



Co-control of carbon dioxide and air pollutant emissions in China from a cost-effective perspective

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Abstract

With increases in the economy and standards of living, energy consumption has grown significantly in China, which has resulted in serious local air pollution and greenhouse gas emissions. Because both carbon dioxide (CO₂) and air pollutant emissions mainly stem from fossil energy use, a co-control strategy is simulated and compared with single control in China, using an integrated assessment model (Global Change Assessment Model-Tsinghua University (GCAM-TU)) in this paper. We find that end-of-pipe (EOP) control measures play an important role in reducing air pollution in the near future, but in the long run, optimizing the energy system is an effective way to control both emissions. Reducing air pollutant might take a “free-ride” of decarbonizing the energy system. Compared with a single control of air pollutants, a co-control strategy is likely to reduce the requirement of EOP control measures. The result guides the Chinese government to consider a systemic and scientific plan for decarbonizing the energy system and co-controlling CO₂ and air pollutant, in order to avoid duplicate investments in infrastructure and lockup effect. The solution could be extended to many other developing countries, such as India and Africa, which is helpful to realize the goals of United Nations (UN) Sustainable Development Agenda.

Keywords Co-control · CO₂ emissions · Air pollution · China · Integrated assessment model

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1 Introduction

The dramatic economic growth and living standard improvements in the past two decades have led to increased energy consumption in China, especially the use of coal. This brings serious local and perhaps international environmental problems, such as air pollution, water pollution, land pollution and global climate change. Air pollution is currently one of the most important political and social issues in China. According to the Ministry of Environmental Protection, only 10.8% of the major Chinese cities met the national clean air standard in 2014 (Ministry of Environmental Protection 2015). Nearly 1 million premature deaths and a 25-month life expectancy reduction are attributed to outdoor pollution (IEA (International Energy Agency) 2016). At the same time, climate change is the most concerning international environmental issue. The Paris Agreement set a goal to limit the global average temperature rise to well below 2 °C relative to pre-industrial levels at the end of this century and even put forward the more ambitious 1.5 °C target (United Nations Framework Convention on Climate Change (UNFCCC) 2015). As temperature change has a nearly linear relationship with cumulative carbon dioxide (CO₂) emissions (Allen et al. 2009; Matthews et al. 2009), global carbon emissions should be strictly controlled. As the largest emitter currently in the world, China has a significant influence on the realization of the 2 °C and 1.5 °C goals.

To limit its CO₂ emissions, China has made a series of announcements both at home and abroad. For example, in 2009, China committed to lowering its CO₂ intensity by 40–45% relative to its 2005 level by 2020 in the Cancun Pledge; in 2015, China submitted its nationally determined contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC). The NDC includes reducing the carbon intensity by 60–65% from the 2005 level by 2030, increasing the share of non-fossil fuels in primary energy consumption to approximately 20% by 2030 and peaking CO₂ emissions by around 2030 with the potential to peak earlier. In terms of air pollution, the Chinese government has long recognized the gravity of this issue (dating back to the 1970s) and is now taking serious efforts to address it. In particular, the Action Plan for Air Pollution Prevention and Control was announced in 2013, which provides a provincial-level roadmap to improve air quality over the period of 2013–2017. It includes detailed measures across sectors and fuels, including adjusting the energy structure, promoting clean energy supply, optimizing economic structures, accelerating technology innovation, enhancing emissions standards for coal power plants, phasing out heavily polluting vehicles and introducing cleaner gasoline and diesel fuels (The State Council 2013). According to the interim report on the implementation of the Action Plan for Air Pollution Prevention and Control (MEP 2016), the direction and implemented measures for air pollution control were effective, and the air quality was improved significantly.

The existing policies to control air pollutant emissions are basically in line with policies for limiting CO₂ emissions in terms of energy conservation and optimizing the energy mix, because a large part of the air pollutants and greenhouse gases stem from fossil fuel use. To separately control air pollution, for example, in the electricity sector, coal-fired power plants may remain the predominant source of electricity generation because implementing end-of-pipe (EOP) measures in coal-based power plants is cost-effective and efficient. However, this may conflict with the carbon mitigation goal which requires reducing coal consumption dramatically. In this regard, an integrated modelling of a co-control of CO₂ and air pollutant emissions in China might be useful and provide dual dividends of maximizing synergy and avoiding conflicts. A co-control analysis will contribute to determining the mitigation potential and the priority inside and among different sectors by identifying key mitigation

measures for each sector at different stages to avoid repeated construction and unnecessary investment.

Although co-controlling China's air pollutant and CO₂ emissions is valuable, comparatively few studies have focused on it. Previous studies paid more attention to co-benefits arising from combinations of climate policies and air pollution policies (Jiang et al. 2013; Ma et al. 2015). For instance, Nam et al. (2014) estimated the potential synergy between pollution and climate control in the United States (USA) and China and found that ancillary carbon reductions resulting from sulphur dioxide (SO₂) and nitrogen oxide (NO_x) control tended to rise with the increased stringency of control targets in both countries; Li et al. (2016) studied the aggregate effect of air pollution control on CO₂ mitigation in China based on a theoretical framework of co-benefits and empirical evidence and found that CO₂ was a net substitute to SO₂; Radu et al. (2016) explored the effect of different climate and air pollution control policies on greenhouse gas and air pollutant emissions and found that climate policy had important co-benefits; Rao et al. (2013) confirmed that cost-related co-benefits arose from combining air pollution, climate change and energy access policies. Although some studies explored how to co-control air pollutant and CO₂ emissions, they concentrated on sector performances. For instance, Mao et al. (2013) used an integrated multi-pollutant co-control strategy to examine the cost-effectiveness of emission reduction measures in the Chinese iron and steel industry; Mao et al. (2014) used a similar framework to analyse the opportunity of co-controlling local air pollutants and CO₂ in the Chinese coal-fired power industry; Jia et al. (2015) applied three assessment methods, including co-control effect coordination system, pollutant reduction cross-elasticity and unit pollutant abatement cost, to assess the co-control effects of optional reduction measures on SO₂, NO_x and CO₂ emissions in the Chinese chlor-alkali/polyvinyl chloride sector, while simultaneous emission control for different sectors is important considering its internal linkages from the perspective of input-output analysis (Zhang et al., 2018; Zhang and Zhang, 2018). Currently, there are comparatively little research on how to realize China's current carbon mitigation goal (NDC) and air pollutant emissions control targets at the same time by taking multiple sectors and aspects into a consistent framework.

To bridge the literature gap, an integrated assessment model, Global Change Assessment Model-Tsinghua University (GCAM-TU) (an extended version of the Global Change Assessment Model), is used to analyse the co-control of CO₂ and air pollutant emissions in China and identify portfolios of associated measures. By doing so, we basically try to address three questions: (i) How does China realize the designed air pollutant control and its NDC (CO₂ emission control goal) targets simultaneously? (ii) What incremental efforts are needed for China to achieve its NDC target when the designed air pollutant control target is met? Or what kind of efforts is required to control air pollutant emissions in China to realize its NDC? Through solving these questions, our study firstly shows China's sectoral efforts to realize its NDC and air pollution control targets, and more importantly, the efforts and costs to gap the bridge between controlling local air pollution and solving global environmental issue.

2 Methods

2.1 Model description

In this study, GCAM-TU, an extended version of the Global Change Assessment Model (GCAM version 4.0), is applied to explore the measures and options for China to realize its

carbon mitigation and air pollutant control targets. The basic structure of GCAM-TU is shown in Fig. 1. Compared with the standard version of GCAM 4.0, GCAM-TU first modifies the energy system module with a more detailed description of the end-use sectors to reflect the urbanization and industrialisation process in China. More importantly, GCAM-TU adds an air pollutant emission control module that includes various EOP control technologies to make the model capable of choosing effective and efficient ways to control air pollution emissions or simulate integrated control scenarios. The other aspects of GCAM-TU are in line with the standard GCAM.

GCAM, developed by the Joint Global Change Research Institute, is a global integrated assessment model that links economic, energy, land use and climate systems. It is widely used to forecast and evaluate the effect of technological innovation, institution transformation, energy policy and climate policy on the economy, energy system, agriculture and land use and climate in international model exercises (Clarke et al. 2009, 2012; Chen et al. 2016). GCAM 4.0 is a dynamic recursive global market partial equilibrium model, calculating output in five-year time steps from 2010 to 2100. There are 32 energy-economic regions in GCAM, linking each other through international trade in energy commodities, agricultural and forest products and other goods as well as emission allowances.

The energy system module is the core of GCAM, which includes the whole process of energy utilization (resource production, energy transformation, energy distribution and final usage) with chosen technologies. A sequence of technology choices in both the commercialization and demonstration stages is covered in this model, such as fossil fuel with carbon capture and storage (CCS), biomass with CCS, hydrogen production, wind power, photovoltaic power generation, solar thermal power generation, coal to liquids, coal to gas, electrical vehicle and fuel-cell vehicle. The market shares of different technologies are determined by a logistic choice methodology based on a probabilistic model of the relative prices of the competing technologies. More details of the standard model and its energy sector module are given in the GCAM wiki (2016) and the work of Clarke et al. (2008).

To better represent the particular circumstances that surround China and its options for mitigation, three end-use sectors, namely industry, building (residential and commercial) and transportation, were further disaggregated in GCAM-TU (Wang et al., 2016, 2017, 2018). China's industry sector was further divided into eleven subsectors from one aggregated sector in the standard version, which includes iron and steel; chemicals; aluminium and non-ferrous metals; other non-metallic minerals; pulp, paper and wood; food processing; other manufacturing; mining; agriculture; construction and cement. In order to better simulate

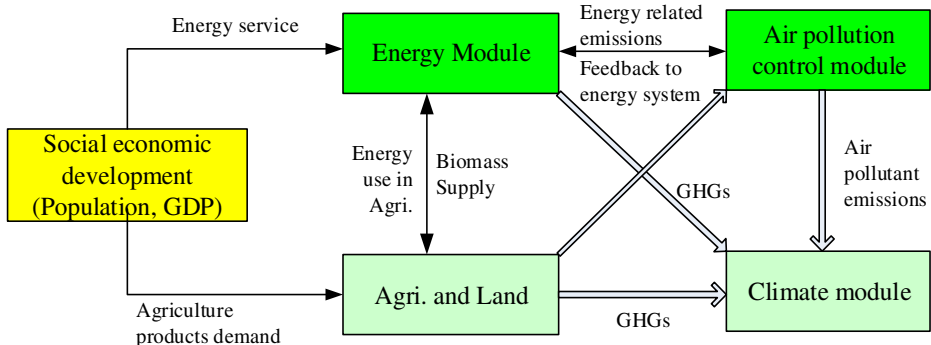


Fig. 1 Basic structure of GCAM-TU

industry energy structure change, six intermediate industrial energy services, namely boilers, process heat, machine drive, electrochemical processes, other energy services and feedstock, are specified for manufacturing sectors. Each energy service is provided by multiple competing technologies, and fuel demands for these technologies are determined from technology choices (Wang et al. 2016). In light of the different climate conditions and living habits among distinct climate zones, the Chinese building sector was disaggregated into four distinct climate zones (severe cold (SC), cold (C), hot summer/cold winter (HSCW) and hot summer/warm winter (HSWW)). Moreover, because of the differences in income levels and standards of living between urban and rural communities, additional types of energy services are considered for urban, rural and commercial demands, such as space heating, space cooling, lighting, water heating and cooking and electric equipment. These services are served by different technologies with specified fuels. For example, lighting is highly related with electricity, solar heaters provide energy services for water heating and geothermal heat pumps are used for space heating services. The transportation sector in GCAM-TU is comprised of five passenger sectors (intercity, urban, rural and business services and international air services) and four freight subsectors (general and rural services and international air and ship services). Each passenger and freight subsector was further divided into specific modes composed of various technologies and fuels. For instance, car (different types), bus (both heavy- and light-duty), rail, high speed rail and airplane would serve intercity passengers. The multiple modes are assumed to be powered by different technologies and fuels.

Because of the lack of specific end-of-pipe control technologies in the standard version of GCAM, GCAM-TU also adds an air pollutant emissions control module, which includes hundreds of EOP control technologies for the electricity, district heat, industry, building and transportation sectors. Those key parameters for EOP technologies, including China-specific technology costs, removal efficiencies and emissions factors (Appendix Tables 2 and 3), are mainly derived from the Greenhouse Gas and Air Pollution Interactions and Synergies China (GAINS-China) model (IIASA 2014). EOP technologies are closely linked to their related energy technologies, and each energy technology may be accompanied by several control technologies, which assures the consistency between energy activities and emission levels. The involved EOP measures are basically in line with those adopted by Peng et al. (2017) when modelling the emission reductions under sectorial scenarios, and their removal efficiencies are adjusted according to the real condition of China's current technology improvement level. Take the power sector as an example, information concerning removal efficiencies of mainstream treatment measures widely used in coal-fired power plant, such as wet flue gas desulphurisation (FGD) for SO₂ removal and selective catalytic reduction (SCR) for NO_x removal, is collected from various previous experimental research papers which have been listed following Appendix Table 2. The values of these key indicators serve as the basis for the simulations and agree well with those used by Wu et al. (2018). It is noted that NO_x mitigation in the transportation sector largely depends on improvements in vehicle emission standards. Because different emission standards for the existing vehicle stock coexist, we assume vehicle emissions will decrease by 25% every 5 years from 2010. Therefore, the emission levels are calculated as in Eq. (1).

$$Em_p = \sum_j \sum_m Act_j \times Ef_{j,p} \times af_{j,m,p} \times (1 - \eta_{j,m,p}) \quad (1)$$

where Em_p denotes emissions of pollutant p (for SO₂, NO_x, NH₃, PM_{2.5}, CO₂, CH₄, N₂O, etc.), Act_j denotes the activity level for activity j , $Ef_{j,p}$ denotes the emission factor of pollutant p for

activity j without any control measures, $af_{j,m,p}$ denotes the penetration rate of control measure m in activity j for pollutant p and $\eta_{j,m,p}$ represents the emission removal rate of control measure m equipped to activity j for pollutant p .

2.2 Scenario design

To analyse how to co-control air pollutant and carbon emissions and the difference between co-control and single-target control, four scenarios were designed: a reference scenario (Ref), an air pollutant emission control scenario (Poll), a CO₂ emission control scenario (NDC) and a hybrid scenario combining air pollutant control and CO₂ emission control targets (NDC_Poll). These four scenarios, described in Table 1, can be divided into two main dimensions: one describing the carbon emission control target (Ref, NDC or NDC_Poll) and the other representing the air pollution control target (Ref, Poll or NDC_Poll). It is noted that this paper mainly focuses on energy-related emissions. In the Ref scenario, there are no additional policies after 2010, and emission factors are frozen after 2010. The Ref scenario is meant to provide a benchmark for showing the impact of CO₂ and air pollutant control policies. In this paper, only SO₂ and NO_x emissions are taken into account to represent air pollutants, and the Poll scenario is designed so that SO₂ and NO_x emissions decline by 8% and 10%, respectively, every 5 years through 2030. This designed emission pathway follows the SO₂ and NO_x mitigation goals set in China's 12th Five-Year Plan. The NDC scenario is designed to simulate China's commitment to lower its CO₂ intensity, specifically that the carbon intensity will decrease by 45% and 65% from its 2005 level by 2020 and 2030, respectively. Here, we chose the upper bounds of China's carbon intensity reduction targets. It is usually difficult to make precise predictions about China's future economic growth, which is subject to complicated factors and might exert substantial impacts on energy consumption and carbon emissions. In this paper, the annual gross domestic product (GDP) growth rates in China for the periods of 2011–2020 and 2021–2030 are set as 7.2% and 6%, respectively. These values are determined based on the predictions made by several research institutions (Appendix Table 4). Relatively higher values are adopted here for the two periods (2010–2020 and 2021–2030) to represent the assumed faster transformation towards higher value-added manufacturing industry structure on the way to achieve NDC. With this assumption, emissions in 2020 and 2030 are estimated to be 10 and 11.3 gigatonne CO₂ (Gt CO₂), respectively, under the constraint of the ambitious carbon intensity mitigation targets of China. The estimate is in the range of previous studies which consider China's NDC emissions by 2030 (Grubb et al. 2015; Meinshausen et al. 2015; Pan et al. 2017). It is noted this study mainly focuses one target of China's NDC pledge, the carbon intensity reduction, while the target of non-fossil energy share is not

Table 1 Scenario designs in this study

Scenario	Description
Ref	Reference scenario. No additional energy and air pollutant emission control policies are implemented.
Poll	Air pollution control scenario. SO ₂ and NO _x emissions decline by 8% and 10% every 5 years from 2010 to 2030, respectively.
NDC	CO ₂ emission control scenario. CO ₂ emissions in 2020 and 2030 are set as 10 and 11.3 Gt, respectively.
NDC_Poll	Combination of NDC and Poll scenarios

configured, but the simulation result (Duan et al. 2018a, b). In addition, the population in China is assumed to reach 1423 and 1445 million in 2020 and 2030, respectively, according to the Population Development Plan 2016–2030 released by the State Council (2017); the urbanization level is assumed to increase from 49.9% in 2010 to 62.5% in 2030. For the rest of the world, the default assumptions in the standard GCAM are kept.

In this paper, to realize the designed carbon emission control targets, a national emission cap for China is set, which is implemented through the implementation of a national carbon price. Similar to controlling CO₂ emissions, the designed air pollutant emissions targets are also given a national cap, and the emission price is endogenously determined until the predetermined target is met. EOP technologies or advanced energy technologies are applied when their marginal cost equals the emission price.

3 Results

3.1 CO₂ mitigation in different sectors

In Ref, CO₂ emission continues to increase from 8.18 Gt in 2010 to 13 Gt in 2030 and mainly in the electricity and industry sectors. The carbon intensity (CO₂ emission per GDP) in 2030 reaches 1.27 t/thousand dollar (2005\$), declining by 37% compared with that in 2005. It is obvious that the carbon intensity reduction in Ref cannot meet China's NDC. Therefore, further efforts are required to decarbonize the economy and society.

The NDC_Poll scenario realizes China's NDC target, and its industrial emission peaks in approximately 2015 (Fig. 2). Its carbon intensity in 2030 is 0.82 t/thousand dollar, decreasing by 65% compared with the 2005 level, which is close to global average level in 2010. In addition, China's per capita emission in 2030 would be approximately 7.5 t/person (t/person), which is near that of the European Union in 2010 but lower than that in Japan and South Korea. During 2011–2030, the cumulative emission in NDC_Poll is approximately 196 Gt, declining by 13.6% relative to the Ref scenario, and the industry, electricity, building and transportation sectors contribute 48.3%, 41%, 10% and 0.7% of the total energy-related CO₂ reduction, respectively. In general, emission mitigation in the transportation sector is smaller because the share of fuel cost in the total cost of transportation technology is relatively small. Thus, changes in transportation mode and reduced transportation services would be more helpful in reducing CO₂ emissions.

3.2 SO₂ and NO_x reduction in different sectors

In the Ref scenario, SO₂ and NO_x emissions continue to increase until 2030, reaching 33.1 and 30.8 million tonnes (Mt) in 2030, respectively, which represents an increase of 46.3% and 22.6% compared with their levels in 2010. SO₂ emissions in the industry and electricity sectors account for nearly 85% of the total emissions in 2010, and this ratio is generally maintained until 2030 under the Ref scenario. NO_x emissions in the electricity sector continue to increase, the industry sector emissions hold steady after 2020, the transportation sector emissions decrease substantially through 2030 due to improvements in emissions standards and the emissions from buildings change very little. It is noted that NO_x emission control mechanisms in the transportation sector are already taken into account in the Ref scenario. If no improvements in emission standards are made in the transport sector, NO_x emissions in the

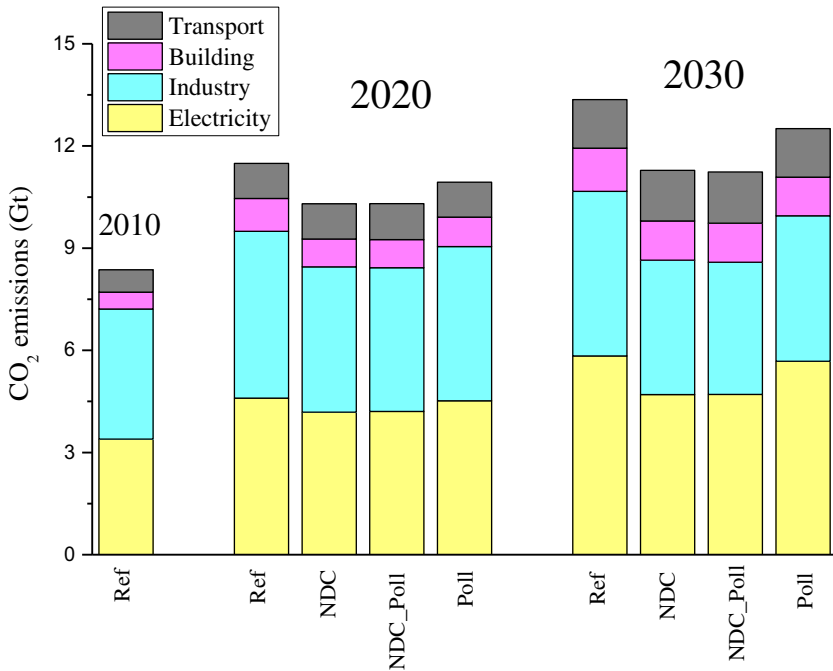


Fig. 2 CO₂ emissions in different sectors

transportation sector would grow, and its share of emissions would increase from 27% in 2010 to 35% in 2030.

In contrast, the SO₂ emissions of each sector decline after 2010 under the NDC_Poll scenario, and total emissions would reach as low as 17.1Mt (Fig. 3), which is 19% smaller than the modelled results of Dong et al. (2015) under the combined policy scenario (20.4 Mt). This gap might indicate that more efforts need to be paid in air pollution abatement than just maintaining current control policies so as to limit emissions to the national emission cap proposed in this work. SO₂ emissions from the electricity sector decrease to 5.6 Mt in 2030, which is only 63% of that in 2010. SO₂ emissions from the industry and building sectors in 2030 are only 74.9% and 78.9% of those in 2010, respectively. In general, the reduction in SO₂ emissions mainly depends on the electricity and industry sectors because of their higher emissions volumes, more diverse emission reduction measures and lower marginal reduction cost. Compared with Ref, SO₂ reductions in the electricity and industry sectors under NDC_Poll contribute nearly 49.5% and 38.4% of the reductions from all sectors during the period of 2011–2030.

Implementation of EOP control technologies is still the main mitigation measure in the electricity sector before 2020. In NDC_Poll, nearly all traditional coal-fired power plants, including existing and new power plants to be built in the future, will be equipped with wet flue gas desulphurisation or high-efficiency flue gas desulphurisation technologies by 2020. The penetration rate of wet flue gas desulphurisation approaches 85% because of its lower marginal reduction cost. Accompanied by energy efficiency improvements, SO₂ emissions per unit electricity output from traditional coal-fired power plants would decrease from 2.6 g/kWh in 2010 to 1.2 g/kWh in 2030. The Chinese government has required coal-fired power plants to equip EOP control technologies since the beginning of this century. The SO₂ removal rate at

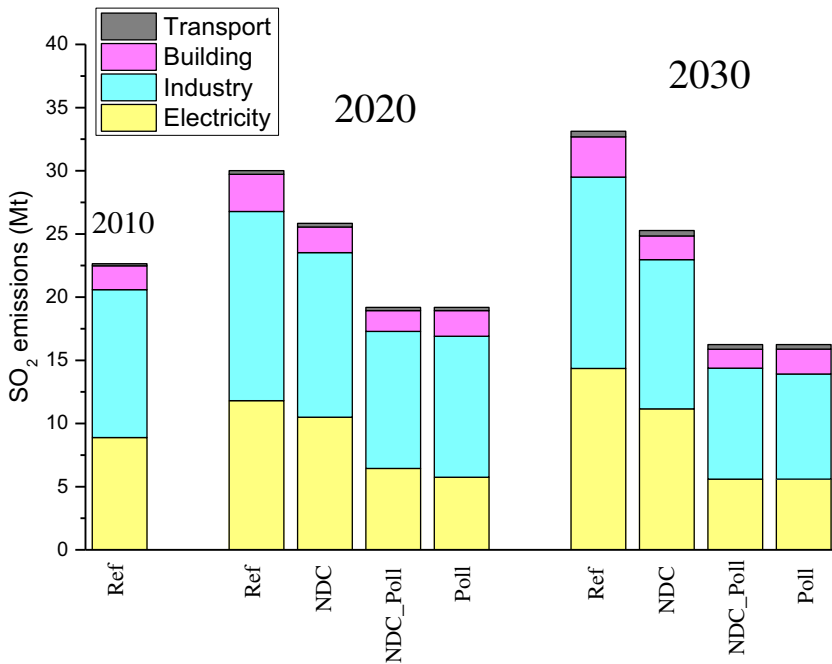


Fig. 3 SO₂ emissions in different sectors

coal-fired power plants in China increased from 69.5% in 2010 to 81% in 2014. In addition to the EOP technologies, the cleaner electricity generation technologies also contribute to the abatement of SO₂ emissions, and they will play an increasingly important role because there is little room left to implement these EOP technologies. Therefore, the SO₂ emissions per unit electricity output in 2020 and 2030 for the whole electricity sector will be 1.07 and 0.62 g/kWh, decreasing by 48.5% and 70% relative to that in 2010, respectively. Generally, SO₂ reduction in the electricity sector depends more on implementing EOP technologies at an earlier stage and later turns to harnessing a cleaner power supply. The contribution of implementing EOP measures in reducing SO₂ emissions in the electricity sector would decrease from 77.4% in 2020 to 61.1% in 2030. Generally, although the absolute SO₂ emission reductions from electricity sector in this work is smaller than the estimation made by Yang and Teng (2018), in which best available technologies rather than the predefined emission amount control would be implemented, the relative reduction contribution from EOP measures falls within the range (60–80%) simulated in their work. Implementing EOP technologies also plays an important role in reducing industrial SO₂ emissions, which are responsible for 38% of industrial emission reductions during the period of 2011–2030. Industrial energy savings and energy structure optimization comprise the remainder of the reduction. The SO₂ emissions per unit industrial energy consumption will decrease by 20% and 40% with respect to the 2010 level in 2020 and 2030 (0.53 and 0.4 kg per ton of standard coal (kg/tce) in 2020 and 2030), respectively. However, the decrease in SO₂ emissions by the building sector is largely due to the increase in the electrification level and share of natural gas, and so SO₂ emissions per unit energy consumption decrease by 34% and 58.3% compared with the 2010 level in 2020 and 2030, respectively.

NO_x emissions in different sectors also decline after 2010 under the NDC_Poll scenario (Fig. 4). In NDC_Poll, the cumulative NO_x emissions in the electricity sector reduce by 65.4% relative to the Ref scenario during the period of 2011 to 2030. Implementing EOP technologies (mainly the selective catalytic denitrification facility) in thermal power plants is the main measure to abate NO_x emissions in the electricity sector. The NO_x emissions per electricity output generated from coal-fired power plant will decrease from 3.1 g/kWh in 2010 to 1.2 g/kWh in 2030. To reduce NO_x emissions, the implementation of denitration equipment in coal-fired power plants was mandated by the Chinese government in the 12th Five-Year Plan. As a result, the removal rate in coal-fired power plants increased dramatically from 6.5 to 37.1% from 2011 to 2014. Generally, EOP measures are responsible for 66.2% of the NO_x emission reduction in the electricity sector during the period of 2011–2030.

Industrial NO_x emissions reduce by 24% and 35.2% relative to the 2010 level in 2020 and 2030, respectively, in the NDC_Poll scenario. This is partly because of the reduction in coal and oil consumption in the industry sector and partly due to the implementation of EOP measures. The EOP measures, such as combustion modification on industrial boilers and furnaces, combustion modification and selective catalytic reduction on industrial boilers and furnaces and combustion modification and selective non-catalytic reduction on industrial boilers and furnaces, are responsible for 60.2% and 50.4% of the industrial NO_x emission reduction in 2020 and 2030, respectively. Overall, the NO_x emissions per industrial energy consumption will decrease by 35.6% and 47.5% with respect to the 2010 level in 2020 and 2030, respectively.

For the building sector, the NO_x emissions per energy use decline by 34.6% and 58.3% in 2020 and 2030 relative to its 2010 level, respectively, through transforming energy consumption patterns and improving the electrification level. Because of the improvement in vehicle

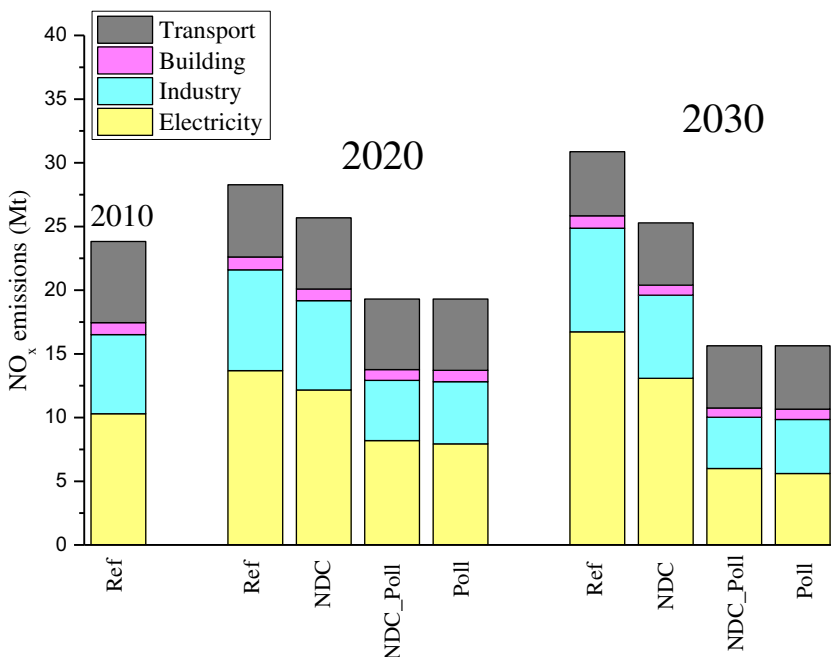


Fig. 4 NO_x emissions in different sectors

emission standards and change in travel modes and tools, the NO_x emissions in the transport sector also decrease significantly after 2010. The NO_x emissions per energy consumption in the transport sector decrease by 45.5% and 67.2% compared with the 2010 level in 2020 and 2030, respectively.

3.3 Impacts on energy system

In general, air pollutant emission control mainly depends on implementing EOP measures in the near term because of the large stock of fossil fuel-based facilities. However, with the penetration rate of EOP technologies approaching saturation, additional and stronger reductions will rely on the transformation of the energy system or a revolution in energy technology. Limiting CO_2 emissions will largely depend on the decarbonization in the energy system, including reducing energy service demands, improving energy efficiency and increasing the share of non-fossil fuels. Therefore, the energy system requires a profound change in order to limit CO_2 and air pollutant emissions.

The final energy consumption in the NDC_Poll scenario increases steadily before 2030, but at a lower annual growth rate (2.2%) compared with that (4.5%) during the period of 1991–2010. The NDC_Poll scenario reduces the final energy consumption to some extent relative to the Ref scenario, with a cumulative reduction of 3.41 gigatonne of standard coal (Gtce) during the period of 2010–2030 (Fig. 5). This reduction is driven by decreasing end-use service demand and a shift towards more efficient end-use technologies. Under an air pollution and CO_2 control policy, energy service demands are reduced as service price increases, which is mainly driven by the implementation of EOP control technologies and switching to lower-emitting technologies with higher costs. The final energy reduction is the largest in the industry sector due to the higher emission levels and higher emission reduction potential. From 2010 to 2030, the cumulative industrial final energy use decreases by 2 Gtce relative to the Ref scenario in the NDC_Poll scenario, accounting for 68% of the decrease in the total final energy consumption.

In addition to reducing energy consumption, the co-control policy also alters the mix of end-use fuels, discouraging the use of coal-based end-use technologies (Fig. 5). Under the NDC_Poll scenario, the share of coal consumption decreases from 38.8% in 2010 to 23.3% in

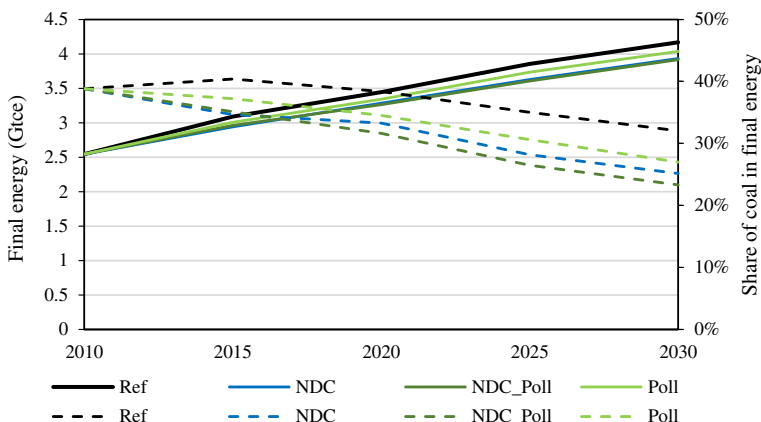


Fig. 5 Final energy consumption and the share of coal in the final energy consumption

2030, which is lower than that in Ref, while the shares of gas and electricity increase by 3.8 and 0.8%, respectively.

Moreover, the electricity generation mix in NDC_Poll is also greener and less carbon intensive compared with that in Ref (Fig. 6). The electricity output from traditional coal-fired power plants decreases by 1500 terawatt hours (TWh), while electricity generated by nuclear, wind and solar increases by 352, 342 and 123 TWh. In general, the shares of electricity generated from non-fossil fuels increase from 20% in 2010 to 39% in 2030, while the share of traditional coal-based power plants is only 46% in 2030, which is obviously lower than that in 2010 (77%). To decarbonize fossil fuels, markets must have access to CCS technology. It is noted that the development of CCS technologies is the key to realizing the 2 °C warming-control target; however, it may encounter a greater number of uncertain challenges than conventional non-fossil energy technologies (Duan et al. 2018a, b). In 2030, the market share of fossil fuel-based power plants with CCS technology reaches 5%. With more electricity consumed in end-use sectors and more electricity generated from non-fossil fuels, the share of non-fossil energy in the primary energy supply increases to 20% in 2030 in NDC_Poll, which is 4 percentage points higher than that in Ref.

3.4 The differences between co-control and individual-control policies

The co-control scenario (NDC_Poll) is aimed at controlling CO₂, SO₂ and NO_x emissions simultaneously, and so total emissions in the co-control scenario (NDC_Poll) are in line with those in the individual-control scenarios (NDC, targeted to control CO₂, and Poll, targeted to control SO₂ and NO_x). However, the emissions from each sector in NDC_Poll differ from those in the single-control scenarios.

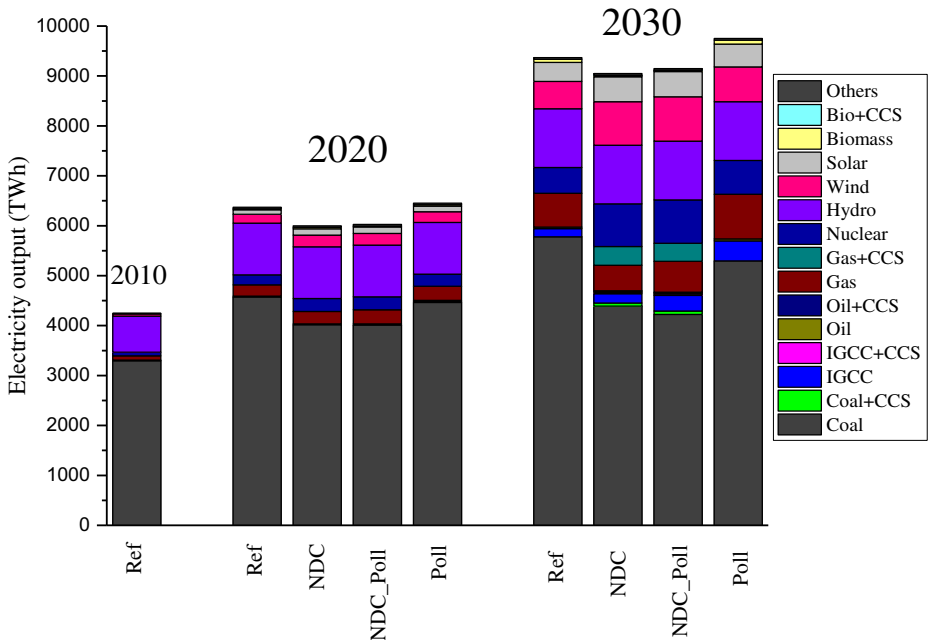


Fig. 6 Electricity generation by different technologies

In general, the CO₂ emissions from each sector change slightly between NDC_Poll and NDC, while the SO₂ (NO_x) emissions of each sector vary greatly between NDC_Poll and Poll. This is because mitigating CO₂ emissions largely relies on energy system transformation, while reducing SO₂ and NO_x emissions largely depends on EOP control measures in the short run. However, it is important to note that reducing SO₂ and NO_x emissions could provide a “free-ride” for decarbonizing the energy system in the co-control scenario, resulting in lower reliance on EOP control measures. For example, EOP control measures are responsible for 73% and 61% of the SO₂ reduction in the electricity sector under NDC_Poll in 2020 and 2030, respectively, which are significantly lower than those in Poll (91% and 83%, respectively). Similarly, EOP control measures contribute 69.4% and 63% to the reduction of the sector’s NO_x emissions in NDC_Poll in 2020 and 2030, respectively, which are lower than those in Poll (89% and 84%, respectively).

Accordingly, the primary energy consumption in NDC_Poll is much closer to that in NDC but is very different from that in Poll (Fig. 7) because decarbonizing the energy system (NDC) reduces the final energy consumption more than Poll. Compared with NDC, NDC_Poll calls for reducing the consumption of coal and biomass further while increasing the use of natural gas, wind, solar and nuclear energy before 2030. For example, coal consumption decreases by 80 million tonnes of standard coal (Mtce), but gas consumption increases by 65 Mtce in 2030. Compared with Poll, the primary energy consumption and its mix are very different in NDC_Poll, and coal consumption decreases to nearly 0.59 Gt in 2030. This also indicates that limiting CO₂ emissions depends mostly on energy system transformation, while reducing SO₂ and NO_x emissions has additional influencing factors.

By comparing the air pollutant emissions in NDC_Poll and NDC, we found that further efforts are required for China to realize the designed air pollutant emission control target while also accomplishing its NDC target. We found that additional cumulative reductions of 109 Mt

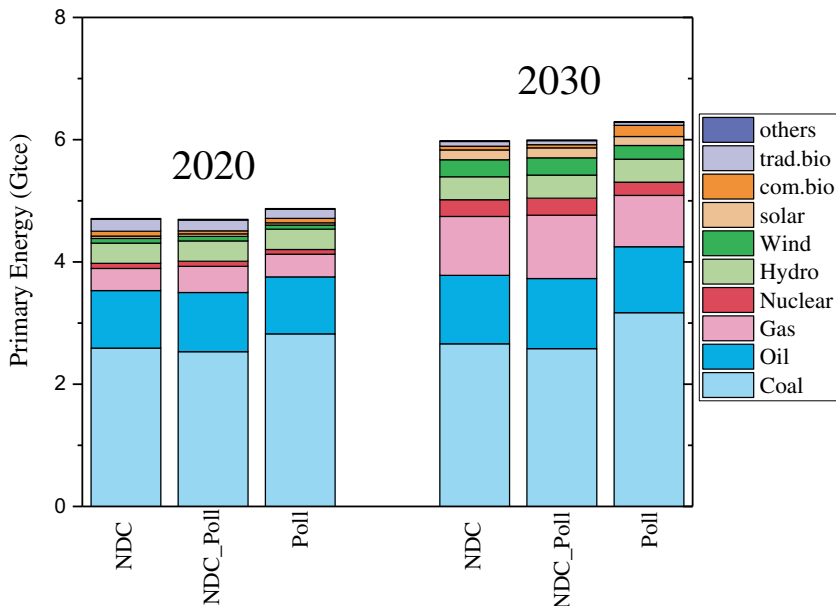


Fig. 7 Primary energy consumption under co-control (NDC_Poll) and individual-control (NDC and Poll) scenarios

of SO₂ and 111 Mt of NO_x need to occur during the period of 2011–2030, which mainly occurs in the electricity and industry sectors. Therefore, coal-based power plants are required to be equipped with EOPs to decrease SO₂ and NO_x emissions per electricity output by 52.3% and 55.9% by 2030 compared with the 2010 levels, respectively. Similarly, the industry sector also needs to implement EOPs to decrease the SO₂ and NO_x emissions per energy consumption by 40% and 48%.

If the priority is to realize the designated local air pollutant emission control target, further decarbonizing of the energy system is necessary for China to reach its NDC target. Comparing the NDC_Poll and Poll scenarios, a cumulative reduction of 106.8 Gt CO₂ needs to occur during the period of 2011–2030. Correspondingly, NDC_Poll requires a further reduction in coal consumption but stimulates the use of other fuels relative to the Poll scenario: the cumulative coal use should be further reduced by 6.2 Gtce, while gas, nuclear, wind and solar energy use should be increased by 1.5, 1.3, 0.32, 0.32 and 0.14 Gtce, respectively, during the period of 2011–2030. In addition, the electricity generation mix in NDC_Poll is more diversified and less carbonized than that in Poll. In 2030, the share of output from coal-based power plants without CCS technology in the total electricity is 46.2% in NDC_Poll, which is 8.1% lower than that in Poll, while the share of non-fossil power plants is 6.3% higher than that in Poll. In addition, to decarbonize fossil fuels, nearly 470 TWh of electricity output generated from fossil fuels needs to equip CCS technology by 2030.

4 Discussions

4.1 Abatement costs of different scenarios

The marginal abatement costs for reducing CO₂, SO₂ and NO_x in NDC_Poll are lower than those in NDC and Poll, and the total abatement cost in NDC_Poll is also lower than the sum of the total abatement costs in NDC and Poll. The CO₂ marginal abatement costs in NDC_Poll are 18 and 30 US dollars per tonne (\$/t) in 2020 and 2030, respectively, which are lower than those in NDC (24 and 40 \$/t in 2020 and 2030, respectively). The marginal abatement costs for SO₂ and NO_x are 2750 and 1690 \$/t, respectively, in 2030 under NDC_Poll, which are 26.2% and 13.1% lower than those in Poll. In GCAM, policy costs are represented by total abatement costs under the marginal abatement costs curve and do not include macro-economic and beneficial implications. The total abatement costs in NDC_Poll are 33 and 66 billion dollars in 2020 and 2030, respectively, which are lower than the sum of NDC and Poll (43.6 and 88 billion dollars in 2020 and 2030). By comparing the total cost of NDC_Poll and Poll, an additional cumulative 217 billion dollars would be required to achieve the China's NDC goal.

4.2 Sensitivity analysis

The effectiveness of EOP technologies in reducing air pollutant emissions is highly related with their removal rates or efficiencies. In reality, EOP technologies sometimes may not fully take effect (i.e. 100% removal), due to poor application environment, mechanical failure or even artificial factors. In order to clarify this sensitivity, we further design two additional scenarios (NDC_Poll_5 and NDC_Poll_10), both of which are evolved from NDC_Poll. NDC_Poll_5 (NDC_Poll_10) means that the removal efficiencies of EOP technologies are 5% (10%) lower than those in NDC_Poll.

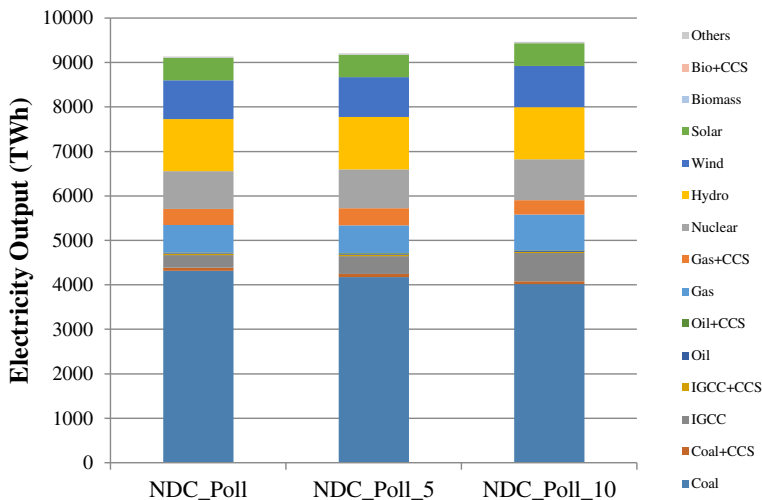


Fig. 8 Electricity generation by different technologies under NDC_Poll, NDC_Poll_5 and NDC_Poll_10 scenarios

Comparing these three scenarios indicates that the EOP removal efficiencies do not significantly change our previous conclusions that both EOP measures and energy transformation are required to control CO₂ and air pollutant emissions, and clean energy will play a more important role in the long run. The shares of electricity from non-fossil fuels are nearly the same under these scenarios (Fig. 8). However, it is noted that the share of electricity generated from IGCC is highest under NDC_Poll_10. This indicates if EOP measures do not totally take effect, cleaner energy technologies need to penetrate into the market more quickly.

5 Conclusions

Currently, China faces great pressure to address air pollution and climate change. To solve these two problems simultaneously, a co-control strategy has been proposed and simulated using an integrated assessment model (GCAM-TU). Four scenarios have been designed to analyse how to realize the co-control of CO₂ and air pollutant emissions and what additional efforts are required to meet the co-control targets if only individual-control targets are accomplished. The results show that energy system transition and EOP measures should work together to realize the co-control targets, but play different roles in different stages. To explore these common and distinguished efforts is the unique contribution of this study, because most of studies focus on realizing a single target (Song and Cui 2016; Zhou et al. 2019). The specific conclusions are discussed below.

Firstly, the control strategies for reducing CO₂ and air pollutant emissions are different. The control of air pollutant emissions depends on both implementing EOP measures and clean energy systems, while CO₂ emissions control mostly on decarbonizing the energy system. However, with the penetration of EOP technologies approaching to saturation, additional and stronger reductions in air pollutants will also rely on the transformation of the energy system and associated technologies. To limit CO₂, SO₂ and NO_x emissions, China's energy system, especially the electricity and industry sectors, are expected to be quickly decarbonized to blend their past high-emission trends.

Secondly, EOP measures play an important role in reducing air pollution in the near future, but in the long run, optimizing energy system is an effective way to control both CO₂ and air pollutant emissions. Besides structural changes of the energy system, lowering end-use service demand is of significant importance in mitigation. For instance, lowering road transport will contribute to the reduction of gasoline and diesel consumption, as well as energy use in many other related sectors such as crude petroleum extraction and nuclear fuel processing (Guo et al. 2018). In other words, although industry and electricity play the most important roles in improving air quality and mitigating global climate change, communities and individuals can also make appropriate contributions by taking initiative measures such as promoting walking and cycling, using public transport, saving energy and water and popularizing green spaces.

Thirdly, unilaterally controlling air pollutant (CO₂) is not sufficient to realizing the CO₂ (air pollutant) reduction target. However, air pollutant reduction is likely to take a “free-ride” of decarbonizing the energy system, and a co-control strategy tends to reduce the requirement of EOP control measures. Co-control also has economic implications, resulting in lower abatement costs than when the issues are addressed separately. Besides enterprise willingness and social supervision, air pollution control and low carbon action should be coordinated from the central government. Therefore, the Chinese government might consider developing scientific plans and regulations for the co-control of CO₂ and air pollutant, in order to avoid duplicated investments in infrastructure and the lockup effect.

Just as the key energy components of the United Nations (UN) Sustainable Development Agenda, universal access to modern energy by 2030, urgent action to tackle climate change and measures to improve air quality are global common goals. The co-control of CO₂ and air pollutant emissions is undoubtedly for China to realize multiple objectives. What’s more, this good and effective solution is also suitable for many other developing countries to address their own issues, such as India and Africa, because many countries which encounter air pollution problems are willing to tackle global climate change.

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Appendix

Table 2 Key EOP control technologies

Air pollutant	Sector and fuel	EOP control technologies	Costs (2010\$/tSO ₂)	Removal efficiency
SO ₂	Electricity and heat (coal)	Limestone injection (LINJ)	638 (coal)	60% ^{a,b,c}
	Electricity and heat (coal, oil)	Wet flue gas desulphurisation (PWFGD)	573 (coal)	90% ^{d,e}
		2701 (oil)		
	Electricity and heat (coal, oil)	High-efficiency flue gas desulphurisation (RFGD)	988 (coal)	95%
		5438 (oil)		
	Electricity and heat (coal)	Low sulphur coal (LSCO)	592 (coal)	38% ^f
		Industry (coal, oil)	Wet flue gas desulphurisation (IWFGD)	2485 (coal)
			5787 (oil)	
	Industry (coal)	Limestone injection (LINJ)	1899 (coal)	60%
	Industry (coal)	Low sulphur coal (LSCO)	688 (coal)	38%
Building (coal)	Low sulphur coal (LSCO)	793 (coal)	24%	
Transportation		5882	33%	

Table 2 (continued)

Air pollutant	Sector and fuel	EOP control technologies	Costs (2010\$/tSO ₂)	Removal efficiency
		Low sulphur diesel oil—stage 1 (LSMD1)		
	Transportation	Low sulphur diesel oil—stage 2 (LSMD2)	7964	10%
	Transportation	Low sulphur diesel oil—stage 3 (LSMD3)	18,498	98%
Air pollutant	Application sector and fuel	EOP control technologies	Cost (2010\$/tNO _x)	Removal efficiency
NO _x	Electricity and heat (coal)	Selective catalytic reduction on coal power and heat plants (PHCSCR)	1512 (coal)	85% (coal) ^{g,h}
	Electricity and heat (oil, gas)	Selective catalytic reduction on oil and gas power and heat plants (POGSCR)	2630 (oil) 8077 (gas)	90% (oil) 80% (gas)
	Industry (coal, oil, gas)	Combustion modification on fired industrial boilers and furnaces (ICM)	588 (coal) 931 (oil) 2507 (gas)	50% ⁱ
	Industry (coal, oil, gas)	Combustion modification and selective catalytic reduction on fired industrial boilers and furnaces (ICSC)	3056 (coal) 4228 (oil) 11,228 (gas)	80%
	Industry (coal, oil, gas)	Combustion modification and selective non-catalytic reduction on fired industrial boilers and furnaces (ICSN)	1608 (coal) 2701 (oil) 5795 (gas)	70%
	Building (oil, gas)	Combustion modification on gas and oil use in commercial and residential sectors (DMDCR)	2126 (oil) 10,183 (gas)	30% (oil) 50% (gas)

^a Chang 2007^b Wang 2008^c Xu and Guan 2008^d Huang et al. 2011^e Wu et al. 2010^f Yang 2007^g Sang et al. 2004^h Wang and Wang 2005ⁱ Han et al. 2016

Table 3 Emissions factors for different EOP control technologies

Air pollutant	Sector and fuel	EOP control technologies	Emission factors (kg/GJ)
SO ₂	Electricity and heat (coal)	Limestone injection (LINJ)	0.338
	Electricity and heat (coal)	Wet flue gas desulphurisation (PWFGD)	0.042
	Electricity and heat (coal)	High efficiency flue gas desulphurisation (RFGD)	0.017
	Electricity and heat (coal)	Low sulphur coal (LSCO)	0.522
	Electricity and heat (coal)	No control measures	0.846
	Electricity and heat (coal for IGCC)	No control measures	0.005
	Electricity and heat (gas)	No control measures	0.01
	Industry (coal)	Wet flue gas desulphurisation (IWFGD)	0.106
	Industry (coal)	Limestone injection (LINJ)	0.282
	Industry (coal)	Low sulphur coal (LSCO)	0.435
	Industry (coal)	No control measures	0.705
	Industry (oil)	Wet flue gas desulphurisation (IWFGD)	0.04
	Industry (oil)	No control measures	0.272
	Industry (gas)	No control measures	0.01
	Building (coal)	Low sulphur coal (LSCO)	0.377
	Building (coal)	No control measures	0.611
	Building (oil)	No control measures	0.023
	Building (gas)	No control measures	0.01
	Transportation	No control measures	0.023
	Transportation	Low sulphur diesel oil—stage 2 (LSMD2)	0.021
	Transportation	Low sulphur diesel oil—stage 3 (LSMD3)	0.0005
	Transportation	No control measures	0.023
Transportation	Low sulphur gasoline (LSGSL)	0.0005	
Air pollutant	Application Sector and fuel	EOP control technologies	Emission factors (kg/GJ)
NO _x	Electricity and heat (coal)	Selective catalytic reduction on coal power and heat plants (PHCSCR)	0.03
	Electricity and heat (coal)	No control measures	0.201
	Electricity and heat (coal for IGCC)	No control measures	0
	Electricity and heat (gas)	Selective catalytic reduction on oil and gas power and heat plants (POGSCR)	0.01
	Electricity and heat (gas)	No control measures	0.05
	Industry (coal)	Combustion modification on fired industrial boilers and furnaces (ICM)	0.125
	Industry (coal)	Combustion modification and selective catalytic reduction on fired industrial boilers and furnaces (ICSC)	0.05
	Industry (coal)	Combustion modification and selective non-catalytic reduction on fired industrial boilers and furnaces (ICSN)	0.075

Table 3 (continued)

Air pollutant	Sector and fuel	EOP control technologies	Emission factors (kg/GJ)
	Industry (coal)	No control measures	0.25
	Industry (oil)	Combustion modification on fired industrial boilers and furnaces (ICM)	0.071
	Industry (oil)	Combustion modification and selective catalytic reduction on fired industrial boilers and furnaces (ICSC)	0.028
	Industry (oil)	Combustion modification and selective non-catalytic reduction on fired industrial boilers and furnaces (ICSN)	0.0426
	Industry (oil)	No control measures	0.142
	Industry (gas)	Combustion modification on fired industrial boilers and furnaces (ICM)	0.034
	Industry (gas)	Combustion modification and selective catalytic reduction on fired industrial boilers and furnaces (ICSC)	0.013
	Industry (gas)	Combustion modification and selective non-catalytic reduction on fired industrial boilers and furnaces (ICSN)	0.02
	Industry (gas)	No control measures	0.067
	Building (coal)	No control measures	0.1
	Building (oil)	No control measures	0.02
	Building (gas)	No control measures	0.023

Table 4 Data sources of GDP growth rate assumptions

Study	Average annual GDP growth rate (%)		
	2016–2020	2021–2025	2026–2030
Li and He 2010	7	6.6	5.9
Chen et al. 2016	7.5	6.6	–
World Bank 2017	6.6	5.6	5
Institute of Economics Research of Renmin University 2016	7.08	6.24	6.24
Mitsubishi Research Institute 2017	6.5	5.4	4.1
Li et al. 2017	6.5	5.6	4.9

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