The quest for improved air quality may push China to continue its CO_2 reduction beyond the Paris Commitment

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China is challenged with the simultaneous goals of improving air quality and mitigating climate change. The "Beautiful China" strategy, launched by the Chinese government in 2020, requires that all cities in China attain 35 μg/m^3 or below for annual mean concentration of $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 μm) by 2035. Meanwhile, China adopts a portfolio of low-carbon policies to meet its Nationally Determined Contribution (NDC) pledged in the Paris Agreement. Previous studies demonstrated the cobenefits to air pollution reduction from implementing low-carbon energy policies. Pathways for China to achieve dual targets of both air quality and CO_2 mitigation, however, have not been comprehensively explored. Here, we couple an integrated assessment model and an air quality model to evaluate air quality in China through 2035 under the NDC scenario and an alternative scenario (Co-Benefit Energy [CBE]) with enhanced low-carbon policies. Results indicate that some Chinese cities cannot meet the $PM_{2.5}$ target under the NDC scenario by 2035, even with the strictest end-of-pipe controls. Achieving the air quality target would require further reduction in emissions of multiple air pollutants by 6 to 32%, driving additional 22% reduction in CO_2 emissions relative to the NDC scenario. Results show that the incremental health benefit from improved air quality of CBE exceeds 8 times the additional costs of CO_2 mitigation, attributed particularly to the cost-effective reduction in household $PM_{2.5}$ exposure. The additional low-carbon energy polices required for China's air quality targets would lay an important foundation for its deep decarbonization aligned with the 2 °C global temperature target.

air quality | CO_2 | energy policy | cobenefit | China

China is facing serious air pollution problems, particularly for ambient $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 μm) which has harmful effects on human health (1–3). To protect human health, strengthened air pollution control policies were recently implemented in China targeting 35 $\mu g{\cdot}m^{-3}$ or less for all cities by 2035 (4). The Action Plan on Prevention and Control of Air Pollution, released in 2013, has resulted in noticeable reductions in urban ambient $PM_{2.5}$ concentrations (5, 6). In 2018, however, China's national $PM_{2.5}$ standard of 35 $\mu g{\cdot}m^{-3}$ annual average was exceeded in 217 of China's 338 cities at the prefecture or higher level, not to mention exceedance of the World Health Organization (WHO) guideline (annual mean $PM_{2.5}$ concentration <10 $\mu g{\cdot}m^{-3}$). A big challenge for future improvement is that advanced end-of-pipe control technologies have already been widely applied in electric and industrial sectors (7, 8). For example, over 90% of coal-fired power plants had installed end-of-pipe control technologies by 2018 (8). Therefore, the potential for further reductions using end-of-pipe control measures might be limited, and implementation of low-carbon energy policies to constrain total energy consumption and promote a transition to clean energy is expected to be an inevitable option for further reducing air pollution (9).

The impacts of climate change on humans and ecosystems have also received considerable attention in China over the past few decades, and strategies for mitigating these impacts have been adopted (10). In 2016, China officially signed its Nationally Determined Contribution (NDC) in the Paris Commitment, which pledges for CO_2 emissions per unit of GDP in 2030 to fall by 60 to 65% compared to 2005. A big concern arises as to whether China will continue its carbon reduction even under a pessimistic international situation after the US withdrawal from the Paris Agreement in 2019. Previous studies (11–18) have suggested that climate

Significance

Pathways for China to achieve its dual targets of air quality and CO_2 mitigation in 2035 were investigated through a newly developed evaluation framework coupling integrated assessment and air quality models. Results indicate that the low-carbon energy policies, traditionally regarded as a primary result of climate mitigation, are likely driven more by the efforts on air quality attainment in China. To achieve air quality attainment in China could lead to more reduction in CO_2 emissions than its Nationally Determined Contribution. In addition, stronger low-carbon policies will bring significant benefits to public health via improvements in air quality. This study also provides a valuable reference for other developing countries to address their duel challenges of climate change and air pollution.

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mitigation-oriented low-carbon energy policies can result in a reduction in air pollution.

Therefore, there is a question as to whether China needs the application of low-carbon energy technologies and fuels to meet its air quality target. Such synergy is important, since many developing countries (e.g., China, India) are currently experiencing serious air pollution problems, and reducing air pollution is typically a more pressing national concern than climate mitigation (19). This could lead to continuous reductions in CO_2 emissions even under a pessimistic international situation for mitigating climate change.

Here, we project future air quality attainment in China through 2035, assess the CO_2 reduction cobenefits associated with attaining the ambient $PM_{2.5}$ standards, and evaluate the health and climate impacts associated with air quality attainment-oriented energy policies. We accomplish this by coupling an integrated assessment model [GCAM, the Global Climate Assessment Model (20)], tuned with a detailed bottom-up emission inventory (21), and an air quality model [CMAQ, the Community Multiscale Air Quality model (22)] to evaluate future air quality and CO_2 emissions, and an integrated exposure–response (IER) model to evaluate the health effects due to the long-term ambient O_3 and both ambient and household $PM_{2.5}$ exposures in China. This integrated approach captures the nonlinearities among energy, emissions, concentrations, and health, thus allowing us to assess the cobenefits of air quality attainment on protecting health and mitigating CO_2 in an internally consistent framework.

This study investigates future emissions of air pollutants and CO_2 in China under three future pathways with different considerations of two energy scenarios and two end-of-pipe control levels (Table 1). We first designed the NDC–current legislation (CLE) pathway to represent the CO_2 intensity reduction targets outlined by China's NDC to meet the Paris Commitment (23), with CLE level of end-of-pipe controls. This pathway represents the current ongoing energy policies and end-of-pipe control measures to be conducted in China following CLE. For the purpose of air quality attainment, we first designed the NDC–maximum feasible reduction (MFR) pathway to represent the same ongoing energy policies as the NDC–CLE scenario, but with MFR level realized by end-of-pipe controls. Additionally, to achieve the air quality attainment in 2035, we also introduce the CBE–MFR pathway, in which low-carbon energy policies beyond the NDC requirements are implemented (i.e., the cobenefit energy scenario [CBE]) with the MFR level of end-of-pipe controls.

Both energy scenarios are projected under the same future socioeconomic assumptions (*SI Appendix*, *Text S1*), and their assumptions about low-carbon energy policies for the industry, building (i.e., residential and commercial), transportation, and electric sectors are detailed in *SI Appendix*, *Texts S2–S5*, respectively. As presented in Fig. 1*A*, the total energy uses in NDC and CBE in 2035 are estimated to be 150 and 126 exajoules (EJ), respectively. These values represent increases of 24% and 4%, respectively, from 2015, driven by the future growth of the economy and population (*SI Appendix*, Fig. S1). The total CO_2 emissions in NDC and CBE are estimated as 11.3 and 8.8 Gt, respectively, in 2035. Two levels of end-of-pipe control are applied to the electricity, industry, transportation, and building and non–energy-related sectors, which are detailed in *SI Appendix*, *Texts S6–S9*. The emission factors for $PM_{2.5}$, NOx (in terms of NO_2), and SO_2 have been greatly reduced with the application of end-of-pipe controls in 2035, compared to 2015 (Fig. 1*B*). Note that the removal efficiencies of control technologies are less than 50% for domestic and agricultural sectors, which are difficult to control. The challenge to reducing the future emissions includes the continuous growth of activities (Fig. 1*A*), as well as limited reduction potentials of end-of-pipe control measures (Fig. 1*B*). For example, the end-of-pipe controls cannot be feasibly applied to domestic stoves. There are still over 200,000 industrial boilers which cannot be well controlled because current available end-of-pipe control techniques for small boilers have relatively lower SO_2 and NOx removal efficiency compared with power plants. In addition, the NMVOCs (nonmethane volatile organic compounds) and NH_3 emissions are very hard to control by current available end-of-pipe control technologies.

Results and Discussion

China Cannot Achieve Its Air Quality Targets in the NDC Scenarios. Along the same NDC energy pathway, emissions of all air pollutants are projected to decrease evidently in the next decade due to end-of-pipe control measures in both NDC–CLE and NDC–MFR scenarios (Fig. 2). Given CLE (NDC–CLE), the emissions in 2035 of SO_2, NOx, NMVOCs, NH_3, $PM_{2.5}$, and BC

Table 1. Design of future projection of air pollutant and CO_2 emissions

Pathway	Energy scenario	End-of-pipe control levels
(1) NDC–CLE	Baseline scenario which considers only CO_2 intensity reduction to meet the Paris Commitment*	CLE†
(2) NDC–MFR	Same as energy scenario in NDC–CLE.	MFR‡
(3) CBE–MFR	Cobenefit energy scenario with implementation of low carbon policies related to energy conservation (e.g., improvement of energy efficiency)§	MFR‡

*The NDC scenario refers to the CLE of energy policies and plans conducted in China. Such an NDC scenario has a relatively conservative CO_2 target, as it only requires a peak in CO_2 emissions before 2030 and this has already been implemented in current Chinese plans. Following Fawcett et al. (23), we set the CO_2 emissions to peak in 2030 at about 12 Gt (excluding agriculture and land use) and decrease by 4.5% every 5 y after 2030.

†At the CLE level, we assume that only the currently existing control policies are in place, including the Three-Year Action Plan for Winning the Blue Sky War from 2018 to 2020 and the 13th Five-Year Plan during 2015–2020. For example, the ultralow emission standard will be applied for all existing coal-fired units nationwide, and newly built coal-fired units in eastern China will be required to have emission rates equivalent to those of gas-fired units (*SI Appendix, Text S6*). Furthermore, the ultralow emission standard will be implemented for key industries, including iron and steel, cement, plate glass, coking, nonferrous metal, and bricks (*SI Appendix, Text S7*). Strengthened emission standards are also applied to the transportation sector, reducing total emissions from the transport fleet despite growing travel demand (*SI Appendix, Text S8*). Advanced, low-emissions stoves will replace traditional household coal and biomass heating and cooking stoves in the commercial and household sector (*SI Appendix, Text S9*).

‡At the MFR level, all of the feasible control policies will be applied to realize the maximal application of end-of-pipe controls. For example, desulfurization and denitrification efficiencies in coal-fired power plants reach their highest levels (99.0% and 91.5%, respectively) (*SI Appendix, Text S6*); maximal application rates of advanced desulfurization, denitrification, and dedusting technologies are also applied in the industrial sector (*SI Appendix, Text S7*); and advanced stoves with low emissions are fully adopted to replace traditional bulk coal and biomass use in the buildings (*SI Appendix, Text S9*).

§The CBE scenario is designed for air quality attainment only, with no further constraints from the long-term climate goals (i.e., to meet the 2 °C global temperature target set out by Paris Agreement).

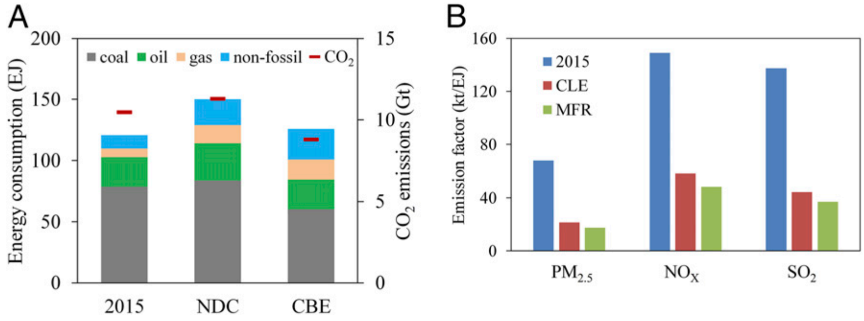

Fig. 1. The energy consumption in units of exajoules (EJ) and CO_2 emissions of two energy scenarios (*A*) and emission factors in two end-of-pipe control levels (*B*) compared with that in 2015.

(Black Carbon) will be reduced by 62%, 51%, 33%, 16%, 61%, and 83%, respectively, relative to 2015 levels. Such substantial reductions indicate the effectiveness of air pollution controls under current policies, even though energy consumption and CO_2 emissions will continue to increase (24). With the maximal application of end-of-pipe controls (NDC–MFR), all pollutant emissions are further reduced, particularly NH_3 and NMVOCs resulting from more effective controls on solvent use and on NH_3 livestock and agriculture-related sources (*SI Appendix*, *Text S9*). The reductions in SO_2 (17%), NOx (17%), $PM_{2.5}$ (19%), and BC (20%) in MFR relative to CLE can be realized by upgrading ultralow emission standards in all thermal power units, industrial boilers, and the building material industry.

Although the end-of-pipe control technologies will continue to play an important role in reducing the emission of air pollutants, there is limited potential for additional end-of-pipe applications. As demonstrated in Fig. 2, the effectiveness of end-of-pipe controls (i.e., percent reduction from CLE to MFR; see red bar in Fig. 2) on SO_2, $PM_{2.5}$, and BC decreases from 26%, 24%, and 39% in 2020 to 17%, 19%, and 20%, respectively, in 2035, implying reduced potential of the end-of-pipe control measures and their decreased effectiveness for achieving long-term air quality targets.

As seen in Fig. 3 *A* and *B*, most Chinese cities exhibit substantial decreases in $PM_{2.5}$ concentrations from 2015 to 2035 with maximum end-of-pipe controls. The number of nonattainment cities among 338 Chinese cities of prefecture level or higher is reduced from 258 in 2015 to 81 under NDC–CLE, and further, to 21, under NDC–MFR. However, there are still 3 (of 11), 4 (of 17), and 9 (of 17) cities in Hebei, Henan, and Shandong provinces, respectively, that cannot meet the national standard under NDC–MFR (Fig. 3*D*), which affects a total population of ~92.8 million. Apparently, the NDC scenarios cannot ensure that China fully attains the ambient $PM_{2.5}$ standards even with the most stringent end-of-pipe controls (NDC–MFR). More importantly, the climate change penalty (considering the impacts of future

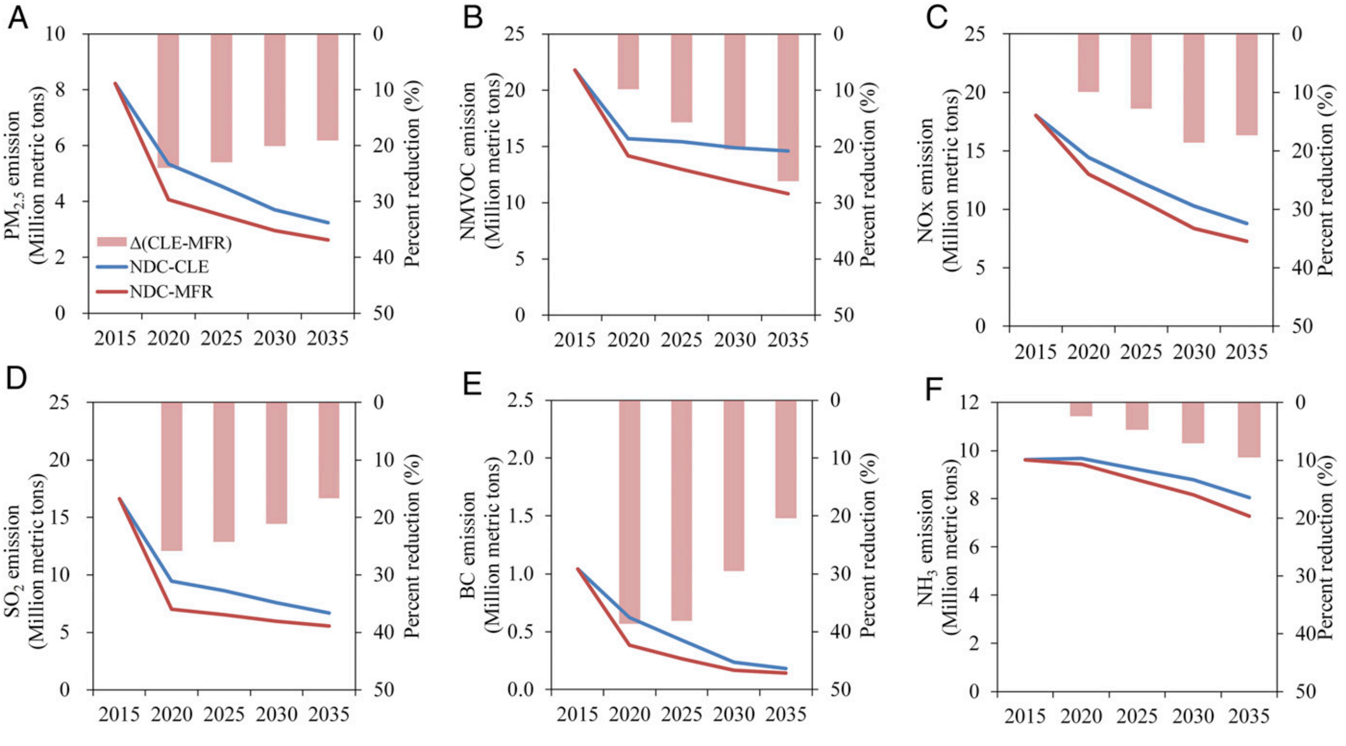

Fig. 2. Impacts of end-of-pipe controls on emissions of air pollutants under the scenarios in NDC–CLE (blue) and NDC–MFR (red) (left axis); bars for right axis represent the effectiveness of end-of-pipe controls, that is, percent reduction from CLE to MFR in each year. (*A*) $PM_{2.5}$, (*B*) NMVOCs, (*C*) NOx, (*D*) SO_2, (*E*) BC, (*F*) NH_3.

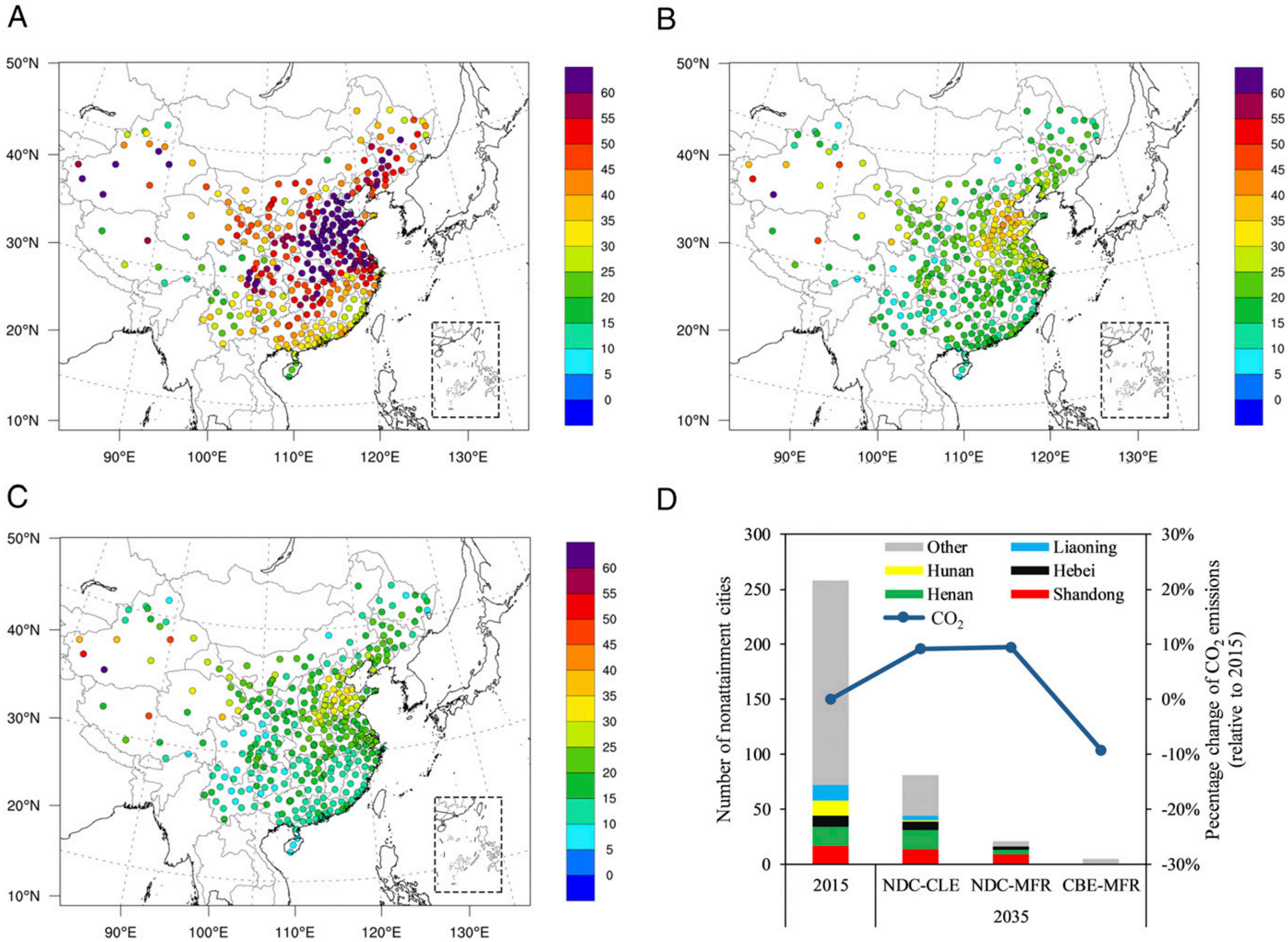

Fig. 3. Projection annual average concentrations of $PM_{2.5}$ in 338 Chinese cities from 2015 (*A*) to 2035 under NDC–MFR (*B*) and CBE–MFR (*C*), as well as the number of nonattainment cities in each province and associated changes in CO_2 emissions (*D*).

meteorology change on air pollution) could bring in additional challenge for air quality attainment, which requires even more strengthened emission reductions (25). The "Beautiful China" target (i.e., all cities in China achieving the annual concentration of $PM_{2.5}$ below 35 μg/m^3 in 2035) (4) would require more aggressive low-carbon energy policies than those in the NDC scenarios.

Air Quality Attainment-Oriented Energy Policies Bring Additional CO_2 Mitigation. The ambient air quality attainment-oriented energy policies in CBE are compared to the NDC scenario in terms of their influences on energy use and air pollutant and CO_2 emissions under the MFR end-of-pipe level (Fig. 4). Energy policies on both energy structure adjustment and energy conservation are considered in CBE. First, relative to NDC, the energy structure adjustment in CBE will lead to a higher share of renewable energy (+45% change from NDC) and natural gas (+21% change from NDC), and less coal (−16% from NDC) and oil (−10% from NDC). The share of renewable energy increases slightly more than natural gas. That is due primarily to the sharp decrease of capital cost for the renewable energy application in electric sector (26). The switch in the energy type to natural gas is mostly driven by the industrial sector, particularly from the steel, building material, nonferrous metal, coke, petrochemical, and chemical industries (*SI Appendix*, *Text S2*). The natural gas allows faster replacement of coal in industrial sectors (e.g., for heating supply) than renewable energy. Coal use is also significantly reduced in the electric sector, accompanied with a large increase of gas and nonfossil energy consumption due to the high electricity demands from end-use sectors (*SI Appendix*, *Text S5*). Enhancing the implementation of clean heating technologies, such as central heating systems, electricity (e.g., electric induction stoves for cooking and heat pumps for heating), distributed gas, geothermal heat, solar energy, and industrial waste heat, leads to a substantial reduction in the use of coal in the building sector (*SI Appendix*, *Text S3*). Those options in the building sector contribute a small fraction of the total reduction of energy use, but lead to a large share of the reduction in air pollution emissions. In total, the energy structure adjustment can result in reduction of $PM_{2.5}$, SO_2, NOx and BC emissions by 3%, 19%, 11%, and 20%, respectively, in 2035 compared to the NDC scenario, and the reduction is mainly achieved through fuel-switching measures in the industrial and building sectors (Fig. 4*C*). Additionally, CO_2 emissions are simultaneously reduced by 0.8 Gt (7%) in 2035 relative to the NDC scenario (Fig. 4*E*), and the industrial sector is the largest contributor for such a reduction. Noticeable contributions to CO_2 reductions also come from the transportation sector through the following mechanisms: promoting public transportation and bicycles to limit the growth of service demands for small passenger vehicles, encouraging the replacement of freight service demands from

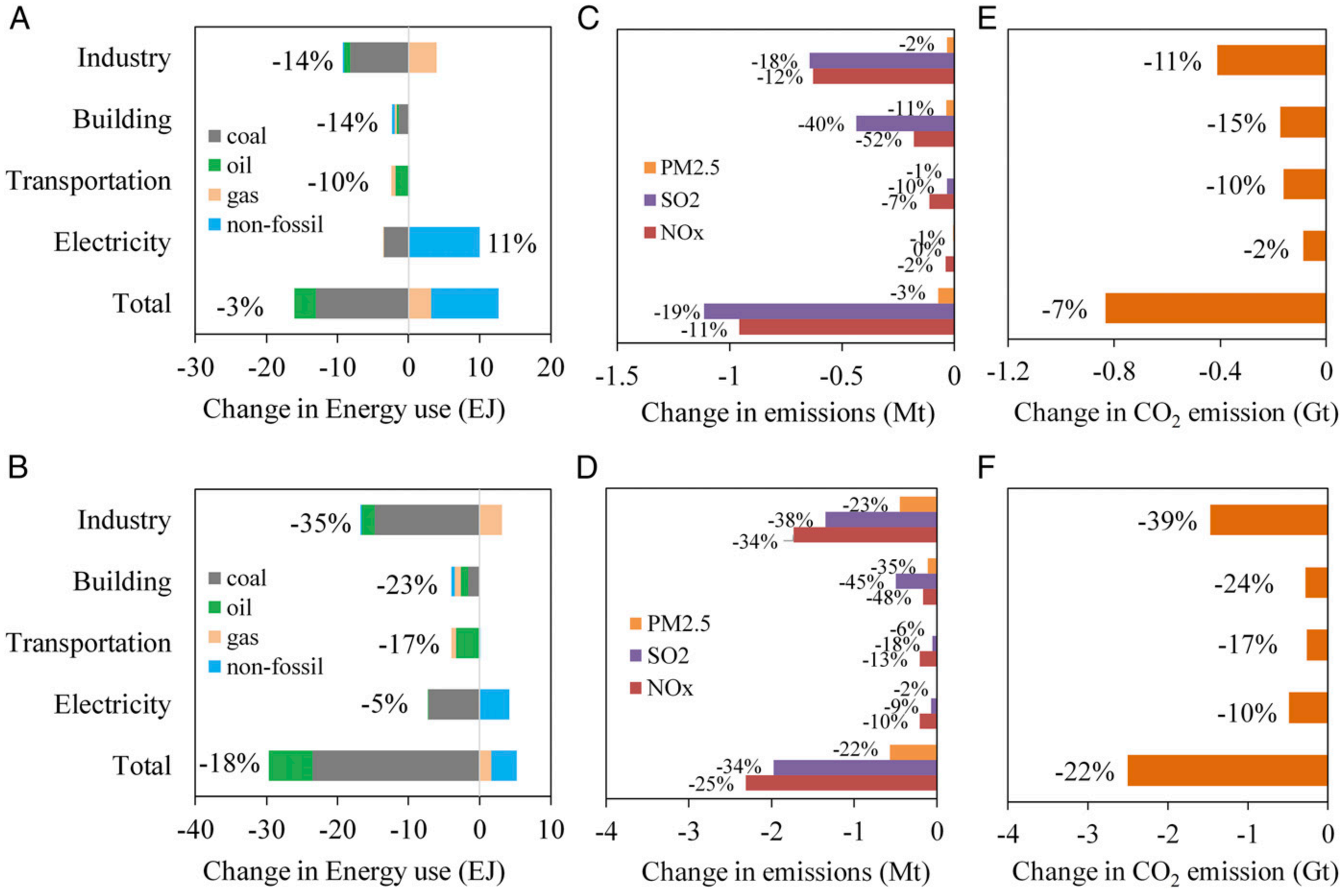

Fig. 4. Changes in energy use and emissions in CBE scenario compared to the NDC scenario in 2035 under the maximum feasible end-of-pipe controls (MFR). Changes in energy use (*A* and *B*); changes in $PM_{2.5}$, SO_2, and NOx emissions (*C* and *D*); and changes in CO_2 emissions (*E* and *F*); all with percentage change at the left/right of each bar.

on-road transport to railroad and water transport, and promoting clean and new-energy vehicles (*SI Appendix*, *Text S4*).

The additional energy conservation policies in the CBE scenario can reduce total energy use by 18% from the NDC scenario (Fig. 4*B*). Such reduction in energy use will come mainly from the industrial sector, by limiting total industrial production and promoting energy intensity improvements to the level of the best available technologies with high efficiency (*SI Appendix*, *Text S2*). The reduced energy use in the electric sector is associated with the decreased electricity demand and improved efficiency of electricity generation (*SI Appendix*, *Text S5*). Considerable reduction of energy use in the building and transportation sectors can also be realized by improving the fuel economy, promoting clean and new-energy vehicle technologies, and eliminating outdated vehicles (*SI Appendix*, *Text S4*), as well as by improving architectural design standards and promoting advanced service technologies with high energy efficiency (*SI Appendix*, *Text S3*). The aggregated effectiveness of low-carbon energy policies (including both energy structure adjustment and energy conservation) in the CBE scenario can result in considerable reductions in the emissions of $PM_{2.5}$ (22%), SO_2 (34%), NOx (25%), BC (28%), and CO_2 (22%) beyond the NDC scenario in 2035 (Fig. 4 *D* and *F*). The effectiveness of energy policies increases from 2020 to 2035, exhibiting an opposite trend to that of end-of-pipe controls, implying its increasing importance in achieving the long-term air quality target (*SI Appendix*, *Text S10*).

Table 2 presents a matrix of future changes in air pollutant and CO_2 emissions under different combinations of energy scenarios and end-of-pipe control levels in 2035 compared with 2015. The low-carbon energy policies in CBE−MFR can further reduce the emissions of SO_2, NOx, NMVOCs, $PM_{2.5}$, and BC to 22%, 30%, 46%, 25%, and 10% relative to the 2015 levels (set as 1). Such emission reductions allow all of the cities in China to achieve the attainment target for $PM_{2.5}$ in 2035 (Fig. 3 *C* and *D*,; the only five nonattainment cities under CBE−MFR are all located in western China, dominantly because of the impacts of windblown dust). The average $PM_{2.5}$ concentration in China's 338 cities is reduced from 49.6 $\mu g{\cdot}m^{-3}$ in 2015, to 21.7 $\mu g{\cdot}m^{-3}$ in 2035 NDC−MFR, and 18.4 $\mu g{\cdot}m^{-3}$ in 2035 CBE−MFR. In addition, the substantial emission reduction in CBE−MFR can also allow all China's 338 cities at the prefecture or higher level to achieve the ozone (O_3) attainment target (i.e., the 90th percentile of daily 8-h maximum concentrations $<160\ \mu g{\cdot}m^{-3}$, about 75 parts per billion [ppb]) in 2035 (*SI Appendix*, Fig. S33). O_3 has recently become another concern for air pollution in most Chinese cities (27).

The implementation of stronger low-carbon energy policies in the CBE scenario, which can achieve attainment of the $PM_{2.5}$ standards, results in a substantial additional reduction in CO_2 emissions (about 2.51 Gt or by 22%) relative to the NDC scenario. In addition, the CBE scenario will lead to additional reduction in methane (CH_4) emissions, equivalent to 0.17 Gt-equivalent CO_2 (CO_2-eq), primarily from avoiding methane leakage from coal mining, which outweighs the increased fugitive

Table 2. Total national emissions of air pollutants and CO_2 in 2035 relative to 2015 (= 1) in China

Year	Scenario	SO_2	NOx	NMVOCs	NH3	$PM_{2.5}$	BC	CO_2	CO_2e[*]
2015		1	1	1	1	1	1	1	1
	NDC−CLE	0.38	0.49	0.67	0.84	0.39	0.17	1.102	1.097
2035	NDC−MFR	0.32	0.40	0.49	0.76	0.32	0.14	1.105	1.099
	CBE−MFR	0.22	0.30	0.46	0.76	0.25	0.10	0.860	0.862
	ΔEOP[†]	−0.06	−0.09	−0.18	−0.08	−0.07	−0.03	+0.003[‡]	+0.002[§]
	ΔENE[¶] (2)	−0.10	−0.10	−0.03	—	−0.07	−0.04	−0.245	−0.237

[*] CO_2e (CO_2 equivalent) includes CO_2, CH_4, and BC, weighted by global warming potential over a 20-y time horizon from the Intergovernmental Panel on Climate Change Fifth Assessment Report (54).

[†] ΔEOP represents the control effectiveness of further end-of-pipe applications in reducing emissions, by taking the differences between NDC−CLE and NDC−MFR.

[‡] The pathway involving strengthening of the end-of-pipe control applications will slightly increase the energy consumption and consequently lead to an increase in CO_2 emissions (*SI Appendix*, *Text S11*).

[§] The end-of-pipe control measures (e.g., manure management) for reducing NH_3 can slightly reduce CH_4 emissions (*SI Appendix*, *Text S9*), but still less than the increased CO_2, due to the extra energy consumption of end-of-pipe control applications.

[¶] ΔENE represents the control effectiveness of low-carbon energy policies in reducing emissions, by taking the differences between NDC−MFR and CBE−MFR.

CH_4 from natural gas systems (*SI Appendix*, Text S12). In total, the CBE scenario would bring an additional reduction by 2.68 Gt CO_2-eq in emissions of greenhouse gases from the NDC scenario in 2035. Compared to NDC, the stronger low-carbon energy policies in CBE required by the air quality targets in China encourage more usage of renewable energy and natural gas in the short term. Future decreases in the usage of natural gas and the promotion of renewable energy, particularly in the industrial sector, can be further considered in evaluating longer-term impacts in addition to those reported here (28).

Stronger Low-Carbon Energy Policies Bring Greater Health Benefits than the Associated Costs. At the national level, ∼158,000 premature deaths can be avoided annually (Fig. 5 *A* and *B*) in China, owing to the decrease of $PM_{2.5}$ concentrations from NDC−MFR to CBE−MFR, primarily in three densely populated provinces (Henan, Shandong, and Hebei). Additionally, the decline of O_3 concentration will avoid about 12,000 premature deaths annually. This implies the important cobenefits of low-carbon energy policies in improving air quality and protecting human health in the future. About 77% of total $PM_{2.5}$-related health benefits come from the reduction of household $PM_{2.5}$ exposure (*SI Appendix*, Fig. S34), indicating the great benefit of low-carbon energy policies (e.g., cleaner energy for cooking and heating) in reducing the indoor exposure in addition to the ambient $PM_{2.5}$ exposure (21, 29). Implementation of low-carbon energy policies also allows other provinces to simultaneously avoid air pollution-related premature deaths and reduce CO_2 (Fig. 5*C*). In total, the implementation of low-carbon energy policies (CBE) could lead to a human health benefit equivalent to ∼890 billion Chinese Yuan (CNY), assuming a value of statistical life (VSL) of 5.24 million CNY. Such monetized benefit exceeds by 8 times the costs associated with the policy implementation (Fig. 5*D*), not considering additional climate benefits. The air pollution-related premature death rate is still significant even after achieving the current air quality standard in China (35 $\mu g/m^3$ for $PM_{2.5}$ annual average). Under the CBE−MFR in 2035, the premature mortalities attributed to $PM_{2.5}$ and O_3 are estimated to be 584,000 and 74,000, respectively. To further improve the air quality to the WHO guidance (10 $\mu g/m^3$ for $PM_{2.5}$ annual average), more strengthened energy policies by promoting renewable energy will be required.

Developing countries such as China and India face challenges from both air pollution and climate change. Low-carbon energy policies will play an important role in addressing both challenges. The current state of the Paris Treaty is subject to uncertainty due to weak international cooperation and US withdrawal. However, an air quality target such as the "Beautiful China" strategy is a national goal that is very likely to be met. Our results demonstrate that, along with the increasing requirements on air quality in China, low-carbon energy policies are necessary to further reduce air pollutant emissions, considering the narrowing reduction potential from end-of-pipe technology applications. The national cost−benefit analysis suggests that such low-carbon energy policies can have great potential in reducing $PM_{2.5}$-related health benefits, particularly from the reduction of household $PM_{2.5}$ exposure with relatively low cost. This study reveals that the implementation of air quality attainment plans would result in greater CO_2 reductions than China's NDC scenario. The results also provide an important reference for other emerging countries such as India to deal with their dual challenges of climate mitigation and air quality improvement.

Methods

Emission Projection. We used the GCAM-China model to project the future CO_2 and air pollutant emissions under different energy scenarios coupled with end-of-pipe control levels. GCAM-China is a version of GCAM with detailed representation of China including 31 provinces, allowing estimation of economic, energy, and emissions impacts at the provincial resolution (30). The GCAM model (20) has been widely applied for projections of future energy and climate (2, 31–34). The emission factors used for estimating CO_2 emissions are obtained from the Carbon Dioxide Information Analysis Center. The base year of the GCAM-China model is 2010. We calibrated the GCAM-China estimated energy consumption for the years of 2010 and 2015. We ran the model through 2035, using 5-y time steps.

The original air pollutant emissions representations in GCAM-China are relatively coarse, with limited differentiation at the technological level. This study coupled GCAM-China with emission estimations based on a detailed bottom-up emission inventory developed at Tsinghua University (ABaCAS-EI) (21), with detailed representations of the air pollutant-related sectors and technologies, localized emission factors, and end-of-pipe control technologies. We mapped the sectors and technologies in GCAM-China with those in ABaCAS-EI to estimate the air pollutant emissions for SO_2, NOx, NMVOC, NH_3, $PM_{2.5}$ and BC.

Air Quality Assessment. This study used the CMAQ model (version 5.2) developed by US Environmental Protection Agency (EPA) (22) to simulate the hourly concentrations of $PM_{2.5}$ and O_3 in 2015 and 2035 for the three scenarios defined in Table 1. The CMAQ simulations were conducted over China domain with 27 × 27 km grid cells, using a 2015 meteorology field driven by the Weather Research and Forecasting Model (version 3.7). The model's performance in reproducing the $PM_{2.5}$ and O_3 concentrations has been evaluated in Ding et al. (5, 35) in comparison with ground-observed concentrations. Both the mean fractional biases (MFB; −14.2% for $PM_{2.5}$ and −11.1% for O_3) and the mean fractional errors (MFE, 21.6% for $PM_{2.5}$ and 17.0% for O_3) meet the US EPA recommended benchmark (MFB within ±60% and MFE within 75%) (36).

The data were analyzed based on the 90th percentile of daily 8-h maxima for O_3 and annual mean of 24-h average for $PM_{2.5}$, to be consistent with the index used in air quality standard in China. Following the method reported in earlier studies (5, 37), the simulated baseline concentrations in 2015 were

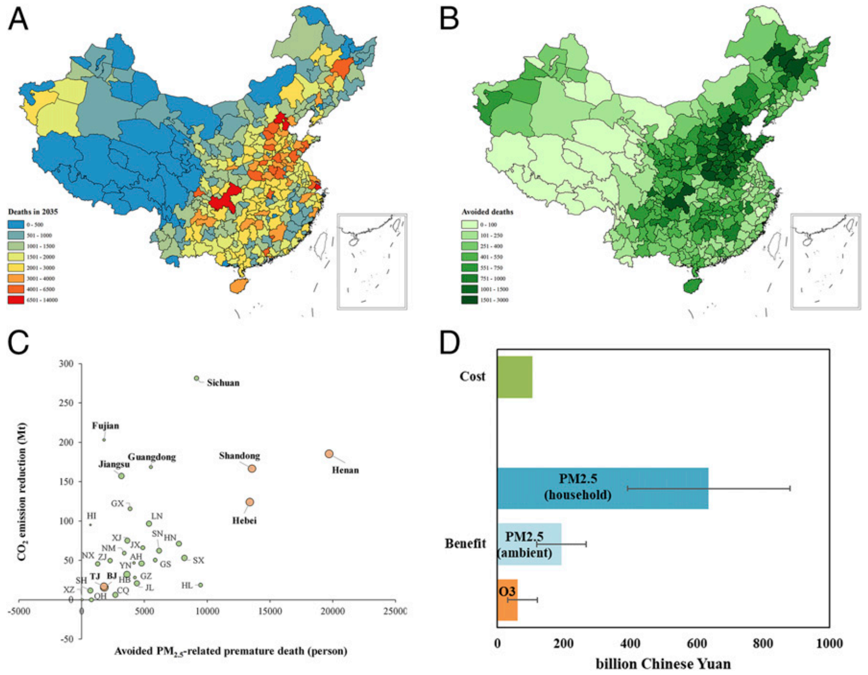

Fig. 5. Benefits of low-carbon energy policies in reducing air pollution-related premature death and CO_2 emissions in 2035. (*A* and *B*) $PM_{2.5}$-related premature death in 2035 under CBE−MFR (*A*) and its change due to the low-carbon energy policies (NDC−MFR minus CBE−MFR) (*B*); (*C*) comparison of the avoided $PM_{2.5}$-related premature death and CO_2 reduction in 31 provinces; the top five provinces with highest $PM_{2.5}$ concentrations in 2015 are shown in orange (NDC−MFR minus CBE−MFR); (*D*) the monetized health benefits and associated cost of low-carbon energy policies (NDC−MFR minus CBE−MFR). The error bar in air quality represents the 95% CI. The associated costs represent the social costs of implementing low-carbon energy policies of CBE relative to NDC. On a per ton of CO_2 basis, the associated cost is estimated at 15 US dollars (USD), which is comparable but slightly lower than that reported in other studies (52, 53), due to different low-carbon energy policies applied in this study. The transition rate of USD to CNY is based on an exchange rate of 1:7.

fused with the observation data of each site obtained from the China National Environmental Monitoring Center (106.37.208.233:20035/) using the gradient-adjusted Voronoi neighbor averaging method. The change in $PM_{2.5}$ and O_3 concentrations in future years (e.g., 2035) was calculated based on the change ratios resulting from simulation and the data-fused baseline concentrations.

Health Effect Estimate and Valuation. In this study, we evaluated the health effects due to long-term O_3 exposure as well as both ambient and household $PM_{2.5}$ exposure. Derived by epidemiological studies, the excess mortality related to air pollution can be calculated by using the relative risk model method (38–42), as follows:

$$\Delta Y = Y_0 \times AF \times Pop, \qquad [1]$$

where ΔY is an attributable case of health endpoint related to $PM_{2.5}$ or O_3 exposure; Y_0 is the baseline incidence rate; *Pop* is the population; and $AF = 1 - 1/RR$ is the attributable fraction, where *RR* is the relative risk for specific health endpoint.

For estimating health effects due to $PM_{2.5}$ exposure, we used an IER model that covers the global range of exposure (43) and updated it with recent epidemiological studies and statistical techniques (3). The IER model has been adopted by the 2015 Global Burden of Disease (GBD) study to estimate global $PM_{2.5}$-related mortality. The RR in the IER model was calculated through

$$RR(z) = 1 + \alpha \times \left(1 - e^{\beta](z - zcf)^{\gamma}}\right), \qquad [2]$$

where z is the $PM_{2.5}$ concentration; *zcf* is the theoretical minimum risk exposure level; and α, β, and γ are the parameters that refer to the US EPA's Benefits Mapping and Analysis Program - Community Edition (BenMAP-CE) v1.4 (44). The *zcf* is in a uniform distribution with lower/upper bounds of 2.4 and 5.9 $\mu g/m^3$. With the IER model, we calculate and add up the mortality for five causes of death: ischemic heart disease, cardiovascular disease, lung cancer, chronic obstructive pulmonary disease, and lower respiratory infections.

The $PM_{2.5}$ exposure is estimated in the following ways. The integrated population-weighted exposure (IPWE) (45) was used to evaluate the total exposure to $PM_{2.5}$. IPWE is the sum of population-weighted exposure (PWE) to both AAP (ambient air pollution) and HAP (household air pollution). PWE_{AAP} and PWE_{HAP} are calculated as follows:

$$PWE_{AAP} = \frac{1}{P}\sum_{i}(P_i \times C_i) \qquad [3]$$

$$PWE_{HAP} = \frac{1}{P}\sum_{i,j,k}(P_{i,j,k} \times HAP_{j,k}) \qquad [4]$$

where P_i is population in the grid i, j refers to the urban or rural area, and k is the household fuel category (coal or biomass). We combined the LandScan dataset and county-level urban/rural populations from Chinese statistics (46) to get the distribution of population of each category. We use the same $HAP_{j,k}$ values for year 2015 and 2035 as our previous studies (21). The *HAP* of coal and biomass are 38 and 223 $\mu g/m^3$ for urban population, while they are 117 and 250 $\mu g/m^3$ for rural population.

For estimating health effects due to O_3 exposure, we refer to the research of Turner et al. (47). It suggested that significant positive associations remained between O_3 and all-cause mortality (hazard ratio per 10 ppb, 1.02; 95% CI, 1.01 to 1.04). We calculated daily 8-h maximum O_3 and appropriately averaged it to match the metric used in the study. All-cause mortality exposure to O_3 was estimated. The threshold is assumed to be 35 ppb.

The annual Chinese national cause-specified mortality rates were obtained from the GBD results tool (ghdx.healthdata.org/gbd-results-tool). The future baseline mortality rates in 2035 were based on the projections from the International Futures model version 7.45 base scenario (https://pardee.du.edu/access-ifs). The city-level population was obtained from the 1 km × 1 km LandScan population dataset (48) adjusted by the population from the China statistical yearbook (49). The prediction of future total population in 2035 is discussed in *SI Appendix*, *Text S1*, and the population structure (the sex and age distribution) was projected to 2035 based on the cohort component method applying the PADIS-INT (International edition of Population Administration and Decision Information System) software developed by China Population and Development Research Center (www.padis-int.org/). We apply the monetary value of a VSL to quantify the economic benefits related to air quality improvement (50). The VSL of 5.24 (95%

CI, 3.51 to 6.98) million CNY estimated through a choice experiment survey with willingness-to-pay method (51) is used to monetize the health benefits.

Data Availability. All study data are included in the article and *SI Appendix*.

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