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Abstract

Air pollution has been recognized as a significant problem in China. In its Twelfth Five Year Plan (FYP), China proposes to reduce SO_2 and NO_x emissions significantly, and here we investigate the cost of achieving those reductions and the implications of doing so for CO_2 emissions. We extend the analysis through 2050, and either hold emissions policy targets at the level specified in the Twelfth FYP, or continue to reduce them gradually. We apply a computable general equilibrium model of the Chinese economy that includes a representation of pollution abatement derived from detailed assessment of abatement technology and costs. We find that China's SO_2 and NO_x emissions control targets would have substantial effects on CO_2 emissions leading to emissions savings far beyond those we estimate would be needed to meet its CO_2 intensity targets. However, the cost of achieving and maintaining the pollution targets can be quite high given the growing economy. In fact, we find that the Twelfth FYP pollution targets can be met while still expanding the use of coal, but if they are, then there is a lock-in effect that makes it more costly to maintain or further reduce emissions. That is, if firms were to look ahead to tighter targets, they would make different technology choices in the near term, largely turning away from increased use of coal immediately.

Contents

1. INTRODUCTION

One of the consequences of China's rapid economic growth has been increased emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and carbon dioxide (CO_2), all strongly associated with rising fossil energy use. Emitted in the process of combusting fossil fuels with high sulfur content, SO_2 is a cause of acid rain and a precursor to the formation of particulates, which are known to cause chronic and acute pulmonary and cardiovascular diseases (Pope and Dockery, 2006). Also formed in the process of combustion, NO_x contributes to acid rain and smog, and plays a key role in the formation of tropospheric ozone. The major source of SO_2 emissions is fossil fuel combustion at power plants and industrial facilities, while sources of NO_x emissions

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include internal combustion engines in vehicles as well as combustion in electric power generation and industrial processes. CO_2 is a byproduct of combustion of any carbon-based fuel. Rapid growth and heavy reliance on coal has made China the world's largest emitter of CO_2, recently surpassing the United States.

Targets developed as part of China's Twelfth Five Year Plan (FYP) call for stricter air pollution controls. Slated to take effect at the start of 2012, the new regulations include SO_2, NO_x, soot, and for the first time, mercury. Our analysis focuses on the SO_2 and NO_x regulations and their interactions with CO_2 emissions control targets. China's official policy goals, specified in the Twelfth FYP, are to reduce emissions of SO_2 by 8% and NO_x by 10% (relative to 2010 levels) by 2015. According to officials, the new SO_2 and NO_x regulations require the domestic power-generation sector alone to reduce 6.2 million metric tons (mmt) of SO_2 and 5.8 mmt of NO_x emissions by 2015 (Li, 2011). Compared with SO_2 and NO_x, China's CO_2 control target is relatively moderate, aiming at a 40–45% reduction of the 2005 CO_2 intensity[1] level by 2020 (Copenhagen Accord, 2010). Given our projections of gross domestic production (GDP) growth, this intensity-based target can translate into an increase of total CO_2 emissions of around 120%, from 4.4 billion metric tons (bmt) in 2005 to 9.6 bmt in 2020.

In this study, we explore two questions: (1) How significant are the climate co-benefits from China's official SO_2 and NO_x emission control targets, and (2) If these proposed policy targets are attained, how will China's energy demand and supply structure change? To answer our questions, we develop a computable general equilibrium (CGE) model with technology-based parameterization of industry-specific pollution control abatement opportunities, and simulate it under multiple policy scenarios. The remainder of our study is structured as follows. The second section reviews the literature and describes the contribution of the present analysis. The third section provides detail on the methodology used, including the endogenous representation of pollution abatement cost. The fourth section presents the results of the analysis based on multiple policy scenarios. The last section summarizes our key findings and draws conclusions.

2. SO_2 AND NO_x EMISSIONS CONTROLS IN CHINA

China has had air pollution controls in place since 1987, starting with the Air Pollution Prevention and Control Law (**Table 1**). This regulation targeted SO_2 primarily to address increasing acid rain, but did not cover power plant emissions. Coverage was expanded to include the power sector when the regulation was amended in 1995. In 1998, a regional control strategy was implemented. This strategy, known as the Two Control Zones policy, divided regulated areas into either the Acid Rain Control Zone, areas suffering from the effects of acid rain or the SO_2 Control Zone, areas mainly responsible for SO_2 emissions. These zones included 175 prefectures across 27 provinces that accounted for 59% of the total SO_2 emissions in 1995 (Hao *et al*., 2001).

[1] CO_2 intensity refers to CO_2 emissions per unit of gross domestic product.

Table 1. Air Pollutant Emissions Regulation in China: Major Developments.

Year	Development
1987	Air Pollution Prevention and Control Law (APPCL) implemented. This did not cover the power sector and areas affected by acid rain expanded (Qian and Zhang, 1998).
1995	APPCL amended to cover the power sector (Hao *et al*., 2007). Shifted to a regional strategy, where priorities to improve air quality and prevent the spread of acid rain would be focused on.
1998	Regional control strategy (the Two Control Zones policy) officially approved.
2010	New regional air quality regulation (SO_2) entered into force.
2011	Twelfth FYP includes goals to reduce SO_2 by 8% and NO_x by 10%. Further, regulations call for a reduction of sulfur emissions from coal-fired power plants of 90%. Comprehensive NO_x control is added to China's air pollutant regulations for the first time.

Several studies have measured China's precursor emissions and industry progress towards meeting control requirements (Akimoto and Narita, 1994). SO_2 emissions fell from an estimated 23.7 mmt in 1995 to 20.0 mmt in 2000, and the percentage of non-compliant prefectures fell from 54% in 1995 to 21% in 2000 (He *et al*., 2002). Small mines producing high-sulfur coal had been closed, leading to an over 50 mmt reduction in high-sulfur coal production by the end of 1999 (Hao *et al*., 2001). By the end of 2000, flue-gas desulfurization systems had been installed on 10,000 MW of power generation assets and a number of small, inefficient generation units had been shut down, reducing coal consumption by 10 mmt and SO_2 emissions by 0.4 mmt (Yang *et al*., 2002).

The impact of such changes in emissions and air pollution concentrations on human health (Matus *et al*., 2012) and infant mortality (Tanaka, 2010; Saikawa *et al*., 2009) was estimated to be substantial. Several studies have also extended their analysis to include the forecast of future air pollutant and GHG emissions under multiple policy scenarios and to estimate their impacts on the environment or on human health. Xing *et al*. (2011), for example, forecast emissions based on a bottom-up study of previous regulatory performance since 2005 and publicly announced provincial control strategies, and Saikawa *et al*. (2011) perform a scenario analysis of the impact of vehicle emissions on air quality.

According to the recent SO_2 and NO_x emissions data, reported by China's Ministry of Environmental Protection (MEP), SO_2 emissions have been declining while NO_x emissions have continued to rise (**Figure 1**). We take this up again in Section 4.1, as there is a growing discrepancy between China's official statistics and estimates by independent research teams (Nielsen and Ho, 2007). If we accept the MEP statistics the SO_2 emissions trend suggests that policy efforts have had some success.

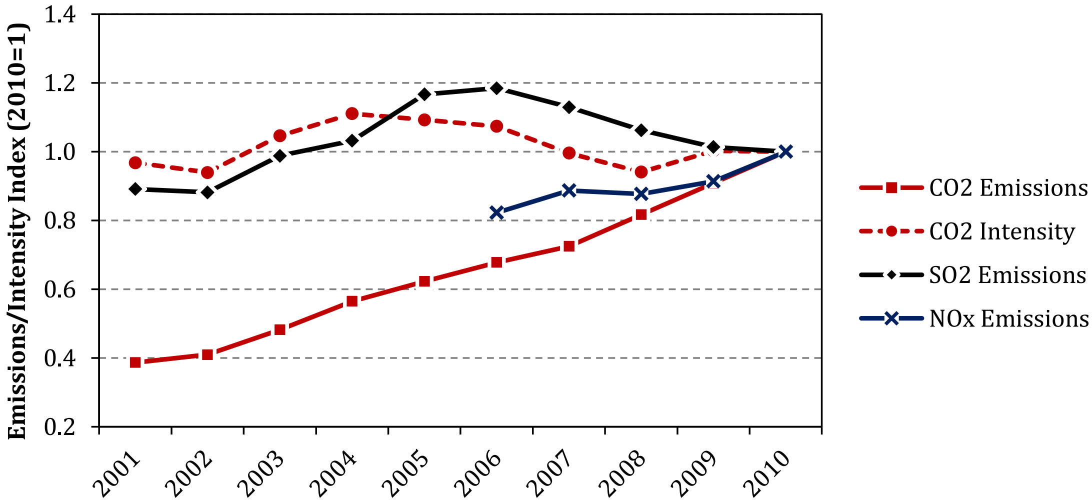


Figure 1. Emissions and intensity trend in China, 2001–2010. Source: SO_2 and NO_x data from MEP (2011); CO_2 data from World Bank (2012).

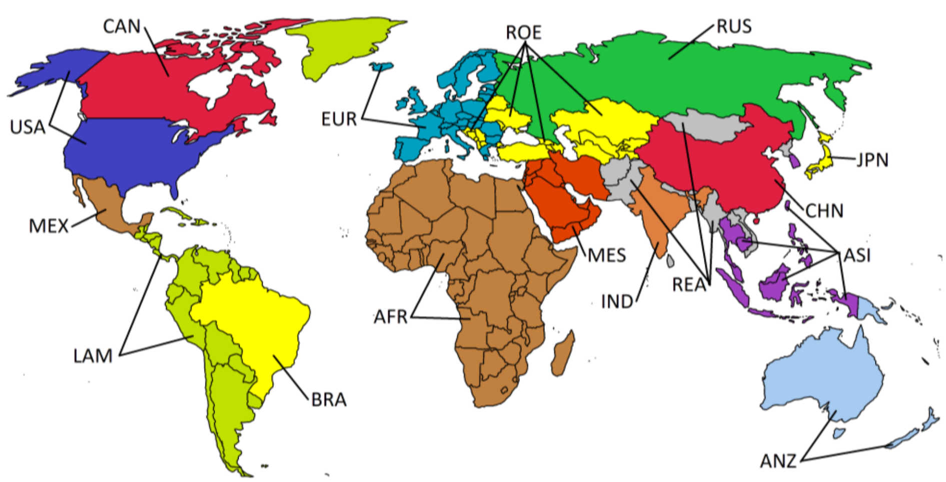
The latest regulations that entered into force under the Twelfth FYP call for a further 8% reduction in SO_2 emissions from 2010 levels and for the first time targets NO_x emissions, calling for a 10% reduction by 2015 (China Climate Change Info-Net, 2011; Li, 2011). These tighter regulations, in effect as of January 1, 2012, will require that power producers adopt abatement technology or shut down the most inefficient plants. In addition to air pollution targets, China's Twelfth FYP also includes economy-wide energy intensity and carbon intensity reduction targets of 16% and 17%, respectively. As shown in Figure 1, although CO_2 emissions have increased rapidly since 2001, CO_2 intensity first rose somewhat and then has declined slightly since 2006. This suggests that in China's current or future settings, decreased CO_2 intensity may not necessarily translate into reduced CO_2 emissions. In recent years, China's leaders have focused on reducing CO_2 intensity as part of overall national policy on climate change. China's Copenhagen commitment for addressing global climate change included reducing the energy intensity of the nation's economy by 40–45% over the period 2005 to 2020. Similar to air pollution targets, responsibility for meeting the energy and carbon intensity targets is shared out among China's provinces (China Climate Change Info-Net, 2011). Some of the strategies employed to meet air pollution targets may also help producers meet the energy and carbon goals, while other pollution control strategies may require energy to operate (e.g., fuel-gas desulfurization equipment) and could potentially conflict with energy saving goals.

3. METHOD

As described in detail by Waugh (2012), our method is built on the developments of Hyman *et al.* (2003), de Masin (2003), and Sarofim (2007). Our approach allows us to evaluate the cost of pollution controls within our CGE framework, incorporating bottom-up engineering data on pollution control costs. It differs from statistical methods (e.g., Selden and Song, 1994; Stern and Common, 2001) that have sought to estimate the relationship between pollution and development following early observations of the existence of an environmental Kuznets curve. These approaches grew out of the observation that in early stages of economic development, pollution rose, but then as it continued, emissions peaked, and then fell.[2] The robustness of this relationship has been questioned (Stern, 2004) but much follow-on work continued to estimate relationships between development (e.g., a GDP per capita or time-trend relationship) and pollution. Whatever the power of such relationships to predict future emission trends, they have limited application to analyzing policy that constrains emissions and seeks to determine compliance costs since costs are not accounted for in emission trends. Under a policy constraint, we expect the quantity of emissions and cost of policy compliance to vary, depending on the stringency of the policy and therefore pollution abatement costs must be represented endogenously. Our approach accounts for this by explicitly modeling the cost of abatement opportunities and the need for regulatory constraints to achieve them.

3.1 Theoretical Framework: EPPA5

We implement our methodology in the MIT Emissions Prediction and Policy Analysis model Version 5 (EPPA5). EPPA5 is a recursive dynamic, multiregional CGE model of the world economy, based on economic data from the Global Trade Analysis Project version 7 dataset (Narayanan and Walmsley, 2008) and emissions data from the Emissions Database for Global Atmospheric Research (EDGAR) model (van Aardenne *et al.*, 2009). EPPA5 contains 16 global regions and 14 production sectors, along with additional technological detail in energy sectors (**Figure 2**). Further details of the model are described in Paltsev *et al*. (2005). One strength of EPPA5 is that it can easily be expanded for the analysis of various energy and environmental policies. For our analysis, we develop a pollution abatement module and integrate it into the standard version of EPPA5 to capture its interactions with other parts of the economy.



EPPA 5 Sectors	
LIVE	Livestock
CROP	Crops
FORS	Forestry
FOOD	Food
EINT	Energy Intensive Industry
HTRN	Household Transportation
TRAN	Other Transportation
OTHR	Other
SERV	Services
ELEC	Electricity
OIL	Oil
ROIL	Refined Oil
COAL	Coal
GAS	Gas

Figure 2. Regional and sectoral aggregation schemes in EPPA5.

[2] The original Kuznets curve was a relationship between development and income inequality where in early stages of development inequality increased and then later decreased as development proceeded.

For fuel related pollution, we represent precursor pollutant emissions (X_E) and emissions abatement (X_A) in the fuel-emissions bundle where (X_F) is the fuel input **(Figure 3)**. The relationship is a fixed proportion (Leontief) production structure. Absent emissions controls that set a price on emissions, each unit of fuel use is associated with a unit of emissions. The abatement-emissions sub-nest is a constant elasticity of substitution (CES) production structure with the elasticity (σ_{fuel}). The specification of production structures within the CGE framework uses expenditures to show the quantity of inputs. Thus, abatement X_A is the capital cost of a unit of abatement. We assess the marginal cost of emissions abatement in the base year, and assign this value to both emissions and abatement (i.e. $X_A = MCA \times x_A$ and $X_E = MCA \times x_E$, where lower case x's are the physical quantities, MCA is the marginal cost of abatement, and the upper case X's are quantities in value terms). Abatement is represented as additional investment and so increasing X_A requires additional capital. The value of σ_{fuel} is estimated from engineering data, and allows for an increasing marginal cost of abatement. As in other parts of the model, we retain a supplemental accounting system that relates expenditures to the quantity of emissions.

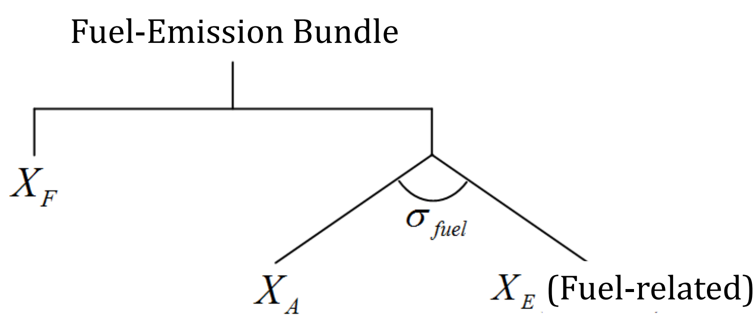


Figure 3. Fuel-emission bundle for fuel-related pollution. Pollution is used in fixed proportion to fuel consumed and pollution can come from either pollution emitted or pollution abated.

The extent to which pollution is either emitted or abated depends on the stringency of emission controls and cost of abatement. In the absence of policy, the cost of emitting is zero and all pollution will be emitted. On the other hand, in the presence of emission controls emitting carries a cost. This creates an incentive to abate, and the overall pollution mix will shift away from emitting and toward abating until the marginal price for abating equals the marginal price for emitting. In the case that both emitting and abating costs are significant, this structure may lead to significant decrease in fuel consumption. In some cases, this may come through a shift away from more pollution-intensive fuels and toward less pollution-intensive fuels (e.g., substituting natural gas for coal to reduce SO_2 emissions); or, in the case of exceptionally stringent emission controls, it may require a large reduction in energy consumption in the sector, which in turn would lead to a significant impact on the overall sectoral production output and eventually GDP.

Pollution unrelated to fuel use is given as an input in the uppermost part of the production nest as illustrated in **Figure 4**. The rising marginal cost of abatement is determined by $\sigma_{Pollutant}$, and in all other ways the approach is identical to that for fuel-related emissions. At this position in the nest, abatement results in a proportional increase in all inputs, if all other prices are unchanged. We separately resolve SO_2 and NO_x emissions by sector and by fuel, and in any sector that has non-fuel related emissions. Thus, the initial marginal cost of abatement and the quantity of pollutant emissions is unique to the fuel source, sector, and pollutant.

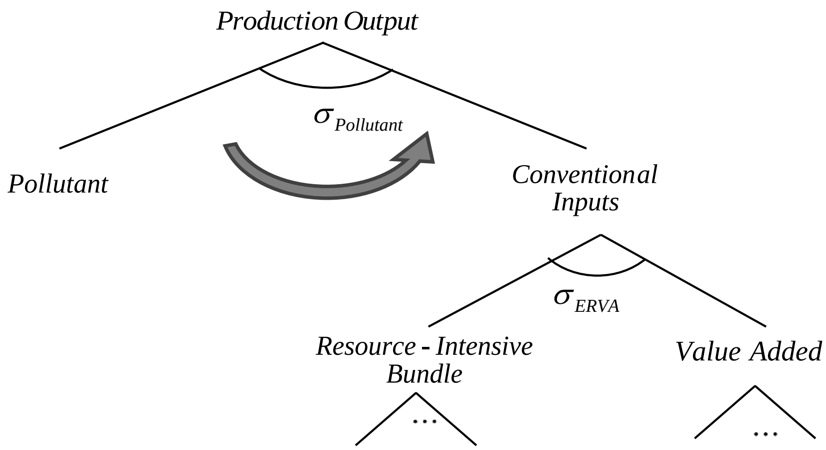


Figure 4. Non-fuel-related pollution represented as an input to production in the top nest of a CES production block.

3.2 Marginal Abatement Cost Curves

As noted above, abatement opportunities and costs are captured in the model through initial parameterization of cost shares and the relevant elasticities. Since abatement opportunities are entirely dependent on the specific abatement technologies available in individual regions and sectors, σ_{fuel} (or $\sigma_{Pollutant}$) must reflect to the largest extent possible the technological detail unique to these levels of disaggregation. This is accomplished first by obtaining a price elasticity of supply for abatement from marginal abatement cost (MAC) curves for SO_2 and NO_x in each sector and region from detailed bottom-up engineering studies, and then relating the own-price elasticity of supply of abatement to σ_{fuel} (or $\sigma_{Pollutant}$). In this manner, we are able to capture the "bottom-up" detail of the technology-specific abatement opportunities within the "top-down" framework of a general equilibrium model.

We estimate the price elasticity and an intercept (P_0) of the sector-specific MAC curve from a log-linear Poisson regression. Since the total quantity of pollution (X_P) occurs in fixed proportion to fuel and since X_P is the sum of X_A and X_E, any reduction in emitting must be made up by abating and vice versa. Therefore, the demand curve for emitting is the same as the supply curve for abating, and the price elasticities are also the same. The supply function for abatement is then given by Equation 1, where P_E denotes the marginal price of emissions, and α and β are parameters to be estimated by the log-linear regression to the engineering data.

$$P_E = P_0 + \alpha \cdot \left(X_E\right)^{\beta} = P_0 + \alpha \cdot \left(X_P - X_A\right)^{\beta} \tag{1}$$

The above equation can be transformed into a log-linear form as shown in Equation 2.

$$\log(P_E - P_0) = \log(\alpha) + \beta \cdot \log(X_P - X_A) \tag{2}$$

The price elasticity of demand for emissions (ε_{D_E}) can be drawn from Equation 2 by taking the partial derivative of the log-linear expression. As shown in Equation 3, ε_{D_E} is equal to the reciprocal of β.

$$\varepsilon_{D_E} = \frac{\partial \log(X_E)}{\partial \log(P_E)} = \frac{1}{\beta} \tag{3}$$

The relationship between this "own-price" elasticity and the elasticity of substitution in the CES nest shown in Figure 3 can be established from a cost minimization problem (CMP). Following standard economic theory, we consider a CMP where the firm seeks to minimize the cost of pollution production (C_P) for a given output subject to the related production technology, given as a CES production function. If P_A denotes the marginal price of abating, and P_E the marginal price of emitting, then C_P can be expressed as a function of X_E and X_A, as shown in Equation 4.

$$C_P = X_E P_E + X_A P_A \tag{4}$$

We assume that the related pollution-production function is given as Equation 5, where γ, ϕ, and σ refer to the efficiency parameter, value share of emissions, and the elasticity of substitution between abating and polluting, respectively.

$$X_P = \gamma\left(\phi X_E^{\frac{\sigma-1}{\sigma}} + (1-\phi) X_A^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{5}$$

Solving this CMP leads to the demand function for emitting given by Equation 6.

$$X_E = \frac{X_P}{\gamma}\left(\frac{\gamma}{X_P}\phi\frac{C_P}{P_E}\right)^{\sigma} \tag{6}$$

From this, we solve for the price elasticity of demand by taking the partial derivative of X_E and obtain Equation 7.

$$\varepsilon_{D_E} = \frac{\partial X_E}{\partial P_E}\frac{P_E}{X_E} = \left(-\frac{\sigma}{P_E}X_E + \frac{\sigma}{C_P}X_E^{\,2}\right)\frac{P_E}{X_E} \tag{7}$$

By Equations 4 and 7, Equation 8 can be derived.

$$\sigma = \frac{-\varepsilon_{D_E}}{1 - \dfrac{X_E P_E}{X_E P_E + X_A P_A}} \quad or \quad \sigma = \frac{-\varepsilon_{D_E}}{1-\theta}, \ where \quad \theta = \frac{X_E P_E}{X_E P_E + X_A P_A} \tag{8}$$

Equation 8 can be further simplified at equilibrium, as firms in this state will be indifferent between emitting and abating, making P_E equal to P_A. This reduces the relationship further to the final form shown in Equation 9.

$$\sigma = \frac{-\varepsilon_{D_E}}{1 - \%Emitted} = \frac{-\varepsilon_{D_E}}{\%Abated} \qquad \text{(fuel-related emissions)} \tag{9}$$

From this, we see that for fuel related emissions, the elasticity of substitution can be estimated if the price elasticity of demand for emission and the initial percentage of total pollution abated can be determined. For non-fuel emissions, the relationship is similar except that we substitute between pollution emitted and other conventional inputs, instead of substituting between pollution abated and pollution emitted. Since the cost of conventional inputs will usually be much larger than the policy cost for pollution emitted, the value share for emitting for non-fuel related pollution is very small and for practical purposes can be neglected. The elasticity of substitution is therefore just the inverse of the price elasticity of demand for emitting:

$$\sigma = -\varepsilon_{D_E} \qquad \text{(non-fuel-related emissions)} \tag{10}$$

To benchmark the elasticities of substitution and percent of pollution abated in our model for the base year 2004, we use technology cost and emission data generated by the baseline scenario of the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model which contains rich technological detail of abatement opportunities and costs (Nguyen *et al*., 2011). We then map the data generated by GAINS into the corresponding regions and sectors in EPPA. An example of the log-linear regression of Equation 2 for abatement opportunities identified by GAINS for reduction of SO_2 from coal consumption used in electricity production in China is shown in **Figure 5**.

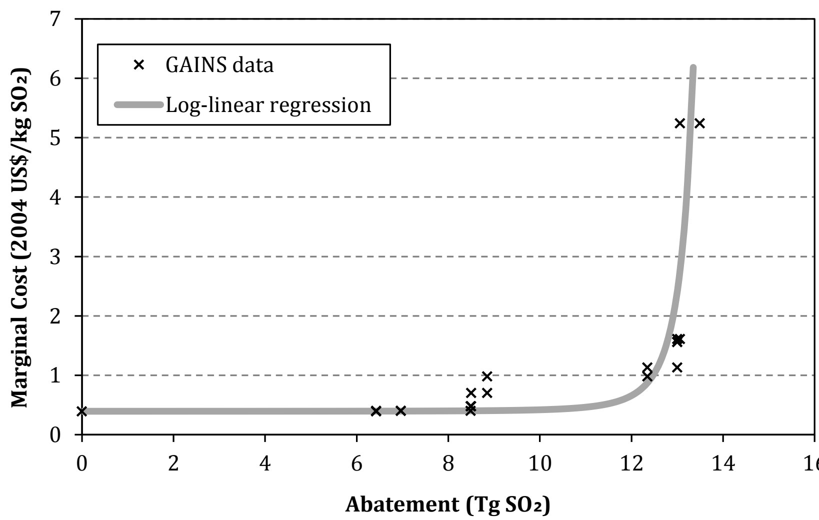


Figure 5. Estimated MAC curve for SO_2 from coal used in electricity production in China.

In the graph, the marginal cost per kg of SO_2 abated is given in 2004 US$ which corresponds to the base year of EPPA5. According to GAINS, in 2005 15.61 Tg of SO_2 was emitted from coal used in electricity production in China. Of the 15.61 Tg emitted, GAINS identified abatement opportunities from the available technologies for 13.49 Tg SO_2, or 86% of current emissions. From the Poisson regression we find the value of the intercept parameter, P_0, that optimizes the correlation coefficient to be $0.395 (2004 US$/kg SO_2). This corresponds to an R^2 of 0.9975, giving a very good fit to the GAINS data. The full set of estimated parameters used to represent abatement costs of SO_2 and NO_x in our model are given in the Appendix.

4. SIMULATION AND RESULTS

We develop a baseline and multiple policy scenarios for the period between 2015 and 2050 for SO_2, NO_x, and CO_2 emissions. Policy scenarios begin with the targets currently announced under the Twelfth FYP. We simulate these policies in the model and discuss the magnitude of the climate co-benefits achieved as well as the implications for sectoral energy use, electricity demand, technology, and welfare.

4.1 Policy Scenarios

To evaluate the potential co-benefits of air quality controls for carbon emissions reduction, we structure our analysis using one reference and seven policy scenarios (**Table 2**). The *REFERENCE* scenario is a business-as-usual scenario, which assumes that no further pollution or climate controls are imposed to reduce the SO_2, NO_x, and CO_2 emission levels expected under existing regulations.

Table 2. Reference and policy scenarios

Scenario	Brief Description
REFERENCE	• *Business-as-usual* scenario. • No policy constraints on SO_2, NO_x, and CO_2 emissions are imposed.
POLL_STR1	• *Pollution-control-only* scenario under the *STR1* reduction schedule. • SO_2 and NO_x meet the 12th FYP goals for 2015 and continue a linear decline by 8% and 10%, respectively, every five years through 2050.
POLL_STR2	• *Pollution-control-only* scenario under the *STR2* reduction schedule. • Ensures the same amount of accumulated SO_2 and NO_x emission reductions as POLL_STR1 does, but avoids early lock-in of investment in higher polluting technologies through pollution banking.
POLL_MOD	• *Pollution-control-only* scenario under the *MOD* reduction schedule. • SO_2 and NO_x meet the 12th FYP goals for 2015 and their emission caps are held constant through 2050.
CLIMATE	• *Climate-control-only* scenario. • Enforces a 17% reduction of CO_2 intensity every five years through 2050.
BOTH_STR1	• *Pollution-climate-control-together* scenario • Enforces POLL_STR1 and CLIMATE policy constraints at the same time.
BOTH_STR2	• *Pollution-climate-control-together* scenario. • Enforces POLL_STR2 and CLIMATE policy constraints at the same time.
BOTH_MOD	• *Pollution-climate-control-together* scenario. • Enforces POLL_MOD and CLIMATE policy constraints at the same time.

Three out of the seven policy scenarios are pollution-control-only scenarios (indicated by the abbreviation *POLL*). *POLL_STR1* places a "stringent" hard cap on SO_2 and NO_x emissions that requires 8% and 10% reductions of each pollutant, respectively, every five years through 2050, following the reduction trajectory established in the Twelfth FYP. *POLL_STR2* achieves the same cumulative reductions in SO_2 and NO_x emissions as in *POLL_STR1*, but requires more stringent reductions in earlier periods and allows more emissions in later periods. This scenario simulates *forward-looking* behavior by recognizing that the economic agents optimizing over time would make different infrastructure and technology choices in earlier periods in anticipation of a large and costly future emissions reduction burden. *POLL_MOD* enforces more "moderate" policy targets than *POLL_STR1* and *POLL_STR2* by imposing post-2015 SO_2 and NO_x emissions caps fixed at their 2015 levels through 2050.

The fourth policy scenario *CLIMATE* constrains CO_2 emissions only, without enforcing emission caps on SO_2 or NO_x. For this scenario, we extend China's climate control targets, as specified in the Twelfth FYP and announced in the Copenhagen Summit, and apply a 17% reduction of CO_2 intensity every five years out to 2050. The other three policy scenarios, whose titles begin with *BOTH*, constrain both pollution and climate control targets by combining one of the three pollution-control-only scenarios with the CO_2-control-only scenario. For example, *BOTH_STR1* enforces the SO_2 and NO_x emission caps, described in *POLL_STR1*, and the CO_2 emissions caps in *CLIMATE* at the same time.

With the existing statistics and the given assumptions for each scenario, we construct the SO_2, NO_x, and CO_2 emissions reduction schedules by case, as shown in **Table 3**. Baseline air pollutant emissions inventories for EPPA5 are obtained by aggregating emission from the EDGAR-HTAP v1 dataset into EPPA5 regions and sectors (Waugh *et al*., 2011). However, there exists a substantial discrepancy between China's baseline SO_2 and NO_x emission levels for 2010, used in this study, and Chinese official estimates reported by the MEP. In the case of SO_2 emissions, this difference for 2010 is over 100%. For the purposes of this analysis, we use the estimates given in the EDGAR database rather than the MEP estimates, as the latter are consistently lower when compared with estimates by many other independent research teams (Nielsen and Ho, 2007). For example, Lu *et al*. (2010) found the 2000–2008 SO_2 emission estimates reported by the MEP were biased downward by 10 to 30% when compared with their estimates. Similarly, Lin *et al*. (2010) arrive at estimates of China's 2006 NO_x emissions, which are 40% higher than comparable numbers from the MEP.

The NO_x and SO_2 policy targets displayed in Table 3 reflect reductions that are quite significant relative to baseline levels but are necessary to address the substantial health and environmental externalities these pollutants impose (**Figure 6**). The 2050 emissions cap for SO_2 in *STR1* (26.1 mmt) is comparable with China's 2003 (23.4 mmt) or 2004 emissions level (27.3 mmt) and is close to the level of emissions reported in the United States in 1985 (25.7 mmt) (EPA, 2012). Similarly, the 2050 NO_x emission cap in *STR1* (10.8 mmt) is no more stringent than 10.7 mmt, China's 1994 level. China's high dependence on coal for electricity generation and industrial use means that compliance will be quite costly but will also carry important and substantial economic benefits. Previous studies have quantified the health effects from China's air pollution. In 2005, for example, anthropogenic PM_{10} concentrations in China, whose primary contributors include NO_x and SO_2 emissions, caused around 3 million cases of premature deaths and over 8 million cases of non-fatal diseases, valued at around 4% of the national consumption level (Matus *et al*., 2012).

Table 3. Annual emission caps by case (mmt), 2015–2050.

	SO_2				NO_x				CO_2	
	BASE	**STR1**	**STR2**	**MOD**	**BASE**	**STR1**	**STR2**	**MOD**	**BASE**	**POL**
2010	50.8	-	-	-	25.1	-	-	-	7,025	-
2015	71.3	46.8	44.5	46.8	33.6	22.6	21.3	22.6	9,516	8,734
2020	97.2	43.0	40.0	46.8	43.8	20.3	18.6	22.6	12,030	9,635
2025	126.5	39.6	36.8	46.8	54.6	18.3	16.8	22.6	14,426	10,981
2030	160.0	36.4	34.8	46.8	66.2	16.4	15.6	22.6	16,747	12,001
2035	199.3	33.5	33.6	46.8	79.0	14.8	14.9	22.6	18,962	12,269
2040	237.6	30.8	32.9	46.8	90.3	13.3	14.5	22.6	20,569	12,110
2045	281.0	28.4	32.6	46.8	102.4	12.0	14.3	22.6	22,026	11,846
2050	331.4	26.1	32.5	46.8	115.7	10.8	14.2	22.6	23,343	11,496

BASE: Baseline case; STR1: Stringent case 1; STR2: Stringent case 2; MOD: Moderate case; POL: Policy case.

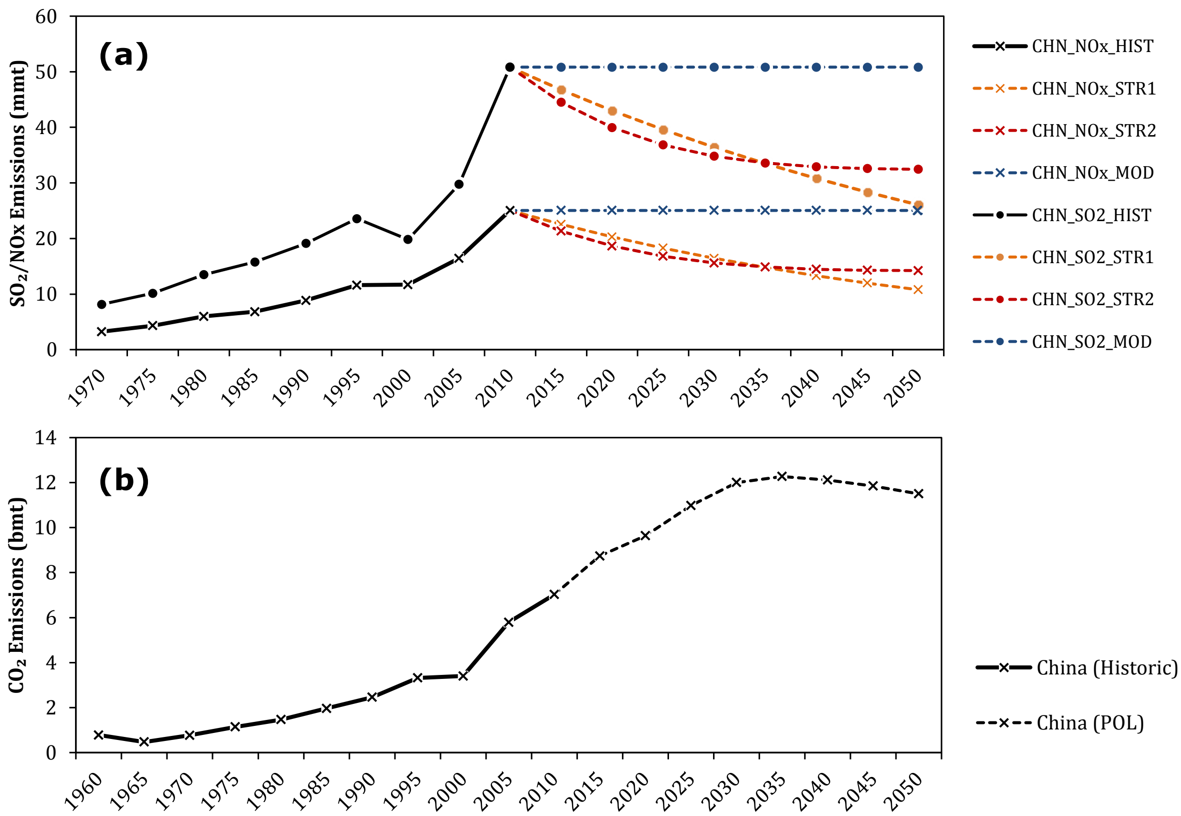


Figure 6. China's proposed emission schedules, extended from its historic levels, 1960–2050: **(a)** SO_2 and NO_x, **(b)** CO_2. Source: Historic SO_2 and NO_x data from van Aardenne *et al*. (2009); Historic CO_2 data from World Bank (2012).

4.2 Simulation Results

In this section we introduce our central simulation results by topic. We focus on quantifying climate co-benefits, changes in industrial output, and changes in the composition of the electricity generation mix.

4.2.1 Climate Co-benefit from SO_2 and NO_x Control

We evaluate the co-benefits of pollutant regulation both in terms of reduced economic welfare and reduced CO_2 emissions. Reduced compliance costs are computed by comparing emissions and costs when pollution and climate policies are implemented together relative to an approach in which each policy is modeled separately and the impact is added. We use the difference in the level of consumption as a measure of economic welfare, expressed as equivalent variation under each policy scenario relative to reference in constant 2004 U.S. dollars. The reduced CO_2 emissions are drawn from the comparison of baseline CO_2 emission levels and CO_2 emissions simulated under the pollution-control-only scenarios.

Our simulation results show that climate co-benefits of pollution control can be substantial. Under the *STR1* targets, the magnitude of consumption loss is estimated to increase from $3 billion in 2015 (0.1% of the reference consumption level) to $586 billion in 2050 (5.1% of the reference consumption level) (**Figure 7**).[3] Co-benefits under the *STR2* or *MOD* targets are exactly the same as that under the *STR1* targets, in absolute terms, as the CO_2 emission reduction targets, specified in the *CLIMATE* scenario, are automatically achieved by complying with any of the *POLL_STR1*, *POLL_STR2*, and *POLL_MOD* emissions caps (**Figure 8**). In other words, in the *STR1*, *STR2*, or *MOD* cases, the co-benefits, measured as avoided consumption loss, equal the entire portion of the compliance costs required to meet the *CLIMATE* targets. When measured in terms of CO_2 emissions reductions, the co-benefit under the *POLL_STR1* and *POLL_STR2* scenarios ranges between 1.5 bmt in 2015 and 21.5 bmt in 2050, showing an increasing tendency over time. The *POLL_MOD* scenario exhibits a similar magnitude of co-benefits, increasing over time from 1.5 bmt in 2015 to 19.5 bmt in 2050.

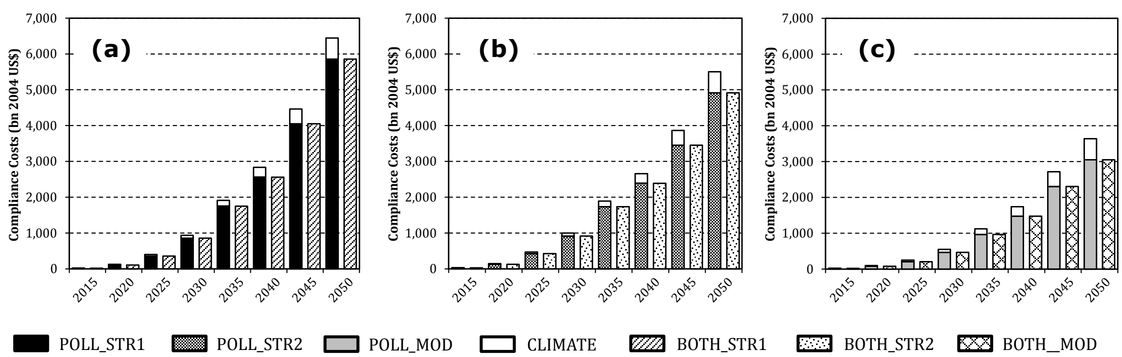


Figure 7. Policy compliance costs: **(a)** Under STR1 targets, **(b)** Under STR2 targets, **(c)** Under MOD targets.

[3] Throughout our study, $ denotes 2004 constant U.S. dollars, unless mentioned otherwise.

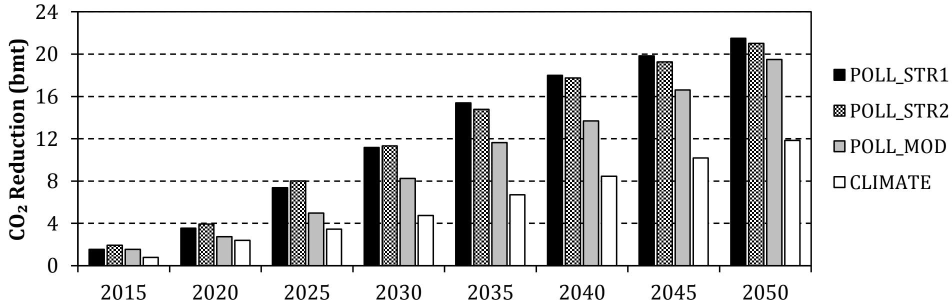


Figure 8. Reduced fossil CO_2 emissions by scenario.

One interesting result is the compliance cost differentials between the *STR1* and *STR2* cases. As briefly mentioned in Section 4.1, the *STR2* schedule ensures the same amount of total cumulative emissions reduction as *STR1* does, but forces economic agents to reduce more emissions today while allowing them to emit more tomorrow, compared with *STR1*. The *STR2* schedule, a strategic inter-temporal redistribution of the pollution reduction targets described in *STR1*, is estimated to save substantial policy compliance costs involved in NO_x and SO_2 emissions control in China. When compared with the *POLL_STR1* case, for example, compliance costs under the *POLL_STR2* scenario slightly increase by \$10 billion to \$70 billion in any given year between 2015 and 2030, but decrease much more significantly (by \$19 billion to \$941 billion) in the years between 2035 and 2050 (**Figure 9**). A simple sum over the periods shows \$5.5 trillion of cumulative compliance-costs savings under *POLL_STR2* during the entire period between 2010 and 2050, if linearity is assumed within each five-year interval. The corresponding net present value (NPV) cumulative savings were \$298 billion, when evaluated in 2010 with a discount rate of 4%.

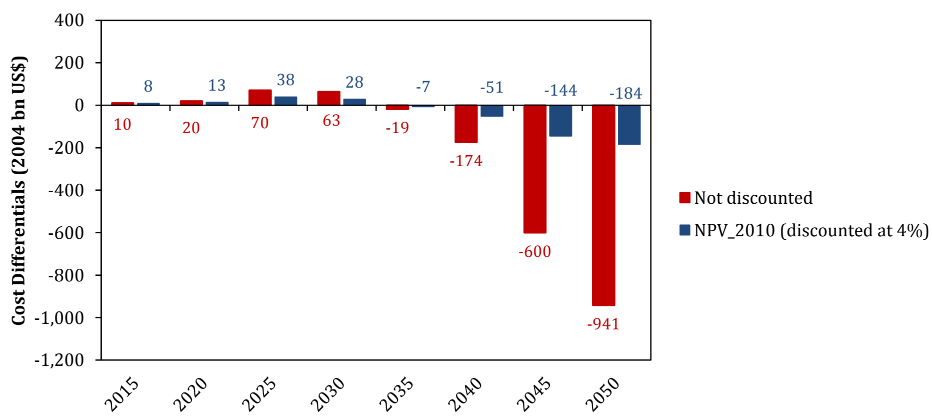


Figure 9. Economy-wide Cost Savings from STR2, Compared with STR1.

This result coincides with our expectation, given that EPPA5, the basic platform of our methodology, is a recursive-dynamic model, where economic agents optimize their decisions in each period only. This myopic behavior may lead to a sub-optimal outcome from a long-term perspective, if there is an external shock to the economy in the future, such as pollution control. In other words, if more stringent regulations are anticipated, economically rational agents may decide against investment in more coal use in the near term, even though adoption of control technology on coal may not cost much at present, because with tightening regulations over time the sunk coal investment makes it more costly to meet the regulations in the long-run. The possibility of such short-sighted (and ultimately inefficient) investment decisions under the recursive dynamic modeling structure can be reduced by reallocating some of the future reduction burden to earlier periods. This is because forcing them to undertake more stringent measures from the outset approximates forward-looking behavior (Gurgel *et al*., 2011).

4.2.2 Impacts on Industrial Production

The pollutant constraints that we model impose costs on the economy and result in reductions in output in most production sectors (**Figure 10**). In particular, proposed pollution control targets penalize energy-producing sectors, such as coal, refined oil, and electricity, and energy-intensive industries[4] more than others in terms of total output. These sectors are all characterized by high emission factors, and their output decrease is driven primarily by a shift toward less-polluting substitute technologies and the high cost or limited availability of abatement technologies. In

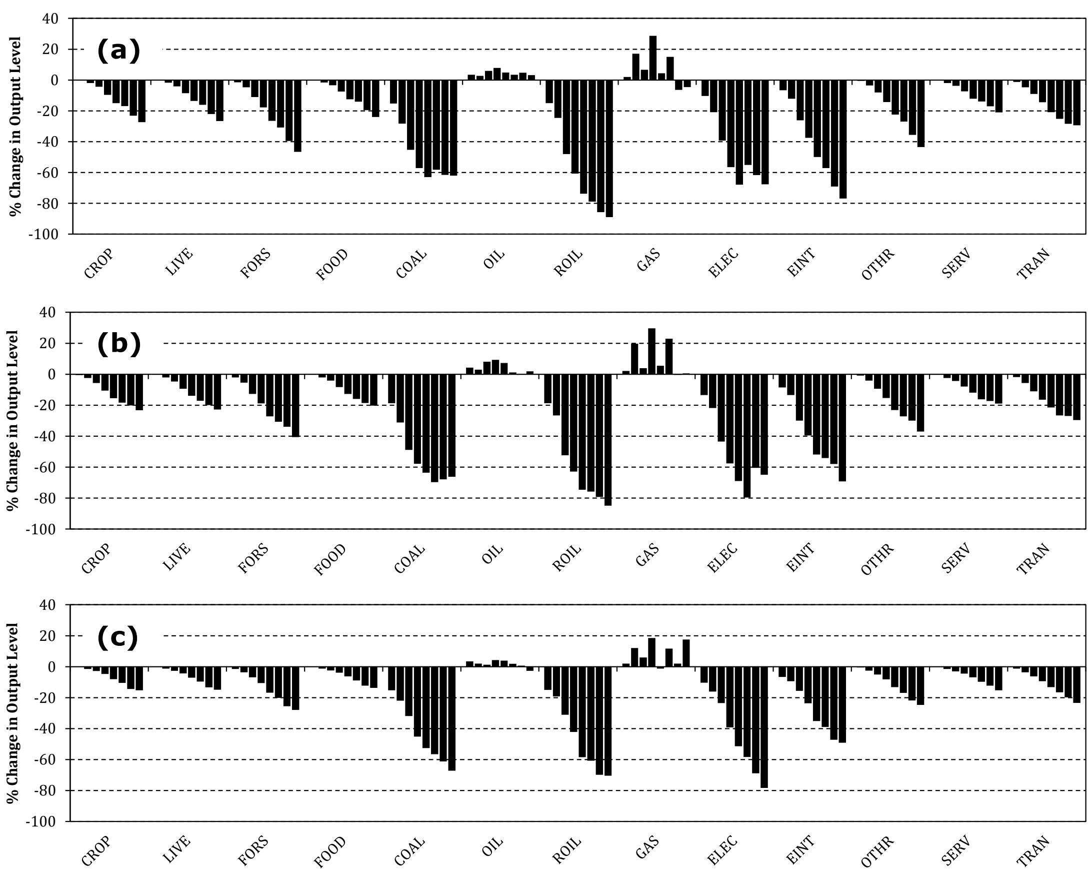


Figure 10. % Change of total output by sector in China, 2015–2050, compared with the reference level: **(a)** POLL_STR1, **(b)** POLL_STR2, **(c)** POLL_MOD.

[4] Energy-intensive industries (EINT) in EPPA include the sectors that produce paper products, chemical products, ferrous and non-ferrous metals, metal products, and mineral products.

contrast, crude oil and gas, which are lower emitting substitutes for such pollution-intensive fuel stocks, see output expand. All of the three pollution-control-only scenarios present a similar picture (i.e. a large output decrease in coal, refined oil, electricity, and energy-intensive sectors, and a modest increase in crude oil and gas production), despite slight differences in the magnitude.

The sectoral contributions to reductions vary across pollutants (**Figure 11**). The energy-intensive industry and power-generation sectors account for a dominant share of the total emissions reductions, due to the large extent of coal use in these sectors. In the case of SO_2 and NO_x, energy-intensive industries contributed most to reductions, followed by the power-

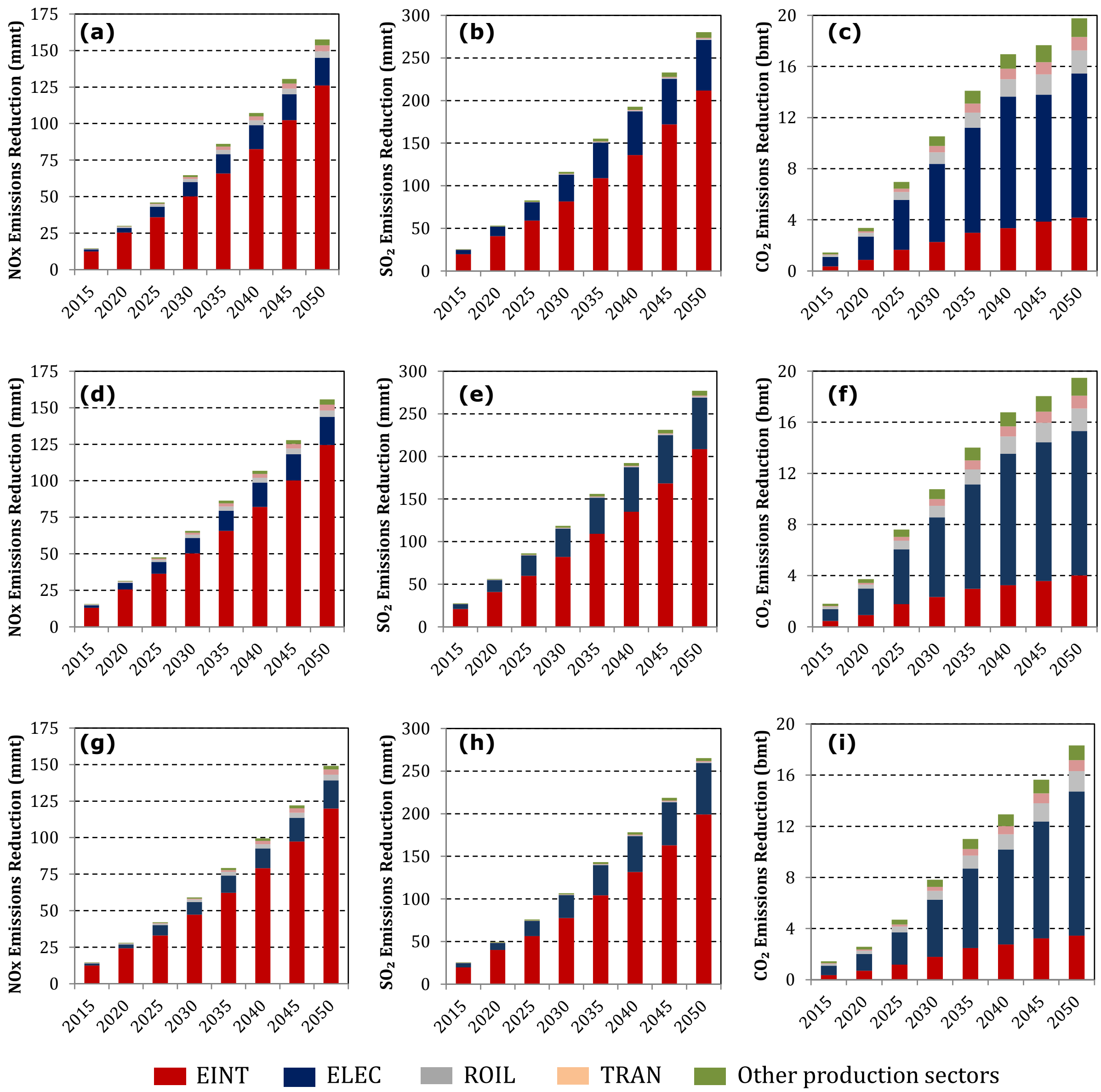


Figure 11. Reduced emissions by sector, 2015–2050: **(a)–(c)** POLL_STR1, **(d)–(f)** POLL_STR2, **(g)–(i)** POLL_MOD.

generation sector. By contrast CO_2 reductions occurred mostly in the power sector. Under the *POLL_STR1* scenario, for example, over 70% of the total NO_x and SO_2 emission cuts are accounted for by the energy-intensive industrial sector, and up to a quarter of them are from the electricity sector. In contrast, over a half of the unintended CO_2 emissions reduction, when the *POLL_STR1* targets are attained, is from the power-generation sector, followed by the energy-intensive industries, which are responsible for around 20% of the total CO_2 reduction. Interestingly, the energy-intensive industries play an important role in pollutant emissions reduction, in contrast to other markets such as the United States where power generation has historically been the main source of NO_x and SO_2 emissions reductions.

4.2.3 Impacts on Electricity Output

The stringent NO_x and SO_2 emission controls have a significant impact on China's electricity output mix, as such restrictions increasingly incentivize the deployment of less SO_2, NO_x, and carbon-intensive generation (**Figure 12**). The stringent pollution targets (*STR1* and *STR2*) displace conventional coal-fired power generation in favor of cleaner alternatives, such as wind power with backup capacity[5] and advanced nuclear.[6] On a short time frame, however, this transition is expected to cause a large supply reduction between 2020 and 2045. This pattern also occurs under the *POLL_MOD* scenario, but its magnitude is much smaller. When only CO_2 emissions reduction targets are enforced under the *CLIMATE* scenario, no such reduction occurs, and instead, a smooth and gradual transition from conventional coal to coal with carbon capture and storage (CCS) takes place.[7]

The primary reason for the large supply reduction under the proposed pollution targets is that the stringency of the pollution control would require capital stock turnover at a rate that exceeds the pace at which old generation can be retired and new, less emissions-intensive technologies can come online. The EPPA model parameterization of the life-cycle of power-generation infrastructure places some limits on the speed of change in the power-generation technology mix or of adopting new technologies, and the transition toward cleaner energy sources is determined largely by the interactions between old power-generation facilities retired from the market and capital available for new construction. This modeling strategy is to reflect the empirical observation that new technologies tend to penetrate the market gradually since local resources or capabilities required for immediate production at competitive costs or rapid market expansion are limited at the beginning (Jacoby *et al*., 2004).

[5] EPPA5 includes two wind-related alternative technology options: wind power supplemented by natural gas (wind-gas) and wind power supplemented by biomass (wind-biomass). The hybrid use of wind and gas/biomass is to allow wind turbines to remain in operation even when wind availability is not sufficient to operate them.

[6] We use the term *advanced nuclear* to refer to generation 3+ nuclear technologies, which are based on reprocessing or breeder-type fuel cycles.

[7] Carbon capture and storage (CCS) is not adopted in the pollution control scenario because, as modeled here, CCS does not reduce SO_2 and NO_x pollution.

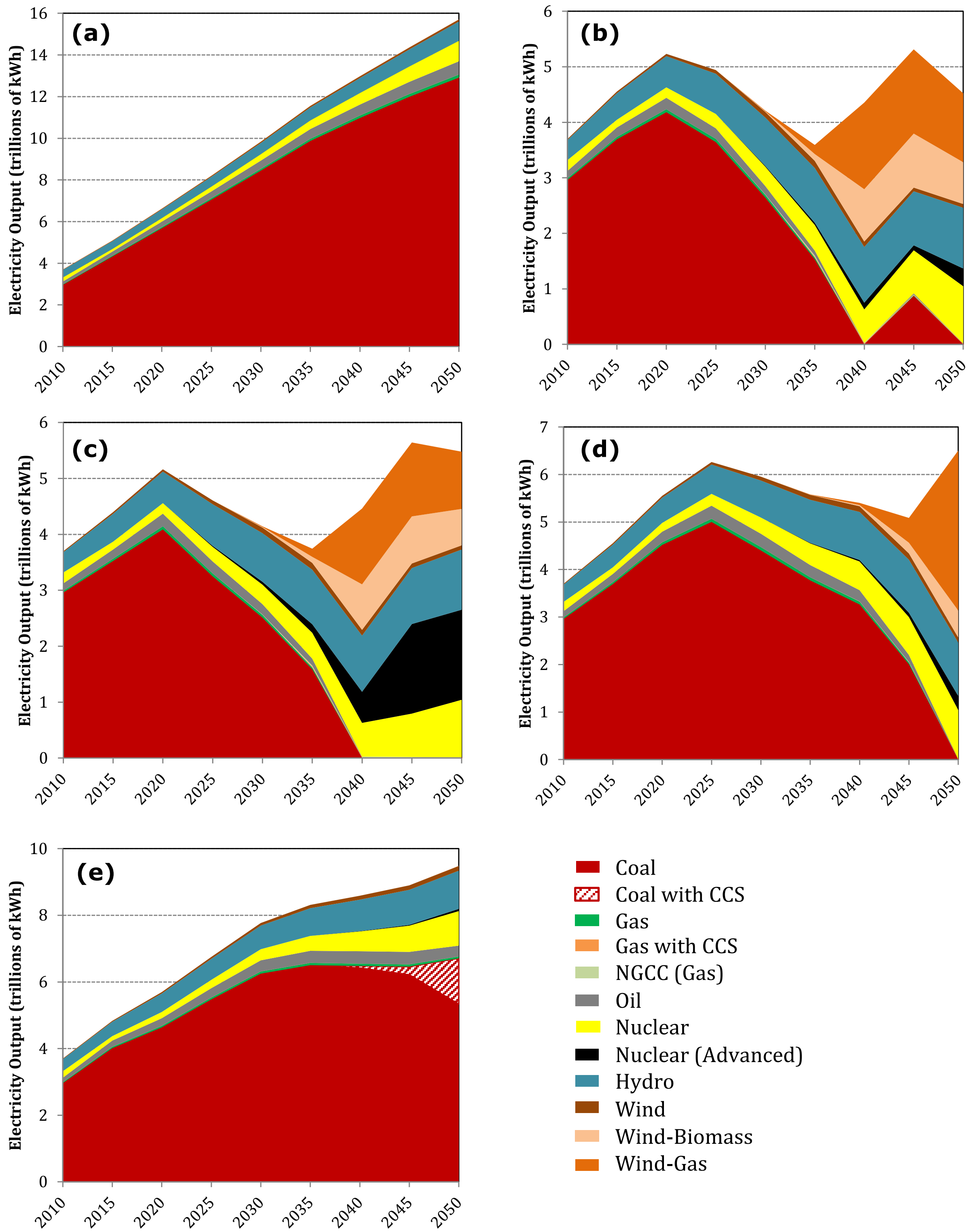


Figure 12. Electricity output mix, 2010–2050: **(a)** REFERENCE, **(b)** POLL_STR1, **(c)** POLL_STR2, **(d)** POLL_MOD, **(e)** CLIMATE.

A comparison of the *POLL_STR1* and *POLL_STR2* cases presents an interesting result. In the *POLL_STR1* case, conventional coal still remains in the market in 2045, while it is completely phased out from 2040 onwards in the *POLL_STR2* case. We trace this peculiar result under *POLL_STR1*—the increase in coal use in 2045 after having disappeared in 2040—to the inability to reduce emissions in the industrial sectors because of the vintage capital structure in 2040, and then greater flexibility in 2045 that allows coal to briefly return in the power sector. This point demonstrates our "early lock-in versus forward-looking investment" hypothesis: early lock-in of capital investment in conventional coal-fired power plants may occur under the *POLL_STR1* case, while it is not as severe under *POLL_STR2*. In other words, assigning more stringent emission caps in earlier periods like *POLL_STR2* simulates economic agents' forward-looking behavior and advances the timing of investment in cleaner energy alternatives to conventional fossil fuel energy sources. This result suggests that if firms have advance notice of the long-term policy target and can plan ahead, they can significantly reduce future costs. Both *POLL_STR1* and *POLL_STR2* are probably unrealistic policy scenarios because China is not likely to impose a policy that requires such a rapid transition of capital stock in a very short time. If sectors saw this trend and planned ahead for it, then the results in *POLL_MOD* would be more realistic.

5. CONCLUSIONS

We investigate the impact of SO_2 and NO_x emission controls in a modeling framework that endogenously represents pollutant abatement opportunities and costs. We find that even the moderate pollutant emissions constraint that we consider achieves CO_2 emissions reductions that exceed China's near term goals. However, to effectively address the air quality and health externalities caused by current pollution, a more stringent policy is needed—and the substantial associated costs can be mitigated if investment decisions early on take into account aggressive long-term reduction goals.

Our analysis illustrates that pollutant emissions constraints are likely to achieve reductions in CO_2 that exceed China's current commitments by a significant margin. The current target of a 40 to 45% reduction in CO_2 intensity below 2005 levels by 2020, and its extension beyond 2020, is by many measures not a very stringent policy goal. It allows CO_2 emissions to continue increasing, and according to many projections, would result from business-as-usual efficiency improvements not unlike trends observed in other parts of the world. Large cuts in China's CO_2 and other greenhouse gas emissions are needed over the long term in order to achieve atmospheric concentrations consistent with long-term global climate stabilization. We estimate that if China achieves the SO_2 and NO_x emission reduction targets proposed in its Twelfth FYP, the associated climate co-benefit will reach \$3 billion, in terms of saved compliance costs, or 1.4 bmt of ancillary CO_2 emission reductions in 2015 alone. However, all three of our SO_2 and NO_x control scenarios suggest that existing CO_2 emissions controls are completely redundant. Several of the cost-effective abatement opportunities pursued under the SO_2 and NO_x policy, particularly fuel switching in electric power and to a lesser extent efficiencies realized in energy-intensive industries, achieve CO_2 emissions reductions well in excess of those targeted by a policy that achieves a 17% reduction in CO_2 emissions intensity every five years. For example, complying with the SO_2 and NO_x reduction targets in the Twelfth FYP will lead to a 20% reduction of China's economy-wide CO_2 intensity (or a 13% increase of CO_2 emissions) between 2010 and 2015. Under the SO_2 and NO_x regulations, thus the CO_2 control target in the same plan, aiming at a 17% intensity reduction (or a 14% emission increase), will not bind.

Our sectoral analysis shows that China's proposed SO_2 and NO_x emission targets will be achieved primarily at the expense of energy-intensive industries and the electric power sector. In particular, under the stringent SO_2 and NO_x emission reduction targets, China is projected to experience a large supply reduction in its domestic electricity market between 2020 and 2040. This is primarily because the phase-in of new advanced technologies needed to comply with an ever more stringent policy cannot proceed fast enough to fill the gap left by the phase-out of coal-fired power plants. Available abatement technologies for coal are not sufficient or not cost effective to meet the increasingly stringent target in the post-2020 time frame. Among the various backstop technologies, we find that wind-gas, wind-biomass, and advanced nuclear are the most cost-effective options to replace conventional coal-fired power generation, but the contribution of each depends on its relative costs.

Finally, our results argue for policy measures that set forth clear long-term reduction goals, thereby discouraging the installation of new generation or incremental control technology that will be incapable of meeting an increasingly stringent target. Meeting the stringent pollution constraint we model here—which is consistent with China's human health and environmental goals—will require substantial reductions in coal use in electricity and energy-intensive industries. If postponed to later periods through temporary fixes, reductions will prove extremely costly. Specifically, we find that China's economy is expected to benefit from substantially reduced policy compliance costs under a reduction schedule that requires early action. This result underscores the importance of designing policy to incentivize forward-looking behavior—for instance, through banking-and-borrowing provisions—to avoid high costs in later periods.

Acknowledgments

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APPENDIX

Table A. Parameters used to benchmark SO_2 abatement opportunities for China in EPPA.

Sector	Fuel	Poll. (Tg)	Emis. (Tg)	Abate. (Tg)	Init. Price ($/kg)	ε_D	θ	σ	α	β	R^2
ELEC	COAL	24.14	15.61	8.53	0.40	-0.25	0.65	0.71	30.03	-4.01	0.99
ELEC	OIL	0.03	0.03	0.00	1.88	-0.14	1.00	2.85	11.96	-7.02	0.88
ELEC	ROIL	0.00	0.00	0.00	4.48	-0.13	0.46	0.24	-36.16	-7.88	1.00
EINT	COAL	20.33	9.64	10.70	0.48	-0.45	0.47	0.85	19.68	-2.23	0.87
EINT	OIL	0.43	0.41	0.02	3.23	-0.13	1.00	2.53	35.93	-7.90	1.00
EINT	ROIL	0.12	0.11	0.01	1.51	-0.62	1.00	12.42	6.38	-1.61	1.00
EINT	PROCESS	6.77	2.90	3.87	0.22	-0.15	0.43	0.15	49.25	-6.88	0.91
TRAN	ROIL	0.40	0.36	0.04	1.96	-1.18	0.90	12.20	5.68	-0.85	0.80
FORS	PROCESS	0.14	0.13	0.01	0.39	-0.31	0.95	0.31	11.06	-3.27	1.00
OIL	PROCESS	0.20	0.15	0.05	0.16	-0.06	0.75	0.06	67.23	-17.70	0.93
FD	COAL	1.63	1.54	0.08	0.44	-0.13	1.00	2.56	50.91	-7.82	1.00

Table B. Parameters used to benchmark NO_x abatement opportunities for China in EPPA.

Sector	Fuel	Poll. (Tg)	Emis. (Tg)	Abate. (Tg)	Init. Price ($/kg)	ε_D	θ	σ	α	β	R^2
ELEC	COAL	5.58	4.52	1.07	0.12	-0.35	0.81	1.85	21.48	-2.82	0.59
ELEC	OIL	0.02	0.02	0.00	0.05	-0.29	1.00	5.82	7.30	-3.44	0.94
ELEC	ROIL	0.00	0.00	0.00	0.53	-0.13	1.00	2.54	-38.29	-7.88	1.00
ELEC	GAS	0.02	0.02	0.00	0.55	-0.13	1.00	2.54	14.73	-7.88	1.00
EINT	COAL	4.61	4.38	0.23	0.13	-0.26	1.00	5.21	30.11	-3.84	0.98
EINT	OIL	0.23	0.22	0.01	0.06	-0.29	1.00	5.81	15.75	-3.44	0.99
EINT	ROIL	0.22	0.21	0.01	0.15	-0.04	1.00	0.71	129.99	-28.23	0.72
EINT	GAS	0.07	0.06	0.00	0.09	-0.27	1.00	5.38	12.61	-3.71	1.00
EINT	BOIL	0.07	0.06	0.00	0.39	-0.13	1.00	2.54	24.90	-7.88	1.00
EINT	PROCESS	24.71	2.52	22.20	0.15	-0.14	0.10	0.14	48.49	-7.33	0.97
OIL	PROCESS	0.07	0.06	0.00	0.35	-0.07	1.00	0.07	44.26	-15.17	0.93
FD	ROIL	0.01	0.01	0.00	8.84	-0.26	1.00	5.11	9.77	-3.92	0.97
FD	GAS	0.01	0.01	0.00	4.92	-0.29	1.00	5.71	9.36	-3.50	1.00

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