CHINA’S ENERGY SYSTEM OPTIMAZATION UNDER INDC COMMITMENTS: STUDY BASED ON CHINA-MAPLE MODEL

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ABSTRACT

China has stepped into the stage of new normal development, with GDP growth rate slowing down. And in 2015, China has submitted its Intended Nationally Determined Contribution (INDC) to UNFCCC, and committed to reduce the emission intensity per unit of GDP by 60%–65% from its 2005 level in 2030, and also peak the carbon emission around 2030. At the same time, the local pollutant problem and haze problem keeps getting worse in China. This paper focuses on these challenges and critical research topic on co-control of carbon emission and local air pollutants, and aims to explore China’s energy system optimization in the 2 degree world, specifically following the carbon mitigation trajectory as the INDC documents committed. This paper is highlighted from three aspects: first, to get the carbon mitigation trajectory and carbon emission allocation in China under the constraints of INDC documents; Second, to get the carbon mitigation trajectory evaluated based on China-MAPLE model, and explore the energy system transformation pathway; Third, the work is based on China-MAPLE model framework, a partial equilibrium model with linkage between carbon emission and local air pollutants at technological level.

1. INTRODUCTION

In the 2013 Warsaw climate conference, an agreement was achieved that “all parties should submit their Intended Nationally Determined Contribution (INDC) documents in 2015.” Responding to the call for submission of INDC, China submitted its INDC at end of June 2015. In the submission (NDRC, 2015), China promised to peak its carbon emission by 2030 and to increase the share of non-fossil fuel consumption in the total primary energy consumption to around 20% by 2030. Compared with the 2005 level, the carbon emission per unit of the gross domestic product (GDP) will be reduced by 60%–65% in 2030, and the forest volume will increase to 4.5 billion m^3.

Apart from facing great pressure to reduce its GHG emissions, China is also facing the multiple challenges of economic development, energy security, environmental pollution, and human health. China’s economy has stepped into the “new normal” stage, and its main feature is the gradually decreasing GDP growth rate. China has ended its 10% growth rate epoch and has started the revolution of the GDP growth pathway. Moreover, the energy structure of China is still dominated by fossil fuel, and the dependence rates on imported crude oil and gas up to year 2013 increased to 58.1% and 27.5%, respectively (Romano & Meglio, 2016). Furthermore, the total energy demand is climbing at high speed. About 70% of the primary energy demands, which have surpassed the scientific production capability, are from coal. The environmental problem in China is also closely linked to fossil fuel consumption.

Air pollution continues to aggravate in China. The air quality of 145 cities, which is nearly 90% among monitored cities, has exceeded the national air quality standard. The haze problem continuous to be serious in mega cities (Ministry of Environment Protection, 2013). Local pollutant emissions are also highly related to the public health problem. According to a study of the World Health Organization in 2010, 17% of premature death can be attributed to air pollutants, and a large portion of air pollutants is related to fossil fuel combustion in China, especially coal consumption. China’s $PM_{2.5}$ exposure damage is expected to be greater than 9% of the GDP (WHO, 2015).

Much evidence shows that carbon dioxide and local pollutant have the homology resources of emission, and thus carbon mitigation has significant benefits in local pollutant reduction. The Fifth Assessment Report of the IPCC (IPCC, 2014) clearly states that climate change mitigation activities will also bring significant benefits. The main benefits are twofold: the cost avoided compared with the non-mitigation scenarios and the co-benefits in other non-climate change fields such as air quality, energy security, and job creation.

The study of co-benefits can help climate negotiations to exit from the “zero-sum game” and aid countries to seriously look at their core interests and propose more realistic targets based on emission reduction. Unfortunately, only a few studies are working on the co-benefits related to China’s INDC of peaking its emission around 2030. In the “post-Paris” period, China faces unprecedented pressure for its deep de-carbonization and air quality improvement. Considering the multiple targets, several critical questions and problems have to be answered and solved, respectively. First, if China keeps pushing for its existing carbon mitigation measures, then what will be the emission of carbon dioxide and local pollutant in 2030 and 2050? Second, can China achieve its air quality target only through stricter end-of-pipe control measures? If not, what kinds of additional measures should be made from the energy conservation aspect? Third, if the co-control initiative is considered, how significant will be the co-benefit of local pollutant reduction caused by the carbon mitigation action?

To answer these questions, the China Multi-pollutant Abatement Planning and Long-term Benefit Evaluation (China-MAPLE), a bottom-up model analyzing economic-wide sectors, is developed in this paper. Based on the model, both carbon mitigation measures and local pollutant control measures are evaluated.

This paper is structured as follows: in Section 2, a literature review of the co-benefit study is presented, and the limitations of recent studies and further improvement of the paper are elaborated. Section 3 introduces the methodology and structure of the China-MAPLE model, including the main scenario design. Section 4 describes the simulation results from the scenario analysis for energy conservation, carbon mitigation, and local pollutant control. Further discussion is presented in Section 5. Section 6 draws the conclusions.

2. LITERATURE REVIEW

Co-benefit has begun to attract wide attention in recent years. After 2010, domestic-related research began to increase gradually. Most of the previous research focused on developed countries, and mainly considered one single sector. For example, Burtraw et al. (2003) conducted co-benefit study of power generation sector in the United States. Jakob M. (2006) evaluated the co-benefits in the Swiss building sector. Rypdal et al. (2007) analyzed the environmental and health co-benefits in Northern Europe. The Center for Health and the Global Environment and Harvard University jointly conducted a study (Driscoll et al. 2015) on the co-benefits in the electricity sector. Van Vuuren et al. (2006) analyzed the co-benefits of 19 European countries based on the E3ME model.

Studies on co-benefits based on the energy model in developing countries have continued to increase in recent years (He et al. 2010a; Xu & Masui 2009; Aunan et al. 2004; Creutzig & He 2009; Mao et al. 2011; Ma et al. 2016; Yang, Teng, & Wang 2013a, 2013b). The co-benefits will be more obvious in regions with relevant lower implementation efficiency of environmental protection policies. He et al. (2010) calculated the carbon and local pollutant emissions under different policy scenarios. Xu and Masui (2009) conducted a local pollutant reduction research and elaborated the limitation of a single tax policy on SO_2. Aunan et al. (2004) used the coal industry in Shanxi Province as a case study and evaluated the impact of carbon mitigation policy on the environmental and health damage effect. Creutzig and He (2009) also evaluated the co-benefits from local pollutant reduction at the provincial and sectoral levels while working in the transportation sector in Beijing. In addition, Mao et al. (2011) and Ma et al. (2016) examined China's electricity generation sector and iron and steel sector to study the co-benefits at the national level. Furthermore, Yang, Teng, and Wang (2013a, 2013b) calculated the co-benefits of SO_2, NO_x, and PM emission reduction in the cement sector. They also evaluated the benefits in 31 provinces in China.

Apart from that in China, the co-benefit research in other developing countries is also gradually increasing. For example, Dessus and O'Connor (2003) analyzed the co-benefits in Chile based on the CGE model. O'Connor (2000) conducted a comprehensive analysis of co-benefits in developing countries. Mestl et al. (2007a, 2007b, 2006) demonstrated that the co-benefits of household and indoor buildings also could not be ignored, especially the additional benefits caused by energy conservation measures.

The study on co-benefits in recent years has greatly improved. It has expanded from developed countries to developing countries and has shifted its focus on the quantitative analysis based on models. However, two shortcomings are observed in the existing literature. First, most of the existing literature focuses on the co-benefit study in specific sectors such as industry, electricity generation, and transportation. Co-benefit studies focusing on the full economy sector in China are quite few. Second, among the energy models considering the local pollutant co-benefits, most of them are linking energy consumption to local pollutant emission at the activity level or at the fuel-consumption level by using a coefficient for air pollutants per unit of energy consumption. This method can cause a few problems. In particular, it will oversimplify the complex mechanism between energy consumption and environmental emissions. Accordingly, the effect between structural change at the upstream and end-of-pipe control at the downstream cannot be separated.

In this paper, the China-MAPLE model is developed by linking the estimation of carbon emission to air pollutants at the technological level. The full economy sectors, including energy supply, energy conversion, and final energy service demand sectors, are considered.

3. METHODOLOGY

3.1 China-MAPLE model introduction

The China-MAPLE model is developed in this paper to evaluate the effects of the energy conservation policies and local pollutant control measures on the energy system. The model includes modules on energy supply and conversion, energy demand, energy system planning, local pollutant, and co-benefit evaluation, and a five-year step is used from 2010 to 2050. The model minimizes the total energy system cost when simultaneously meeting the final energy service demands and external constraints. With detailed definition of technologies and emission factors of both carbon dioxide and typical local pollutants including SO_2, NO_x, and primary PMs, the model can perform analyses at the technological level for multiple sectors.

3.2 Basic model assumptions

Given that the model is based on the bottom-up model framework, the general economic parameters, including GDP growth rate, population, urbanization rate, and industry structure, are exogenous for the model. The main assumption of the model is set to be consistent with the study of the World Bank (2012) and other literature. The average annual growth rate of China's GDP will drop to nearly 6.2% in 2020 and will further decrease to approximately 4% after 2030. The model assumes the population growth scenario that having a second child is allowed publicly. According to various sources (Zeng et al. 2013), the model assumes that China's total population will gradually increase to 1.433 billion by 2020 from 1.36 billion in 2010, will peak at around 2025–2030, and will then reduce to 1.385 billion by 2050. The urbanization rate of China reached 54.77% in 2014, and it will reach 58.2% in 2020, 67.1% in 2030, and 75.2% in 2050. Table 1 summarizes the major economic and social drivers used in the model.

Table 1 Social economic assumptions in China-MAPLE

	2010	2020	2030	2040	2050
Population (billion)	1.36	1.52	1.89	1.47	1.42
GDP per Capita (10^4 RMB/capita)	2.95	5.74	9.88	15.08	19.81
Urbanization rate (%)	51.1	58.2	67.1	72.4	75.2

3.3 Energy module

The energy module is based on TIMES, which is a bottom-up optimization model (Bouckaert et al. 2014; Cayla and Maïzi 2015; Chen et al. 2007; Chen et al. 2014) with rich technical details for economy-wide sectors, and solves the linear programming problem to optimize the energy system. The main target functions are presented in Formulas (1)–(3), which follow the basic bottom-up model design.

$$TOT\_OBJ(z) = \sum_{r} REG\_OBJ(z,r) \quad , \tag{1}$$

$$REG\_OBJ(z,r) = \sum_{y} (1+d_{r,y})^{(y_r - y)} \times ANCOST(r,y) - SALVAGE(z,r) \quad , \tag{2}$$

$$\begin{aligned} ANCOST(y) &= INVCOST(y) + INVTAXSUB(y) + INVDECOM(y) + FIXCOST(y) \\ &+ FIXTAXSUB(y) + VARCOST(y) + ELASTCOST(y) - LATEREVENUES(y) \quad , \end{aligned} \tag{3}$$

where y^t is the reference year compared with year y, and *SALVAGE* is the residual assets for region *r*. Function (3) shows that the annual cost (*ANCOST*) is the sum of investment cost (*INVCOST*), investment relevant tax and subsidy (*INVTAXSUB*), investment of decomposition (*INVDECOM*), fixed operating cost (*FIXCOST*), fixed operating relevant tax and subsidy (*FIXSUB*), variable operating cost (*VARCOST*), and cost of change in demand owing to the change in price elasticity (*ELASTCOST*) minus the payback of the removal device (*LATEREVVENUES*).

China-MAPLE analyzes the full economy sectors including the energy supply of natural sources, secondary energy transformation sectors, electricity generation sectors, and final demand sectors. The structure of the final demand sectors in the China-MAPLE model is presented in Figure 1.

3.4 Local pollutant module

In the China-MAPLE model, the local pollutant module is embedded into the energy system model. Therefore, the local pollutant emission coefficient is directly set at the technology level rather than at the sectoral activity level. Most of the existing pollutant emission coefficients in China are based on the total output of industry products, the overall fossil energy consumption, and the related emissions, which can be inferred from statistical data. This emission coefficient is an aggregated average at the sector level, and it reflects the combined effect of technology mix, energy mix, and level of end-of-pipe removal technology. To separate the different effects, the following methodologies are adopted in this paper by using: 1) technology-specific emission coefficient for air pollutants as by-products of energy related processes, and 2) measures to mitigate emissions and the amount of emission reduction to determine the “abated” emission coefficient. According to a large number of industrial research and literature review, a database of pollutant emission coefficients and mitigation technologies for each industry is established in this paper. The calculations of the emissions of pollutants based on different technologies are expressed as Formulas (4) and (5).

$$E_{j,y,z} = \sum_{k,m} A_{j,k,m,z} ef_{j,k,m,z} \quad , \tag{4}$$

$$ef_{j,k,m,y,z} = EF_{j,m,y,z} f_{j,m,y} \sum_{n} C_{j,m,n,z} (1-\eta_{m,n,y}) \quad , \tag{5}$$

where *j* is the sectors; *k* is the fuel type; *m* is the technology type; *n* is the control facility or technical type of pollutant emission; *y* is the type of pollutant; *z* is the time (year); *A* is the activity level of the emission source, such as the fuel consumption if the emission is based on fuel types and the product output if the emission is based on the unit output; *ef* is emission factor after end-of-pipe control measures (“abated emission factor”); C is the share of different end-of-pipe control measures; EF is the emission factor before the end-of-pipe measures; f_y is the share of the particles with a size of y in the particle emissions and f_y is 1 if other non-particulate air pollutants; and η_y is the pollutant removal rate of end-of-pipe control technology of type y.

3.5 Scenario definition

Three scenarios are developed to analyze the relationship between local pollutant and GHG emission reduction. First, a reference scenario (REF scenario) based on the current regulations and implementation status of air pollutants and GHG emissions. Second, the strengthening of the end-of-pipe control scenario (EPC scenario), in which strict enforcement of end-of-pipe control and technically feasible control strategies are assumed to be fully applied by 2030, and the energy scenario is the same as that in the reference case. Third, a co-control scenario (COC scenario), in which the end-of-pipe control technology in the EPC scenario is maintained and new energy saving policies are introduced, will lead to the peaking of China’s carbon emission by 2030.

The EPC scenario is designed to test the possibility of improving China’s air quality by using only the end-of-pipe control technology by promoting the best available technology (BAT) in all sectors, such as near-zero emissions of the power industry and the most advanced emission standards of European transportation. The COC scenario is defined to consider the combined effect through both the carbon peaking target by 2030 and the enhanced air pollutant reduction measures in the EPC scenario. The COC scenario includes the improvement of energy structure adjustment, technological progress, and the end-of-pipe control.

4. RESULTS

4.1 REF scenario

In the REF scenario, the final energy consumption keeps increasing, and the total amount will reach 4.6 billion tons of coal equivalent (tce) in year 2030 and around 5.1 billion tce in 2050. These amounts are nearly 1.75 and 1.95 times those of the final energy consumption amounts in 2010. The annual growth rate decreases from 4.42% in the period of 2010–2020 to 1.30% in the period of 2020–2030, and to 0.51% in the period of 2040–2050. Clearly, the increasing speed of energy consumption will slow down after year 2020, and the speed will be at around 0.5% on average after year 2030.

The primary energy consumption will reach 5.96 billion tce in 2030 and around 7.29 billion tce in 2050. These amounts are around 1.83 times and 2.23 times those of the 2010 level. With the continuous growing energy demand in the transport and building sectors, China's energy consumption is growing continuously, and fossil fuel energy still dominates in China's energy mix. The proportion of coal decreased from 68.8% in 2010 to less than 50% in 2030 and around 45% in 2050.

China's total energy-related carbon dioxide emissions in the REF scenario will continue to grow (see Figure 1). In 2030, the energy-related carbon dioxide emissions will reach 11.88 billion tons and will increase to 13.97 billion tons in 2050. The average annual growth rate in the period of 2010–2020 is around 3.08%. This rate will then slow down to 0.89% in the period of 2020–2030 and to 0.8% in the period of 2030–2050.

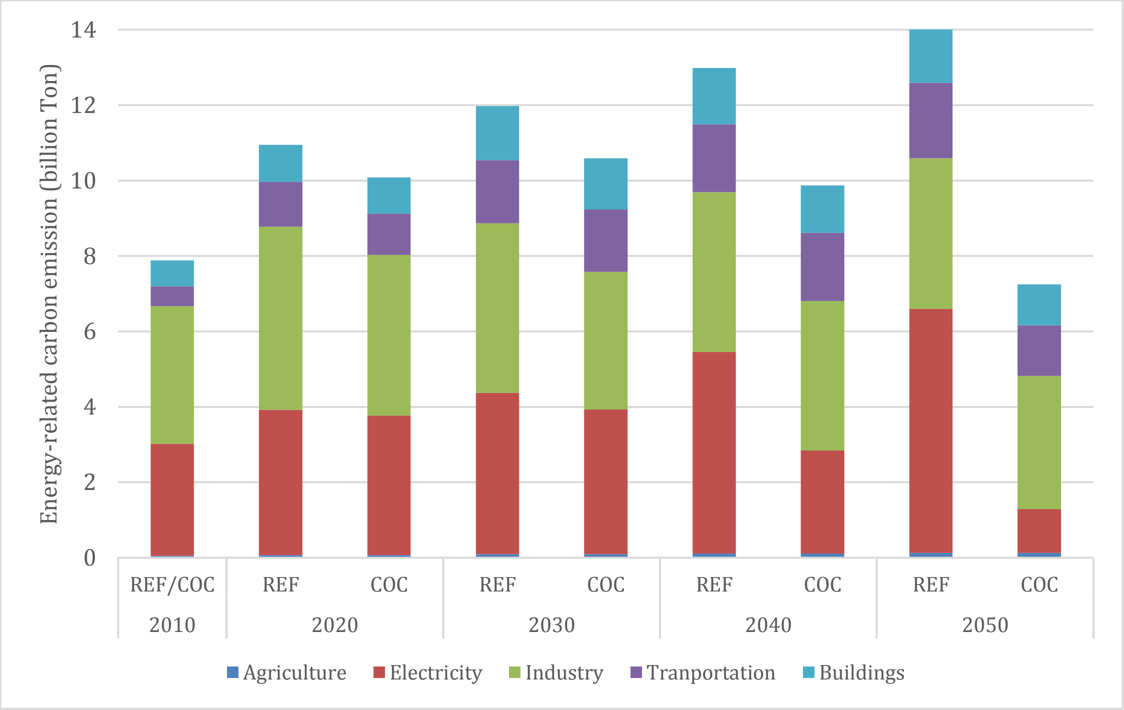

Figure 1 Energy-related CO_2 emission by sector in the REF and COC scenarios of the China-MAPLE model

In terms of primary energy consumption per unit of the GDP, energy intensity in the REF scenario will be reduced by 49% in 2030 and 68% in 2050 compared with base year 2010. The carbon intensity per unit of GDP is reduced by 47% compared with the 2005 level. Therefore, the 40%–45% reduction target in 2020 can be achieved in the REF scenario. Compared with that in 2005, the reduction of emission intensity will be 56% in 2030 and 72% in 2050. To fulfill the INDC target of 60%–65% reduction in 2030, further energy conservation potential still has to be explored.

In the REF scenario, the end-of-pipe control measures are assumed to be frozen at the same level of 2010. The SO_2 emission is nearly 41.42 million tons in 2010, and it will increase to 109.31 million tons in 2030 and will peak at 115.22 million tons in 2040. This emission will finally decrease to 110.23 million tons in 2050. The NO_x emission is nearly 41.58 million tons in 2010, and it will increase to 75.64 million tons in 2030 and will increase to nearly 81.77 million tons in 2050. The primary particulate matter $PM_{2.5}$ emission is considered in the particulate matter emission. The total emission in 2010 is around 10.93 million tons, and it will increase to 17.51 million tons in 2030, peak in 2050, and then decrease to 15.97 million tons. The secondary particles formed by the physical and chemical reactions are ignored in this paper.

From the sectoral level, the main sources of SO_2 emissions are from the power sector (15%), industrial boilers (42%), and industrial processes (28%) in 2030. The main sources of NO_x emissions are the industrial sectors (51%), power sector (18%), and transportation sector (14%) in 2030. $PM_{2.5}$ emissions are mainly emitted by the building sector (39%) and the industry sector (35%) in 2030. In the reference case, SO_2, NO_x, and $PM_{2.5}$ will increase by 163.2%, 81.9%, and 60.2% until 2030, respectively, compared with the 2010 level. Air quality will continue to deteriorate. Therefore, taking more stringent pollutant emission control is necessary to reduce air pollutants and improve air quality.

4.2 EPC scenario versus REF scenario

In the EPC scenario, the end-of-pipe control measures are comprehensively promoted in each sector, including BAT. This scenario also assumes that the end-of-pipe control technology in the proportion of each sector gradually reaches the maximum level.

SO_2 emissions in this scenario show a significant declining trend from the base year level. The emission in 2030 will reduce to 9.82 million tons, a reduction of 68.1% compared with that in 2010. The contribution of SO_2 emission reduction mainly comes from the industrial sector (73%) and the power sector (21%).

NO_x emission in the EPC scenario also achieves significant reductions. The NO_x emission in 2020 and 2030 will be 42.9% and 61.4% lower than the 2010 level, respectively. The NO_x emission reduction is mainly attributed to the industrial processes (67%), power sector (17%), and transport sector (13%).

For $PM_{2.5}$, the emission at the year 2010 level will be reduced by 59.5% and 73.4% in year 2020 and 2030, respectively. The $PM_{2.5}$ emission reduction is mainly due to residential and public buildings, which contribute 47% to the total reduction. This finding is highly related to the inefficient use of decentralized heating in rural China.

In summary, the promotion of the stringent end-of-pipe technologies is effective in the EPC scenario. The emission of SO_2, NO_x, and $PM_{2.5}$ in 2030 will decrease to 31.9%, 38.7%, and 26.6% from the 2010 level, respectively. Although significant reduction potential can be achieved, stricter end-of-pipe regulation is still insufficient to achieve the goal of improving the air quality standard, which demands the major air pollutants to be reduced by around 80% from year 2010 level (The New Climate Economy Report, 2014).

Although the end-of-pipe control measures should be vigorously promoted, the air quality standard cannot be achieved only by strengthening the end-of-pipe control measures. To achieve full compliance of air quality requirements by 2030, the end-of-pipe measures must be combined with source control measures in structure shift of both economy and energy mix. The contribution to local pollutant reduction from energy conservation, such as technological improvement and shift in economic structure and energy mix, should be further enhanced.

4.3 COC scenario versus EPC scenario

In the COC scenario, apart from the end-of-pipe control measures, energy conservation measures in each sector are also considered (NDRC, 2015). These measures aim to improve energy conservation and to enable the carbon peaking by 2030.

The primary energy consumption in the COC scenario will be largely improved. Compared with that in the REF scenario, the total primary energy consumption in the COC scenario will be reduced by 4% to 2.86 billion tce in 2030 and by 15% to 6.17 billion tce in 2050. The proportion of coal consumption will be reduced from 48% to 40% in 2030 and will be further reduced to 20% in 2050. The proportion of non-fossil fuel in the COC scenario will increase from 18% to 25% in 2030 and from 20% to 45% in 2050 compared with that in the REF scenario. The total emission in the COC scenario will reach its peak by 2030 with a total amount of 10.58 billion tons, which is a 12.4% reduction compared with that in the REF scenario. After 2030, the decreasing rate of total emission in the COC scenario is around 1.55%, about 0.8% higher than that in the REF scenario. Referring to the 2005 level, the carbon intensity reduction is around 51.3% in 2020 and 62.9% in 2030. The considerable reduction of carbon intensity in the COC scenario can fully achieve the target of 40%–45% reduction in 2020 and 60%–65% reduction in 2030 from the 2005 level.

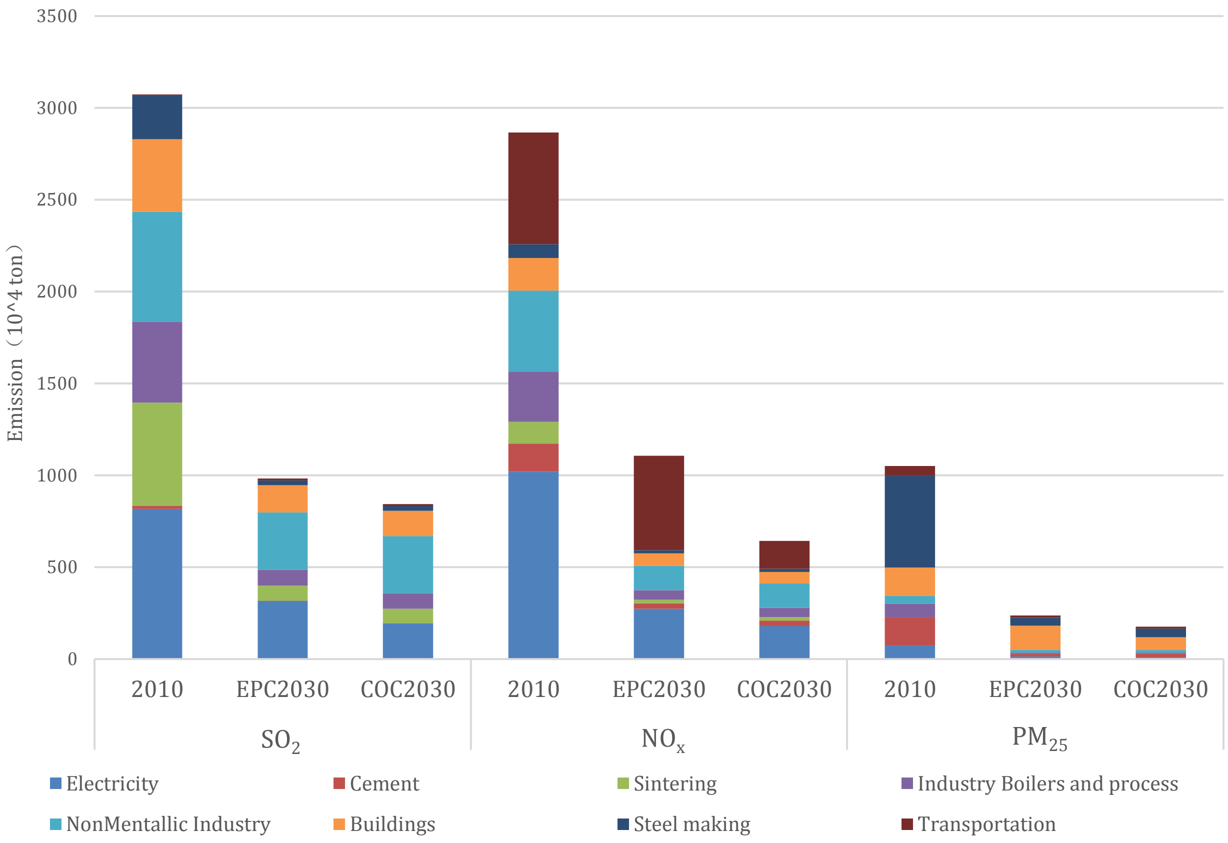

Figure 2 SO_2, NO_x, and $PM_{2.5}$ emissions in the EPC and COC scenarios in 2030

As revealed in Figure 2, the SO_2, NO_x, and $PM_{2.5}$ emissions in the COC scenario decrease to 21.15%, 22.44%, and 16.68% in 2030 from the 2010 level, respectively. Given the combination of downstream end-of-pipe control policy and upstream energy policy, air pollutants can be reduced to around 20% from the 2010 level. This reduction is consistent with the target to improve air quality in major Chinese cities by 2030.

At the sectoral level, the SO_2 reduction mainly comes from the industrial sector (46%) and the power sector (19%) in 2030. The NO_x emission reduction comes mainly from the industrial sector (35%), the power sector (22%), and the transportation sector (21%). The $PM_{2.5}$ emission reduction mainly comes from the household sector (49%), the industrial sector (32%), and the electricity sector (6%). In the household sector, emission reductions are mainly due to the improvement of energy mix in rural area.

The largest contribution of SO_2 emission reduction is from the power sector, the steel sector, and other industry sectors. The contribution rates are 32% and 40% in 2030. The top two contributing sectors to the NO_x emission reduction are the power sector and the industrial sector. In the industrial sector, the non-metal emission reduction contributes the most. The $PM_{2.5}$ emission reduction in the COC scenario is mainly attributed to the building sector, the industrial sector, and the power sector.

5. CONCLUSION

The concept of INDC is a real game changer to climate negotiation. INDC asks host countries to consider their possible contribution from a bottom-up perspective. When preparing such a contribution, evaluating the co-benefit of the INDC on the domestic interests of host countries is important. In this paper, the air quality benefit of China's INDC is examined by using a bottom-up model to examine the control strategy on carbon emission and air pollutants by linking emission coefficient at the technology level.

The scenario analysis indicates that China is facing great pressure from both deep de-carbonization and air quality improvements. When maintaining the existing mitigation measures, carbon mitigation cannot achieve its peak before 2030. Given the increasing energy consumption, air quality will also be even worse. The end-of-pipe control measures can help China to significantly reduce air pollutants, but these measures are inadequate to achieve the air quality target of the country. Even with the most stringent penetration rate of BATs in each sub-sector, the air quality in 2030 still cannot achieve the reduction target, which is necessary to fulfill the national standard. More effort should be made from the aspect of upstream mitigation to substantially reduce energy consumption. When the co-control measures are considered, both the air quality target and the carbon emission peaking target can be achieved by 2030.

In China, air quality is an important driving force to incentivize more ambitious mitigation measures. These measures can contribute to the simultaneous reduction of carbon emission and air pollutants. The assessment of air quality benefit also has an important implication for the discussion on the possible early peaking of China's emission target. In the EPC scenario, a stringent assumption on end-of-pipe measures is presented. If such an assumption is not achieved, then additional upstream mitigation measures may be demanded to deliver more air pollutant reduction which also can help to achieve the early peaking of the carbon emission.

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