-carbon transition strategies, might be one of the core questions in local mid-to-long-term transition pathway design. Our case study of Sichuan Province shows that co-achieving multiple green-growth goals could be possible. The low-carbon transition policies and actions at the provincial level in line with China’s carbon-neutrality goal would not only further improve local environmental quality and public health, but also have high benefit-cost ratios and are economically feasible.

Therefore, when policy-makers formulate regional green transition blueprints, both carbon mitigation policies and pollution control policies should be considered. Deep carbon mitigation policies can not only help attain the carbon emission reduction targets, but also bring significant co-benefits on air quality and public health, with monetized health co-benefits comparable with mitigation costs. Considering the limited emission reduction potential of end-of-pipe control, low-carbon energy policies are necessary to further reduce air pollutant emissions at the provincial level.

Our study also highlighted the advantages of provincial-level co-benefits study with a local focus by incorporating more practical data input based on deep literature investigation for localized air pollution control targets and actions. We also raise the opinion that a comprehensive integrated assessment framework is helpful for unveiling the evolution and interactions between the energy and economic system at the provincial level. By taking the advantages of the CGE model in simulating dynamic interaction between economic development and energy structure evolution and their impacts on emissions projected in the GAINS model, the health benefits from climate or air pollution control policies as well as the cost-effective pathways could be identified.

Besides, when evaluating the policy effects and air quality benefits, both actual pollution and population exposure should be taken into consideration. In our study for Sichuan province, although the regional weighted PM\textsubscript{2.5} concentration reaches the standard, the population-weighted concentration remains a relatively high level, above the air quality standard and far exceeding WHO’s guideline concentration to ensure minimum health damages. It is also worth noting that since the government generally formulates a package of policy measures, including the development of renewable energy, end-of-pipe control, and other environmental protection actions, the actual improvement in air quality might exceed the results predicted by our model. Nevertheless, more attention should also be paid to further reduce the exposure
level of population, especially in regions with high density of population and economic activities.

5. Conclusion

Based on the integrated assessment method, this study combined the local issued policy documents to quantitatively evaluate the impacts of carbon mitigation policies and end-of-pipe pollution control measures in one of China’s rapidly developing inland provinces—Sichuan. In addition, we combined the future air pollutant emission with the air pollutant emission inventory of the base year to analyze the mitigation potential of sectors. We found that in Sichuan Province, the implementation of carbon mitigation policies could reduce carbon emissions and lead to an earlier emission peak by 2020, and bring significant air quality and public health co-benefits.

By 2035, the implementation of end-of-pipe control measures can reduce air pollutant emissions in Sichuan, but PM$_{2.5}$ concentration in some regions of this province would still not achieve the national air quality standard. By maximizing the use of end-of-pipe pollutant control technology (BaU_MFR), the emissions of SO$_2$, NOx, VOCs, NH$_3$ and PM$_{2.5}$ would be reduced by 5.5%, 27%, 46%, 11% and 55% in 2035 compared with 2015 level. However, there is still a large space for emission and pollution reduction.

Under such conditions, the co-benefits of carbon mitigation are also essential for the improvement of air quality. Carbon mitigation policies in Sichuan can not only reduce the CO$_2$ emissions, but also further reduce air pollutant emissions and greatly improve air quality in the southeastern part of Sichuan Province. In the 1.5 degree scenario, carbon emissions would peak around 2020, and decrease by about 6.1% in 2025 and 42% in 2035 compared with 2017. Achieving the 1.5deg_MFR scenario would bring even more significant emission reduction effects, SO$_2$, NOx, VOCs, NH$_3$ and PM$_{2.5}$ would be reduced by 41%, 54%, 52%, 12% and 63% in 2035 compared with 2015. The regional average concentration of PM$_{2.5}$ would be further reduced to 27 $\mu$g m$^{-3}$, reaching the NAAQS. However, the population-weighted concentration of PM$_{2.5}$ would be 51 $\mu$g m$^{-3}$, which means there are still health risks from exposure to relatively high levels of PM$_{2.5}$.

In terms of the cost and benefits of mitigation policy, we found that benefits from public health improvement could fully cover the cost of carbon mitigation in the 1.5 degree scenario, where the net benefit of carbon mitigation would be 9.0 billion USD in 2025 and 22 billion USD in 2035. Moreover, in addition to improving air pollution in the short term, carbon mitigation would bring broader economic benefits by avoiding more frequent climate extremes and natural disasters in the long term induced by severe climate change, which is not quantified in our study but worth further analysis in future studies.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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