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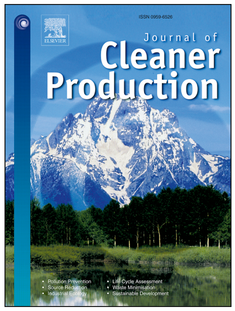

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Exploring the Potential of Introducing Technology Innovation and Regulations in the Energy Sector in China: A Regional Dynamic Evaluation Model

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Abstract

The Chinese government has introduced stricter environmental regulations to address the rapid increase in GHG emissions and environmental deterioration associated with energy demand. In this research we analyze the potential environmental and socio-economic benefits of introducing such regulations coupled with the promotion of advanced technological innovation for power generation. We selected Chongqing city, one of the most polluted cities in China, as the case study. The study proposes 5 scenarios that range from baseline to technology promotion through the introduction of carbon tax and subsidy schemes and the implementation of regulations for regional air emissions reduction. We constructed a dynamic evaluation model based on an Input-Output (I/O) analysis for the period 2010-2025. The results show an overall benefit on the quality of the environment and energy conservation efforts. The study demonstrates that the introduction of regulations without promotion of technological innovation will dramatically affect economic growth. The results also show that innovations in the energy sector alone will reduce both air pollutants and energy intensity to a certain extent. In this regard the promotion of innovation in other economic sectors is necessary. Another important finding is the fact that the introduction of regulations will actually curb air emissions and energy consumption. This research provides a strong platform for policy makers to realize the urgency and importance of promoting technology innovation through environmental regulations.

Keywords: environmental regulation; cleaner power technology; air pollution, GHG emissions, technology innovation, energy conservation

1. Introduction

China quadrupled its GDP while only doubling its energy consumption in the last two decades of the 20th century effectively doubling its energy efficiency. However this trend started to change from the late 1990's and it was attributed to the rapid growth in power demand and an increase in energy intensive sectors especially steel, cement and chemicals (Hara et al., 2011). Due to rapid energy demand growth China overtook the USA as the largest emitter of CO_2 in 2007 accounting for 21.7% of the global emission (UNSTAT, 2010). Obviously the current trends in energy supply and demand in China are far from sustainable. The high reliance on coal to meet the increasing energy demand has triggered not only a rapid increase in GHG emissions but also led to deterioration in the quality of the environment in many parts of the country.

The electricity supply sector is one of the main sources of CO_2 emissions. Power generation in China relies heavily on coal as the primary energy fuel accounting for 79% of supply and the electricity sector accounts for more than 44% of the total CO_2 emissions (Baron et al., 2012). In addition to the large CO_2 emissions coal-based power generation is also associated with air pollution and health damage (see Kanada et al., 2013; Liu and Wen, 2012 for details). Chinese Academy of Environmental Planning, which is part of the Ministry of Environmental Protection, reported that the cost of environmental degradation in China was about 230×10^9 USD in 2010, or 3.5 percent of the nation's GDP (NYTAP, 2013). To address these challenges the Chinese government has placed special emphasis on promoting energy efficiency and improving energy intensity by boosting cleaner technologies.

The decrease of the quality of the environment has caused discomfort in many parts of China. Chongqing is one of the most affected cities in this regard. The reason for major air pollution in the city is the use of high sulphur and ash content coal as the main fuel. In fact the proportion of coal in total energy utilization reached 70% in 2010 (BSC, 2011). Chongqing city is one of the Acid Rain Control Zones designated by the Chinese Central Government. The main factors responsible for acid rain are SO_2 and NO_x emissions due to utilization of low quality coal in the power sector combined with the lack of emission control systems (Zhou et al., 2013).

Technology development and innovation play a central role in reducing GHG and pollutant emissions by promoting renewable and cleaner fossil fuels (Hascic et al, 2009; Cravinho Martins et al., 2011; Liu and Liang, 2013; Shi and Lai, 2013). However, due to the existence of externalities, effective policies and regulations are necessary to induce environmental innovations (Popp et al, 2006; Yabar et al, 2013). Various studies have addressed the issue of the impact of regulations on GHG and pollutant emissions in China. Liu et al. (2009) employed a bottom-up model to analyze the impact of new energy technologies under China's GHG mitigation scenario and found that high-efficiency coal power and nuclear power will have a positive impact in the short term only. Wang and Nakata (2009) explored the policy potential of carbon tax/subsidy for promoting clean coal technologies in the Chinese electricity sector and found that such policies can actually shift China's electricity structure in the mid-term. These and other studies have addressed this issue at a national level but, as we know, China is a vast country with regional disparities and national-level policies need to be adapted to incorporate regional characteristics before their implementation. In addition, many of the previous studies have used a bottom-up approach that assessed regulations and technology innovation in the power sector only, ignoring the interrelationships of different economic activities (industrial sectors, household and government) and the state of national economy-energy-environment system. A regional top-down model takes into consideration the inner interrelationships between these sectors resulting in a comprehensive understanding of the mechanisms of regulation and technology innovation. Therefore, in this study we focus on a regional level and utilize a dynamic model that can simulate the interrelationships between different sectors and comprehensively evaluate the effectiveness of the proposed policy. Tools such as input-output (I/O) and Computable General Equilibrium (CGE) are widely used to analyze government policies (see for instance Shoven et al., 1992; Wiedmann et al., 2007). In theory CGE models could reduce the shortcomings of I/O models because they more realistically represent relationships in the economy and thus more accurately project the impact of a new activity on the whole economy (Berck et al., 2002). However data requirements for CGE models are enormous requiring the same type of data as I/O models and much more (Cansino et al., 2014). Although the complex parameters (such as prices for every good, every service, consumption patterns, inter-industry purchasing and so on) included in the CGE model significantly improve the model's ability to adapt to exogenous changes in the economy, it also substantially increases the data requirements (Charney et al., 2003). That is why CGE models are mostly applied at national level studies. In the case of China, for instance Dai et al. (2011 and 2012) employ a CGE model to study China's future energy policy and in the model they consider the industrial structures and the change in socio-economic conditions over time. In studies like this it is easier to obtain data such as input-output tables, future population forecasts, etc. For regional studies, on the other hand, much of the data for CGE models are not regularly collected. For a regional area such as Chongqing, since the forecasting data is difficult to obtain and the uncertainties are much higher than the national data (for example, population projections) it is more practical to use I/O model. Additionally, this study uses Chongqing's latest I/O table available (2010) to forecast socio economic and environmental indicators for the period 2010-2025 (the short time period of study and latest data can improve the accuracy of forecast indicator as the industrial structure and many socio-economic conditions change in the time horizon).

The purpose of this paper is to estimate the socio-economic and environmental impacts derived from a policy of regional regulation and promotion of advanced technological innovation in the energy sector by means of a carbon tax/subsidy system through a regional dynamic input output model. Simulation results allow policy makers and the public to understand the potential for air pollution and GHG emission reduction and the necessity for technology innovation in other sectors. The study suggests that introducing more flexible regional regulations combined with promotion of technology innovation in the energy sector will likely maintain a moderate economic growth and promote energy conservation and pollution reduction. This research also contributes to improving public policy design for implementing air emissions reduction policies that can guarantee a sustainable economic development.

The rest of the paper is organized as follows. Section 2 introduces the potential of fossil fuel energy technology options in the future. The model framework including mathematical equations in the dynamic I/O model and scenarios description is illustrated in section 3; and the main results as well as discussion are presented in section 4. Finally, the conclusion and policy implications are presented in section 5.

2. Global Trends in Power Generation: Coal Dependency and the Role of Cleaner Technologies

Coal is the world's most abundant and widely available fossil fuel, with proven reserves reaching nearly 1 trillion tons (IEA, 2010a). Given these characteristics, coal has been a key component of the electricity generation mix worldwide supplying more than 40% of the world's electricity (IEA, 2010a). Moreover, since the energy needs of the developing world will continue growing coal will remain an important component of the power generation mix in the future (IEA, 2010a; IEA, 2010b).

Efficiency is a very important performance parameter in coal-fired power generation because it provides benefits such as (IEA, 2011b):

- CO_2 emission reduction where 1% overall efficiency improvement can reach up to 3% CO_2 emissions reduction;
- conventional pollution emission reduction; and
- Resource conservation.

Chinese energy supply relies heavily on coal as the primary energy fuel. Sub-critical technology (SUB), which is less energy efficient and more polluting, accounts for more than 70% of the coal power generation in China (Platts, 2011). Recently advanced coal power generation technologies including super critical (SUP) and ultra super critical (USC) have received special attention due to their high energy efficiency and low emissions. Integrated Gasification Combined Cycle (IGCC) has also gained popularity due to its high efficiency and low carbon emissions characteristics. In addition to power generation from cleaner fossil fuels, Carbon Capture and Storage (CCS) is gaining attention in recent years. CCS is a series of technologies and techniques that capture CO_2 from combustion or industrial processes, then transports it via pipelines or ships and finally stores it underground. Some studies suggest that CCS will be a key option to cut CO_2 emissions in the mid to long term accomplishing up to one sixth of the CO_2 emissions reduction in 2050 and 14% of the cumulative emissions reductions between 2015 and 2050 (IEA, 2013).

The main alternatives to improve both energy efficiency and reduce emissions based on fossil fuel power generation are summarized in Table 1 and their characteristics are shown in Table 2 and 3.

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3. Methodology

This study combines both scenario design and dynamic I/O analysis to forecast economic growth trends, energy demand and intensity as well GHG and air pollutant emissions in Chongqing for the period 2010 to 2025. The economic I/O analysis, developed by W.W. Leontief, studies the relationship between economic sectors (Leontief, 1941, 1986). From the 1970s to the present many authors have investigated extensions of the I/O model for environmental issues (e.g. Wright, 1974; Bullard III and Herendeen, 1975; Wilting, 1996; Cruz, 2002; Miller and Blair, 2009). In this study, the main aim of the I/O energy analysis is not only the calculation of energy intensity but also energy related air emissions (GHG, SO_2, NO_x, PM_{10}, $PM_{2.5}$) and to monitor the technology innovation trends in the power sector. At the Copenhagen Climate Summit in 2009, China committed to decrease its CO_2 emissions per unit of GDP by 40%-45% by 2020. In this regard an I/O based environmental model can support stakeholders to monitor their emission trends and to evaluate the effectiveness of proposed environmental policies.

3.1 Scheme of the Simulation Model

The simulation model is composed of 3 sub-models (socio-economic, air emissions and energy demand-supply models) and one objective function (Figure 1). Chongqing's social and economic activities as of 2010 provide the simulation base and reflect real social and economic development. Three economic agents (industry, household, government) were assumed in this research.

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Figure 2 shows the commodity, air pollutant and GHG and carbon tax/subsidy flow between economic agents. Based on the relationship between economic agents, we designed a comprehensive evaluation model. The dynamic simulation model is constructed based on three viewpoints of value flow balance, energy flow balance, and commodity flow balance, which are necessary for comprehensive environmental evaluation. In this model, all the economic entities can be divided into two groups: industry and final demand.

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As shown in Table 4, there are four main industries in the model. Each industry contains several sectors. We calculated the input coefficients between economic agents based on the "2010 Input-Output table of Chongqing" (BSC, 2011).

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3.2 Design of the Simulation Model

In the simulation model, variables are divided into endogenous (en) and exogenous (ex). The exogenous parameters are calculated based on current data; the endogenous variables will be determined by the model structure. The research period is 15 years, from 2010 to 2025.

3.2.1 Objective function

The objective function of this model is to maximize the sum of discounted GDP from 2010 to 2025, subject to all the constraints. They can be formulated as:

$$Max\sum_{t=1}^{11}\left(\frac{1}{1+\rho}\right)^{t-1} GRP(t) \qquad (\rho = 0.05) \tag{1}$$

$$GRP(t) = \sum_{1}^{4} V_i X_i(t) \tag{2}$$

Where, *GRP (t)* is the gross regional product in term t (en), $X_i(t)$ is the production of each industry *i* in term t (en) and ρ is the social discount rate. V_i is the value-added rate of industry i (ex). The objective function is subject to the following constraints. Subscript *i* are the industries shown in table 4.

3.2.2 Energy consumption and energy intensity

The energy consumption in this model is defined by 7 energy carriers mainly used in Chongqing (Coal, Coke, Gasoline, Kerosene, Diesel Oil, and Natural Gas) and secondary energy electricity. All the energy units are unified as tons of coal equivalents (TCE). Industry energy consumption and household consumption amount in the base year is calculated based on (BSC, 2011).

$$ED(t) = \sum_{1}^{4} ED_i(t) + ED_c(t) \tag{3}$$

Where *ED(t)* is the total primary energy consumption in term t *(en)* and $ED_c(t)$ is a column vector with 7 elements (7 kinds of energy) $ED_i\ (t)$ is industry energy consumption (en). $ED_c(t)$ is household energy consumption *(en)*.

Total energy consumption *TED(t)* is the summary of 7 elements in *ED(t)*. Therefore, energy intensity in term t ($E_{intensity}$(t), en) will be identified through the formula $E_{intensity}$ (t)=*TED(t)/GPR(t)*, which is an effective index to evaluate the effectiveness of technology innovation and environment regulation.

3.2.3 Secondary Energy: Electricity Flow Balance

$$S(t) = D(t) \tag{4}$$

$$S(t) = S_h + S_{sub}(t) + S_{sc}(t) + S_{usc}(t) + S_c(t) + S_{cs}(t) + S_n(t) + S_{ns}(t) \tag{5}$$

$$D(t) = \sum_{1}^{4} D_i(t) + D_c(t) \tag{6}$$

The electricity flow balance module measures the balance between electricity demand and supply. In the simulation model, electricity supply (S(t), en) mainly consists of three different types of electricity generation: thermal power, hydropower and small amount of other renewable energy sources. Due to the environmental and socio-economic impacts associated with development of hydropower (impact on wildlife, ecosystems and displacement of local population) and the fact that it has almost reached its full capacity, we assume that Chongqing will not build any other large hydropower facilities by 2025. The generation of hydropower (Sh(t), en) is fixed as the base year over the simulation period in the model. The electricity supply in the Baseline scenario mainly depends on SUB critical thermal power. In contrast, we plan to use the energy supplied by a thermal power base on High Efficiency Low Emission (HELE) technologies. To evaluate the mitigation effects of technology innovation the thermal power sector is divided into five types: traditional technology type subcritical technology (Ssub(t), en) and HELE such as SUP (Ssc(t), en), USC(Su(t),en), IGCC (Sc(t), en), IGCC+CCS (Scs(t),en), NGCC (Sn(t),en), NGCC+CCS (Sns(t). Electricity demand (D(t), en) is determined by each of the industrial economic activities and government and household activities. To maintain the electricity flow balance, the electricity supply is not less than electricity demand in each year.

3.2.4 GHG and air pollutants emission and emission intensity

The GHG and air pollutants emissions in this model are defined by the total quantity of energy consumption related emissions i.e. emissions by industries energy consumption and household energy consumption.

$$W^{gas}(t) = \sum_{1}^{4} ED_i^T(t)\bullet EEng_i^{gas} + ED_c^T(t)\bullet EEng_c^{gas} \quad (\text{gas } = GHG,\ SO_2,\ NO_x,\ PM_{10},\ PM_{2.5}) \qquad (7)$$

Where W^{gas} is a vector of 5 elements denoted by the emission amount of the 5 kinds of gases shown above. $EEng_i^{gas}$ and $EEng_c^{gas}$ are gas emission coefficient matrixes that correspond to the energy carriers consumed in *i* industry and household consumption. Emission intensity in term t (E_{inten_gas}(t), en) will be identified through the formula;

$$E_{inten\_gas}(t) = W^{gas}(t) / GRP(t) \qquad (8)$$

This is an effective index to evaluate the impact of technology innovation and environment regulation.

3.2.5 Balance of the Material Flows

In Formula 8, the left side represents the supply and the right side represents the demand. Usually, the supply is not lower than the demand. The input coefficient of production is calculated based on the 2010 input-output table of Chongqing (BSC, 2011).

$$X_i(t) \geq \sum_{j=1}^{4} A_{ij} X_j(t) + C_i^h(t) + \overline{C_i^g} + I_i(t) + \overline{E}_i - M_i(t) \qquad (i = 1...4) \qquad (9)$$

Where $X_i(t)$ is an endogenous vector which represents the commodities of all the sectors in industry *i*; A_{ij}, calculated based on the input-output table, is an exogenous midrate input coefficient from industry *i* to industry j which shows the technology level of the social economic activities; $C_i^h(t)$ is an endogenous vector which shows the household consumption amount of each sector in industry *i*; $\overline{C_i^g}$ is an exogenous vector which shows the government consumption amount of each sector in industry *i*. I_i is an endogenous vector which shows the investment amount from each sector in industry *i*, $\overline{E_i}$(t) is a vector of the export amount of each sector in industry *i and* $M_i(t)$ is an endogenous vector of the import amount of commodity of each sector in industry *i*.

3.2.6 Value Balance

The left side of the formula is the gross sales by the industry in the market. And the right side specifies the total cost of each industry, including intermediate input (from the first item to the third one) and industrial value added (from the fourth one to sixth one).

$$P_i(t)\tilde{X}_i(t) = P_1(t)A_{1i}\tilde{X}_i(t) + P_e(t)A_{ei}\tilde{X}_i(t) + P_3(t)A_{3i}\tilde{X}_i(t) + Y_i^h(t) + \delta_i\tilde{X}_i(t) + \tau_i\tilde{X}_i(t) \qquad (10)$$

Where $P_i(t)$ *is* the endogenous price rate vector of each sector in industry *i*; Y_i^h is the endogenous vector of household income of each sector in industry *i*, δ_i is the exogenous vector of depreciation rate of each sector in industry *i and* τ_i is the exogenous indirect tax rate vector of each sector in industry *i*.

3.2.7 Regional government environmental regulation constraints

In order to improve the quality of environment in China, the Central government and local governments implement a Five Year development plan. Based on the central government plan and Chongqing's environmental situation, the Chongqing government plans to reduce SO_2 and NO_x emissions by 10% every five years. In this study we use the government mandatory environmental targets and analyse its impact in integrated evaluation models. In this research we mainly put constraints on SO_2 and NO_x emissions that will indirectly curb PM_{10}, $PM_{2.5}$ and GHG emissions. This assumption is based on Liu et al. (2013) that identified strong synergies between air quality and climate relevant measures that would allow improvement in cost-efficiency of air pollution policies.

3.3 Scenario design

The purpose of this research is to find the optimal policy to achieve the regional environmental regulation target through promotion of advanced technological innovation in the energy sector (see figure 3). There is already extensive literature that suggests that developing countries first adopt and later develop advanced technological innovations (Popp, 2009). Government regulation and carbon tax/subsidy system provide effective policy motivation for promoting technology innovation (Hascic, 2009; Wang and Nakata, 2009). In this study, the proposed policies include regional environmental regulation (ER) and a carbon tax/subsidy system (CTS), which are drivers that induce advanced technological innovation (see Table 5):

- *Government regulation*: In this study, government regulation specifically means mandatory environmental targets for reduction of SO_2 and NO_x emissions by 10% every 5 years. We also assumed a scenario where the emissions reduction is 5%. We not only evaluate the impact of government regulation alone on social economic development (S1' and S2'), but also evaluate its contribution on advanced technological innovation (S1 and S2).
- *Carbon tax/subsidy*: Carbon tax is a cost effective instrument in achieving a specific abatement target and highly recommended by economists and international organizations (EEA, 1996). It can promote the substitution of fuel products and change the structure of energy production and consumption, realize energy conservation as well as energy efficiency improvement (Baranzini, 2000; Wang, 2009). Carbon tax revenue can be used to lower income tax or indirect tax, or be returned as subsidies to promote technological development. In this study, the carbon tax is levied on one of the largest emission sources – the thermal power industry, and the revenue will be used as a subsidy incentive to develop highly efficient energy technology. Chongqing city has been selected as a carbon tax pilot city and the tax rate is decided based on the Chinese pilot city carbon pricing survey (Jotzo et al., 2013).

- *Advanced technological innovation*: In this study, conventional and advanced technology options are shown in Table 1-2. These technologies options are provided by the IEA technology roadmap (see IEA, 2012). Advanced technologies are endogenously adopted to substitute low efficient technology and the substitution is affected by many factors such as government regulation level, carbon tax/subsidy level and technology features (cost, energy efficient, and emission efficient, et al.). Our comprehensive model (see Figure 1) creates optimum power technologies combination based on regional economic, energy and environmental conditions.

We design 5 policy scenarios including Baseline, S1', S2', S1 and S2 to identify the impact of different policies (see table 6).

Baseline: This scenario acts as a reference to identify the significance of ER and TI. Without these policies, the air pollution problem and energy crisis problem could threaten regional sustainable development.

S1'/S1: In these two scenarios we assume 5% air pollution mitigation every five years without and with the promotion of advanced technological innovation. They also act as reference scenario for S2'/S2 which are based on the government regulation to reduce air pollution by 10% every five years.

S2'/S2: These scenarios rationale is the same as of S1'/S1 but are based on the government environmental plan.

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We tried to analyse the effectiveness of the government regulations by introducing enhanced technological innovation in the energy sector coupled with tax/subsidy system for both S1 and S2.

4. Results analysis and discussion

Based on the simulation results, the integrated assessment system can estimate the impact of policies including technology innovation in the energy sector and regulations on the regional GHG and air pollution emission and economic development trends. By comparing the different scenarios, we will be able to identify the contributions from different policies through improvement in energy intensity and emission intensity, which are important indicators to demonstrate the implication of such policies.

4.1 Economic development trends

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Fig.4 shows the impact of integrated policy (including regional environmental regulation and promotion of technology innovation in the energy sector) on economic development (S1, S1', S2, S2'). Both S1' and S2' (which are affected by environmental regulation at current technologies level but have no policy promotion for technology innovation) have a remarkably lower economic performance. S1 and S2, on other hand, provide a much better economic performance. This demonstrates that introducing regulations without promotion of technological innovation will dramatically affect economic growth. In this case, for instance, in order to achieve the environmental target, the interaction of sectors can only reduce air emissions through decreasing production and hence energy consumption.

Based on these results our analysis focused on S1 and S2. Since the high cost of HELE technologies is a barrier for technology innovation we propose the implementation of a government subsidy system to induce such innovations. The subsidy distribution is decided based on both costs and air emissions mitigation. In this case the subsidy will cover the extra cost necessary to produce the same amount of electricity adjusted to price with current technology.

We assume that the subsidy funding comes from special-purpose taxes (carbon tax) gathered from GHG emission related to technologies in the energy sector. Government must implement a subsidy system in order to reduce the extra cost of electricity generated by advanced technologies. The GRP average annual growth rate is 9.16%, 6.00%, and 4.24% respectively for baseline, S1 and S2 scenarios. The results show that environmental regulation constraints can slow economic development. However, the introduction of cleaner technologies and carbon tax/subsidies can mitigate this slowdown. In this research the carbon tax can reach up to 70 RMB (roughly 11 USD) and is endogenously decided. This value is based on China's pilot emission trading schemes (Jotzo et al., 2013)

Figure 4 also shows that technology innovation has positive impact on economic development up to a certain point. In this case, for instance, from 2019, we will need to consider technology innovation in other sectors to alleviate economic decline.

4.2 Energy consumption

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In the case of energy consumption trends figure 5 shows that under the baseline scenario the accumulated energy consumption is 23.6% and 30.7% higher than S1 and S2 respectively. This is because regulations will constrain economic growth and hence decrease energy consumption. At the same time this figure also shows that the introduction of regulations will effectively curve the trend of coal dependence and promote the rapid adoption of cleaner natural gas. This is a very important outcome because it will alleviate the dependency on coal as a primary energy source. Chongqing's electricity supply sources are mainly dependent on coal-fired power (79%) and Hydropower (less than 20%) as of 2010. As the increasing demand for electricity and Hydropower has already reached its peak, Chongqing will be locked in a coal-fired power system. In other words, it will be much more difficult to change the coal-dominant electricity supply system and reduce its relative environmental cost in the future if no measures are taken now.

The situation above calls for technology innovation in the electricity supply sector. A previous study found that renewable energy will only contribute a little to meet increasing energy demand in Chongqing (Zhou et al, 2013). Therefore we need to promote practical HELE cleaner coal-fired and natural gas based electricity technology to improve regional environmental quality as well as diversify energy supply sources and boost energy conservation. As we know natural gas potential will be a promising energy source in the near future. The gas deal announced on 21st, May 2014 between Russia and China for 30 years will increase Chinese natural gas energy security. In addition thanks to the application of horizontal drilling and hydraulic fracturing, commercial exploitation of shale gas has provided new opportunities for cleaner and efficient energy production. In its 2011 Annual Energy Outlook, the U.S. Energy information Administration (EIA) estimates that the recoverable gas resources from U.S. shale gas plays have more than doubled in the previous year, in large part due to the successful use of advanced drilling techniques (Rahm, 2011). The shale gas technology innovation has affected not only the American but also the global energy structure and future perspectives in terms of energy security and potential reduction in global GHG emissions and regional air pollution. China has the largest proven shale gas reserves in the world (EIA, 2013) and hence a huge potential for its commercial exploitation.

4.3 Air emissions mitigation and emission intensity trends

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Figure 6 shows that, in the absence of any regulation, air pollution and GHG emissions will skyrocket. Under the baseline scenario GHG, SO_2, NO_x, PM_{10} and $PM_{2.5}$ emissions amount will be 82%, 80.1%, 127%, 68%, and 77% higher than the emission amount in 2010. This is a very important outcome because Chinese Academy of Environmental Planning, which is part of the Ministry of Environmental Protection, reported that the cost of environmental degradation in China was about 230×10^9 USD in 2010, or 3.5 percent of the nation's GDP (NYTAP, 2013). On the other hand, the environmental and socio-economic benefits of the avoided emissions will have a significant positive impact. In the case of GHG emissions the proposed scenarios also have a positive impact. In fact S1 and S2 scenarios will reduce the total GHG accumulated emissions by 36% and 44% respectively compared to baseline scenario.

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The amount of air pollution and GHG mitigation shown in Figure 6 shows the actual improvement in air quality and climate change mitigation efforts. We also evaluate technology innovation impact by analyzing air emissions and energy intensity. The intensity trends can help us measure the overall decoupling improvement in the economy. In Figure 7 all air emissions trends in S1 and S2 show a decreasing pattern thanks to the energy intensity improvements induced by the technology innovation. The figure also shows that the intensity improvements are much stronger in the first half of the study period followed by a rather weak trend. This is because as time passes it will be more difficult to achieve the regional regulation targets without further innovation promotion in other sectors specially energy intensive industries. In the absence of additional innovation promotion the industry will decrease economic growth in order to meet those targets.

4.4 Regulation and impacts on technology adoption

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Under Baseline conditions i.e. no environmental regulation, SUB will dominate the electricity grid due to its low cost. In other words high capital, operation and maintenance costs will make it very difficult for more advanced technologies to be adopted. This could pose a serious threat because of the lock in and dependency phenomena (Morioka et al, 2006).

Along with stricter environmental regulation a diverse portfolio of energy sources can guarantee energy security. NGCC technology can greatly contribute to air pollution mitigation. In this regard, as we mentioned before, the shale gas development potential (see EIA, 2013 for details) and the recent gas deal signed with Russia can meet the increasing natural gas demand. Therefore, as shown in Figure 8 we must promote a gradual adoption of innovation first followed by stricter regulations. This way we can simultaneously induce environmental protection and economic growth. The mechanism would work like this: in each industry, the policy makers can first introduce a relatively flexible pollution emission target as incentive for existing industries to modernize their technology, and encourage the new industries to adopt the newer alternatives. Then, economic development and increasing demand for electricity will allow policy makers to introduce stricter regulations. This type of mechanism should be applied to the other industrial sectors as well.

5. Conclusion

The Chongqing government has set a target to reduce 10% of its air pollution emissions in its FYP. In this study we constructed a top-down assessment model and 5 scenarios representing different regulation and alternative technology options to simulate dynamic future trends of GHG, air pollution, energy utilization and economic development. The scenario design was based on the regional government regulation and the potential of clean technology adoption in the energy sector. In order to promote clean power technologies we proposed the introduction of a carbon tax and subsidy system to find out whether such innovations in the energy sector alone would be enough to achieve both regional government regulations and maintain moderate economic growth. We analysed the environmental and socio-economic performance of a less ambitious air pollution reduction plan of 5% based on the integrated policies. The results of the study show that the proposed government policy alone will seriously hurt the economy (Fig. 4). The introduction of integrated policies, on the other hand, will both achieve the government targets and maintain moderate economic growth. The study also found that when we introduce a more moderate 5% reduction target economic growth would not only be higher than the government proposal but the air pollution and energy intensities will be lower in the later half of the research period.

This study suggests that the promotion of advanced technological innovation cannot only help improve the quality of the environment (Fig. 6) but also reduce energy consumption (Fig. 8). When we compare the two scenarios (with and without integrated policy), both achieve the regional government environmental regulation targets, but the scenario with embedded integrated policy including diversification of technology innovation in the energy sector has a positive impact on economic development, energy conservation and environmental preservation. Trade-offs between environmental conservation and economic development could be improved through effective environmental regulations coupled with promotion of technology innovation.

The implications of this study are very important. Firstly the results clearly show that integrated policies are the most effective tools to both promote environmental protection and economic growth. Secondly we found out that, in the absence of any serious energy policy, the Chongqing power sector will rely almost totally on coal-based low efficient sub critical power generation. It is imperative to introduce comprehensive policies to change this trend and allow for a more diversified and high efficiency power generation grid. This study provides a very strong platform for policy makers to gain a general idea about the urgency and importance of promoting technological innovation in other industries. In this sense future studies must also pay attention to the promotion of technology innovation in other industrial sectors especially energy intensive ones such as the cement, steel and chemical sectors.

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Figure captions

Figure 1: Comprehensive model framework

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Figure 3: Scenario design and policies proposals

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Table 1

Evaluated technology and emissions type

	Technology options	**GHG and air pollution types**
Conventional type	Subcritical technology (SUB)	SO_2
Advanced technology options (High-Efficiency, Low-Emissions Fossil Fuel-Fired Power Generation)	Supercritical technology (SUP)	NO_x
	Ultra-Supercritical (USC)	PM_{10}
	Integrated gasification combined cycle (IGCC)	$PM_{2.5}$
	IGCC and Carbon capture storage (IGCC+CCS)	CO_2-e
	Natural gas combined cycle (NGCC)	
	NGCC+CCS	

Table 2

Parameters of Chinese power generation technology

	Capital costs ($2010 per kW)			O&M Costs ($2010 per kW)			Efficiency (gross, LHV)		
	2010	*2020*	*2035*	*2010*	*2020*	*2035*	*2010*	*2020*	*2035*
Steam Coal - SUB	600	600	600	21	21	21	37%	37%	37%
Steam Coal - SUP	700	700	700	28	28	28	42%	42%	42%
Steam Coal - USC	800	800	800	32	32	32	46%	48%	50%
IGCC	1100	1100	900	50	50	41	47%	49%	51%
IGCC + CCS	1800	1800	1600	81	81	72	38%	40%	44%
NGCC	550	550	550	18	18	18	57%	59%	61%
NGCC+CCS	1000	1000	1000	33	33	33	49%	51%	54%

Source: Based on IEA, World Energy Outlook, 2011.
http://www.worldenergyoutlook.org/media/weowebsite/energymodel/WEO_2011_PG_Assumptions_450_Scenario.xls

Note:

O & M: operation and maintenance; SUB: subcritical; SUP: supercritical; USC: ultra-supercritical; IGCC: integrated gasification combined cycle; NGCC: natural gas combined cycle; USC: ultra-supercritical; IGCC + CCS: integrated gasification combined cycle with CCS; NGCC + CCS: natural gas combined cycle with CCS; LHV: lower heating value;

Table 3

Coal based technology energy consumption and emission intensity

Technology	Coal consumption	CO2 intensity factor (Efficiency[LHV,net])
A-USC(700 ^{0}C)	290-320 g/kWh	670-740 g CO2/kWh (45-50%)
IGCC(1500 ^{0}C)	290-320 g/kWh	670-740 g CO2/kWh (45-50%)
Ultra-supercritical	320-340 g/kWh	740-800 g CO CO2/kWh (up to 45%)
Supercritical	340-380 g/kWh	800-880 g CO CO2/kWh (up to 45%)
Subcritical	≥380 g/kWh	≥880 g CO CO2/kWh (up to 45%)

Source: IEA, 2012.

Table 4

Classification of sectors in the comprehensive model

Industry	Sector
1. Usual Goods and Services	Agriculture, Forestry, Animal Husbandry and Fishery Transport and Postal Services Waste Treatment Other Industries
2. Conventional Energy Industries	*Hydropower and Subcritical Technology Power Supply* Production and Supply of Gas
3. Energy Intensive Industries	Mining and Washing of Coal Manufacture of Raw Chemical Materials and Products Manufacture of Non-metallic Mineral Products Smelting and Pressing of Ferrous Metals
4. Adcanced Technology Options (High-Efficiency, Low-Emissions Coal-Natural Gas Fired Power Generation (HELE))	*NGCC+CCS* *NGCC* *IGCC+CCS Technology Power Supply* *IGCC* *USC Technology Power Supply* *SUP Technology Power Supply*

Table 5

Scenario design (varied with mandatory environmental targets for reduction of SO_2 and NO_x emissions, promotion of advanced technological innovation and carbon tax/subsidy system)

Scenarios	**Environmental Regulation**	**Enhanced Technological Innovation**	**Carbon Tax/ Subsidy System**
BAU	No	No	No
S1'/S1	Air pollution 5% Mitigation	No/Yes	No/Yes
S2'/S2	Air Pollution 10% Mitigation	No/Yes	No/Yes

Table 6

Comparison of the Impact of policies on proposed scenarios

	Baseline	S1’	S2’	S1	S2
Baseline	--	ER	ER	ER+CTS+ATI	ER+CTS+ATI
S1’	ER	--	ER	CTS+ATI	ER+CTS+ATI
S2’	ER	ER	--	ER+CTS+ ATI	CTS+ ATI
S1	ER+CTS+ ATI	CTS+ATI	ER+CTS+ ATI	--	ER
S2	ER+CTS+ATI	ER+CTS+ATI	CTS+ATI	ER	--

Note: ER: Environmental Regulation; CTS: Carbon Tax/Subsidy; ATI: Advanced Technological Innovation;

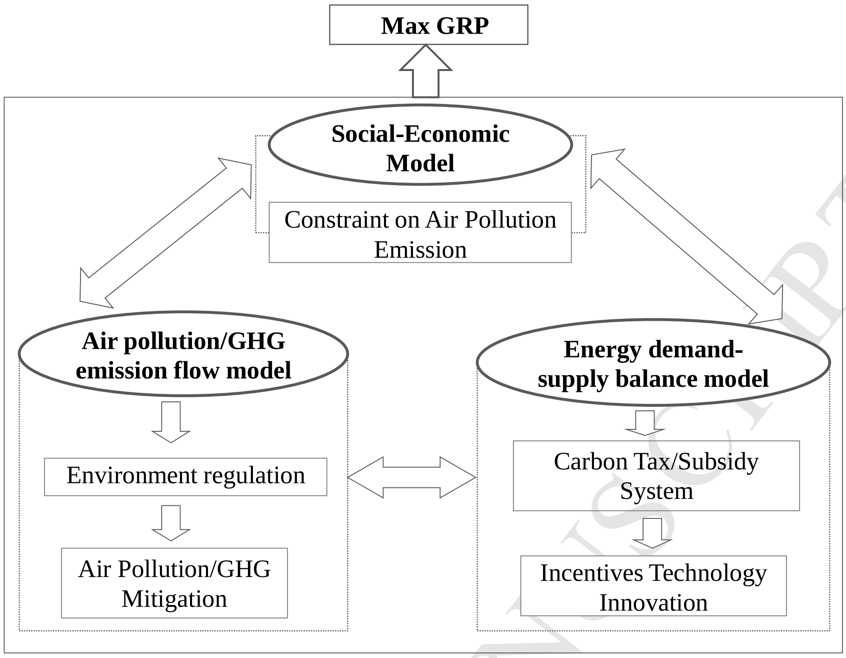


Figure 1: Comprehensive model framework

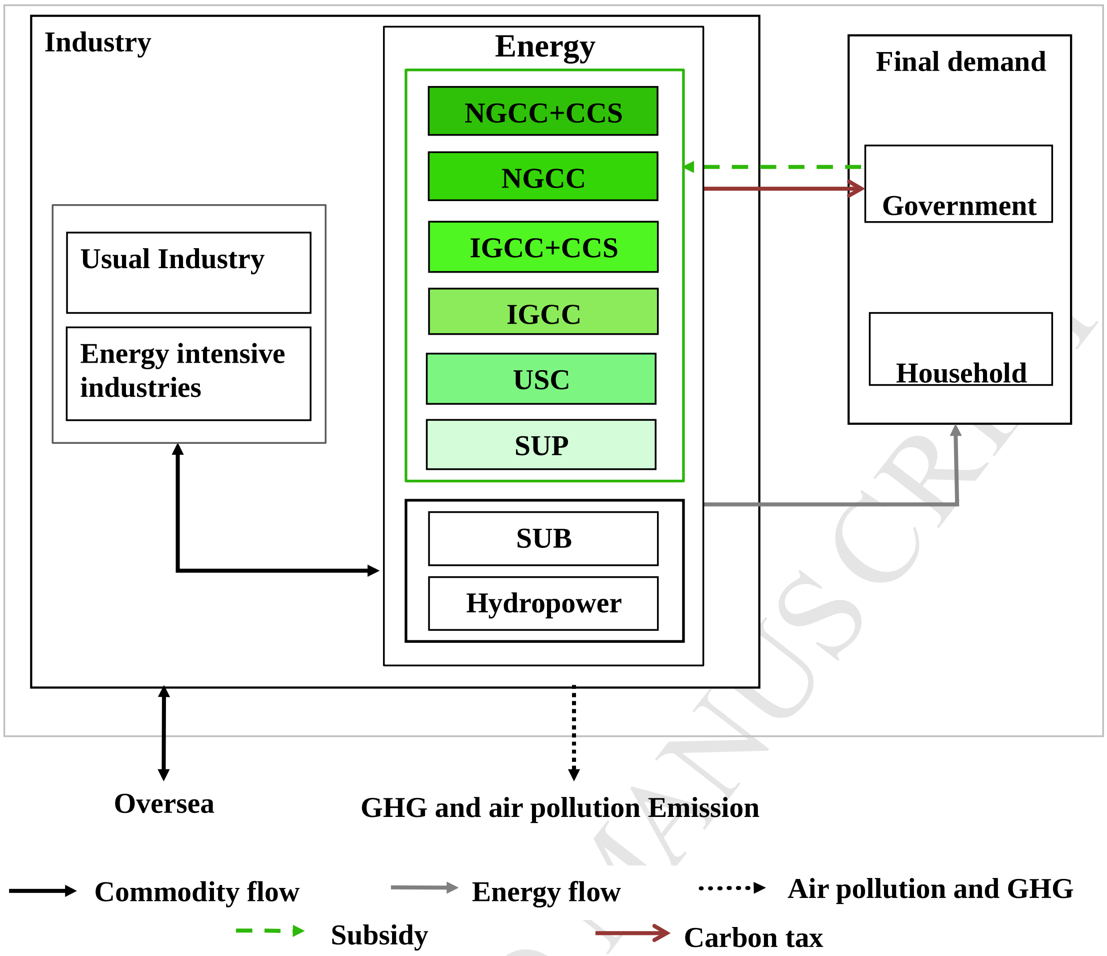


Figure 2: Interrelationship between agents in the environmental-social economic model

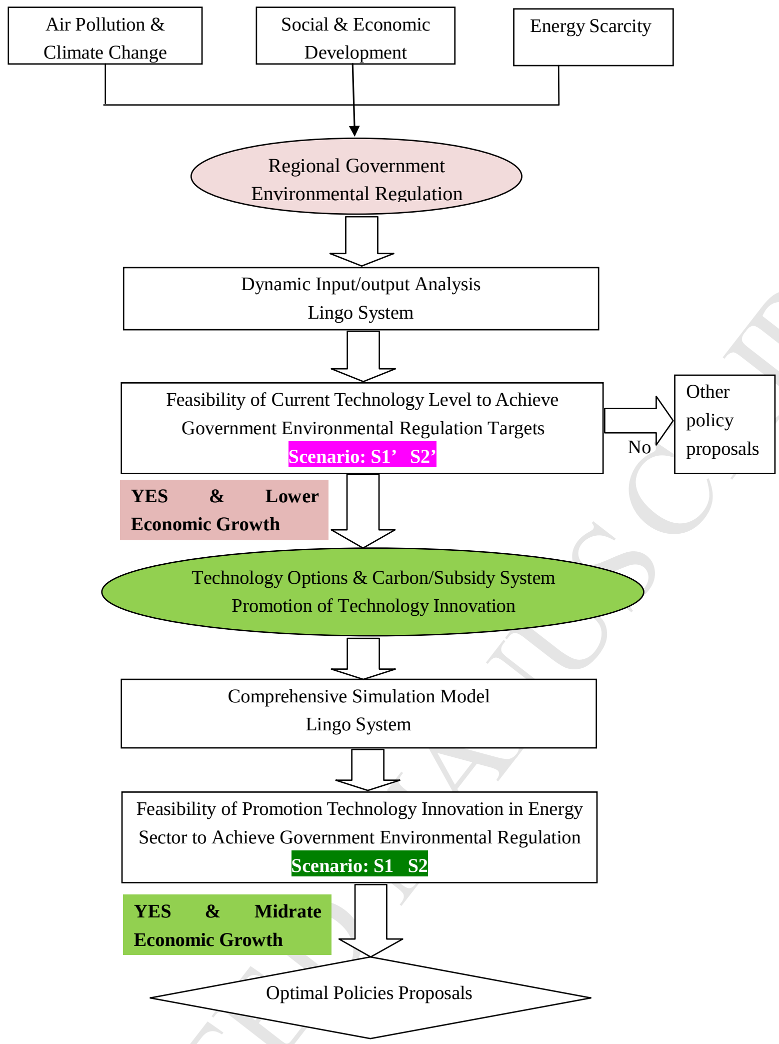
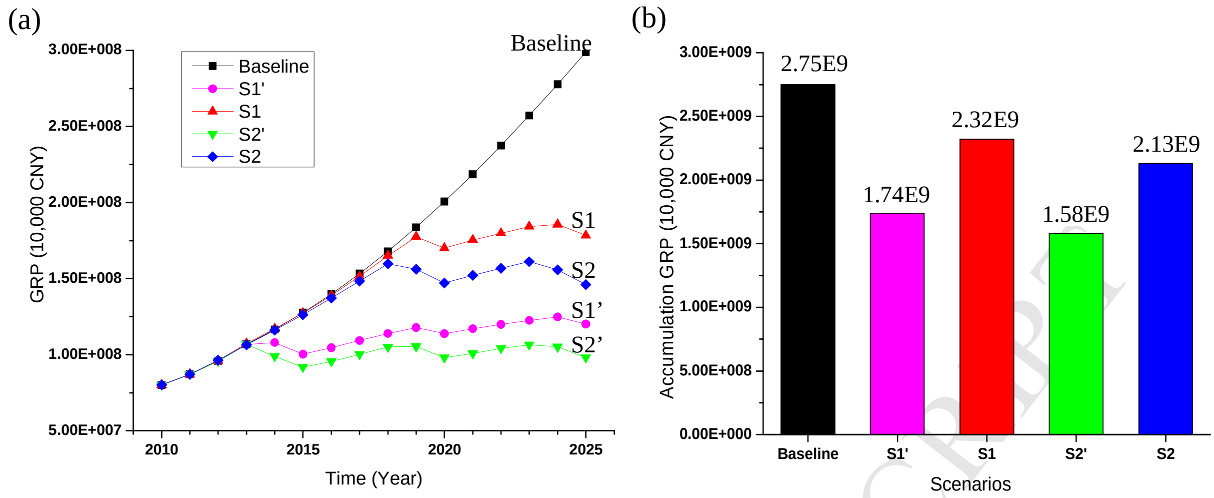


Figure 3: Scenario design and policies proposals



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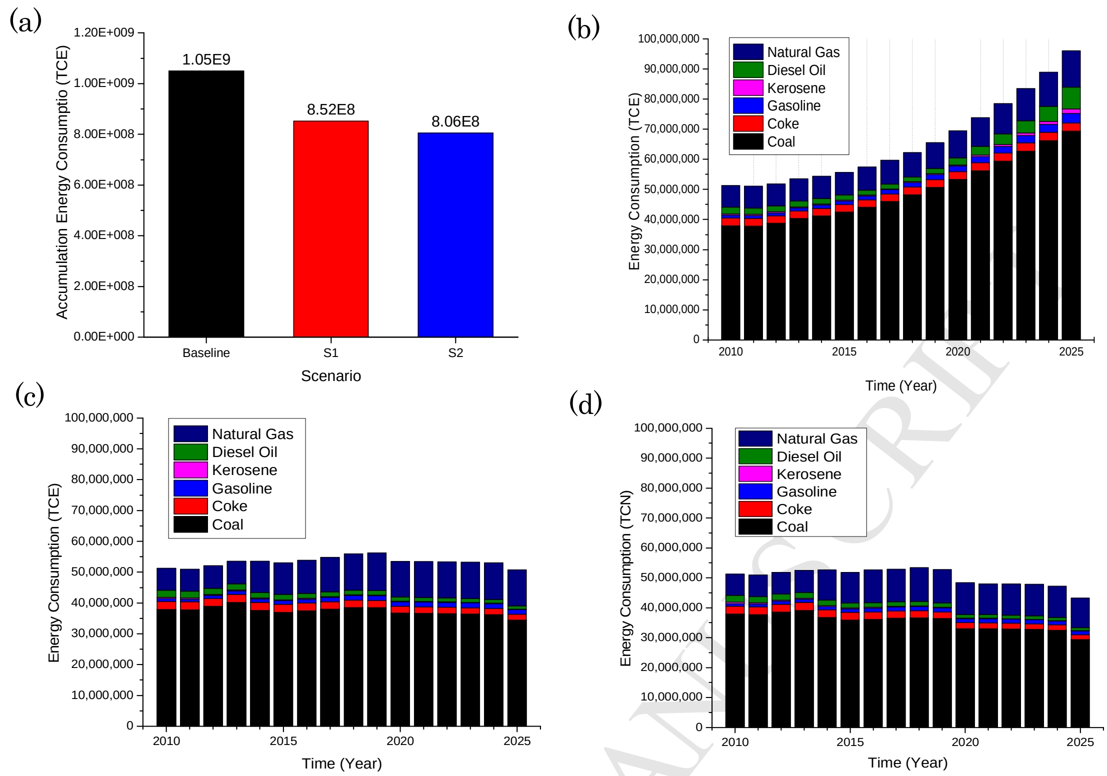

Figure 5: Energy consumption; (a) Accumulation energy consumption in Baseline, S1 and S2; (b) (c) and (d) Energy consumption trends in Baseline, S1 and S2

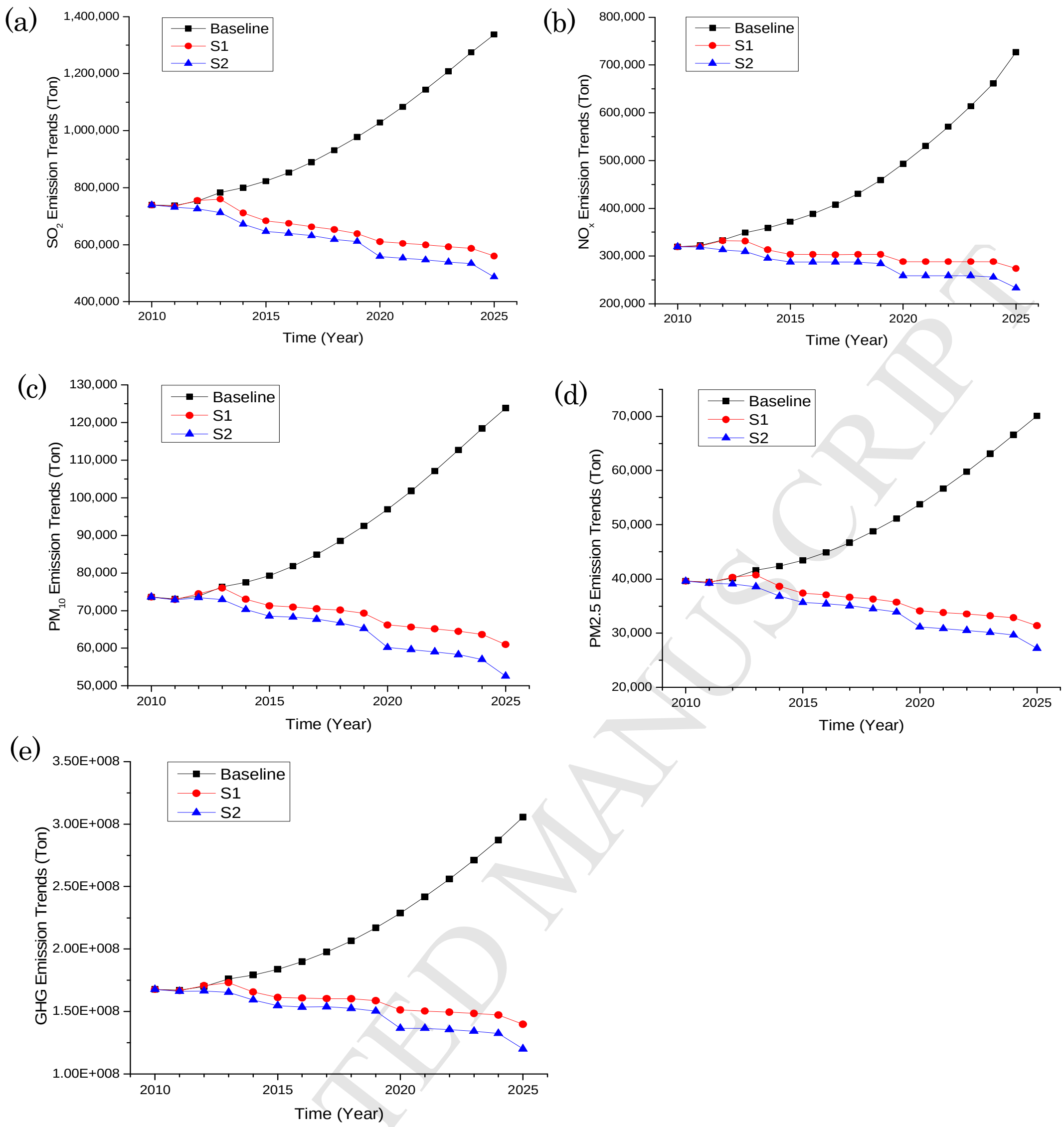

Figure 6: Comparison of air pollution mitigation in different scenarios

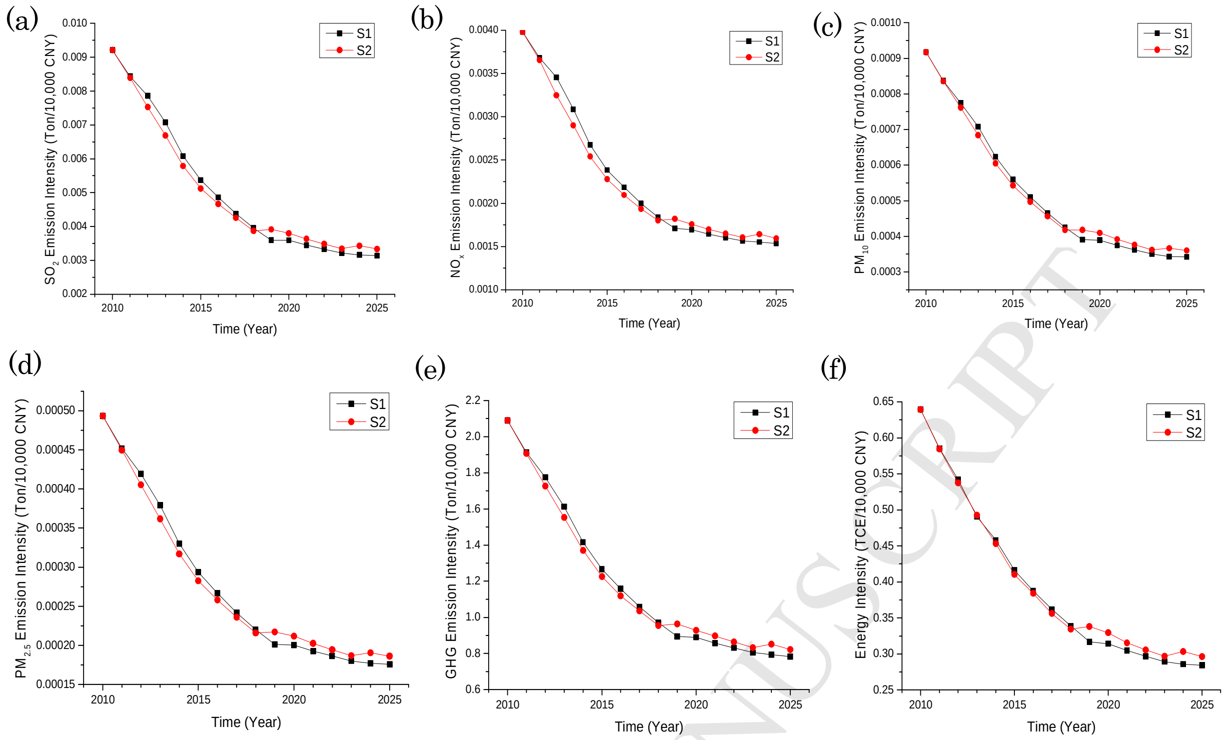

Figure 7: Air pollution emission intensity and energy intensity

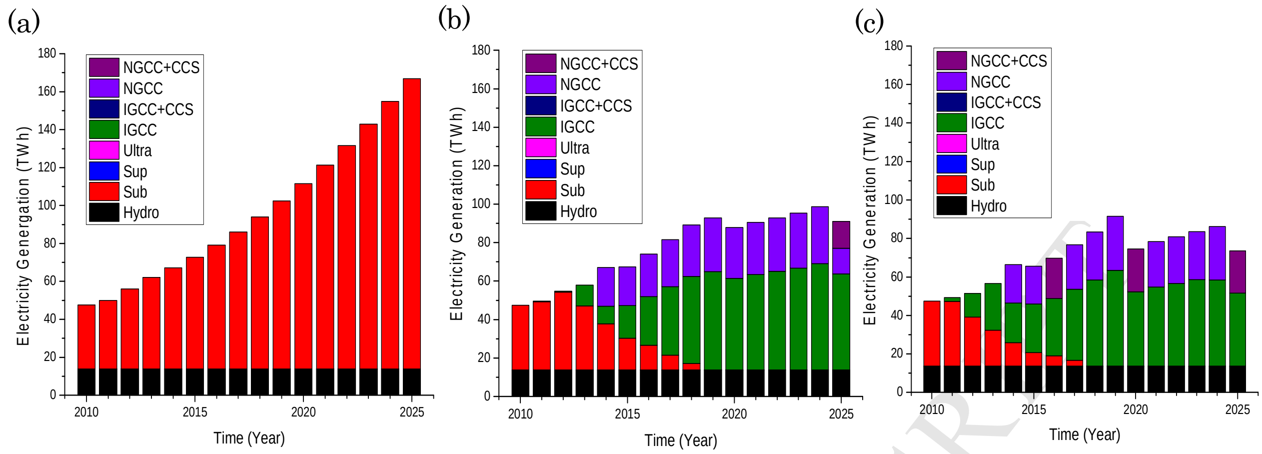

Figure 8: Technology adoption in different scenarios; (a) Baseline; (b) S1; (c) S2

- Technological innovation with a subsidy/carbon tax system is effective up to a certain level.
- Implementing environmental regulations alone will hurt economic growth in China.
- Technological innovation in the energy sector with a 5% air pollution reduction has better environment-economy trade-offs
- Promoting technological innovation in other key industrial sectors is necessary

APPENDIX A

The following tables present the data for the variables used in the simulations.

Table A1

Input coefficients to Usual Industry by Usual Industry (A_{11})

	Agriculture, Forestry, Animal Husbandry and Fishery	Transport and Postal Services	Waste Treatment	Other industries
Agriculture, Forestry, Animal Husbandry and Fishery	0.10292	0.04132	0.00000	0.02833
Transport and Postal Services	0.00725	0.03219	0.03676	0.02530
Waste Treatment	0.00004	0.00000	0.24663	0.00035
Other industries	0.17149	0.34879	0.17321	0.40213

Table A2

Input coefficients to Traditional Energy Industries by Usual Industry (A_{12})

	Hydropower and Subcritical Technology Power Supply	Production and Supply of Gas
Agriculture, Forestry, Animal Husbandry and Fishery	0.00000	0.00000
Transport and Postal Services	0.01237	0.14608
Waste Treatment	0.00000	0.00000
Other industries	0.20007	0.24115

Table A3

Input coefficients to Energy Intensive Industries by Usual Industry (A_{13})

	Mining and Washing of Coal Smelting and	Manufacture of Raw Chemical Materials and Products	Manufacture of Non-metallic Mineral Products	Pressing of Ferrous Metals Metal products
Agriculture, Forestry, Animal Husbandry and Fishery	0.00759	0.02025	0.00372	0.00000
Transport and Postal Services	0.03760	0.02609	0.03001	0.02391
Waste Treatment	0.00000	0.00088	0.02627	0.04476
Other industries	0.16815	0.17774	0.16879	0.25092

Table A4

Input coefficients to usual industry by traditional energy industry (**A_{21}**)

	Agriculture, Forestry, Animal Husbandry and Fishery	Transport and Postal Services	Waste Treatment	Other industries
Hydropower and Subcritical Technology Power Supply	0.00361	0.00531	0.06216	0.02484
Production and Supply of Gas	0.00002	0.00026	0.02473	0.00155

Table A5

Input coefficients to Traditional Energy Industry by Traditional Energy Industry (**A_{22}**)

	Hydropower and Subcritical Technology Power Supply	Production and Supply of Gas
Hydropower and Subcritical Technology Power Supply	0.16301	0.02142
Production and Supply of Gas	0.00000	0.21227

Table A6

Input coefficients to Energy Intensive Industry by Traditional Energy Industry (**A_{23}**)

	Mining and Washing of Coal Smelting and	Manufacture of Raw Chemical Materials and Products	Manufacture of Non-metallic Mineral Products	Pressing of Ferrous Metals Metal products
Hydropower and Subcritical Technology Power Supply	0.05337	0.02129	0.02611	0.06372
Production and Supply of Gas	0.00000	0.00496	0.00375	0.00572

Table A7

Input coefficients to Usual Industry by Energy Intensive Industry (**A_{31}**)

	Agriculture, Forestry, Animal Husbandry and Fishery	Transport and Postal Services	Waste Treatment	Other industries
Mining and Washing of Coal Smelting and	0.00019	0.00000	0.00125	0.00327
Manufacture of Raw Chemical Materials and Products	0.03877	0.03144	0.10450	0.03085
Manufacture of Non-metallic Mineral Products	0.00034	0.00158	0.00460	0.04292
Pressing of Ferrous Metals Metal products	0.00004	0.00073	0.09241	0.06096

Table A8

Input coefficients to Traditional Energy Industry by Traditional Energy Industry (**A_{32}**)

	Hydropower and Subcritical Technology Power Supply	Production and Supply of Gas
Mining and Washing of Coal Smelting and	0.22063	0.00160
Manufacture of Raw Chemical Materials and Products	0.00204	0.02440
Manufacture of Non-metallic Mineral Products	0.00058	0.01491
Pressing of Ferrous Metals Metal products	0.00013	0.00848

Table A9

Input coefficients to Energy Intensive Industry by Traditional Energy Industry (**A_{33}**)

	Mining and Washing of Coal Smelting and	Manufacture of Raw Chemical Materials and Products	Manufacture of Non-metallic Mineral Products	Pressing of Ferrous Metals Metal products
Mining and Washing of Coal Smelting and	0.12370	0.01008	0.22037	0.03549
Manufacture of Raw Chemical Materials and Products	0.02414	0.37122	0.10713	0.03658
Manufacture of Non-metallic Mineral Products	0.00580	0.00557	0.05760	0.00880
Pressing of Ferrous Metals Metal products	0.00425	0.00327	0.00423	0.27408

Table A1

Government consumption ($\overline{C_i^g}$), export ($\overline{E_i}$) in base year, depreciation rate δ_i, indirect tax rat τ_i and value-added rate V_i

	$\overline{C_i^g}$ (Million yuan)	$\overline{E_i}$ (Million yuan)	depreciation rate δ_i	Indirect tax rate τ_i	value-added rate V_i
Agriculture, Forestry, Animal Husbandry and Fishery	283511.24196	195141.94131	0.002287	0.002287	0.675328
Transport and Postal Services	495736.47053	47524.61010	0.056729	0.056729	0.53837
Waste Treatment	0.00000	3299.04028	0.099023	0.099023	0.253745
Other Industries	9394350.51666	13550389.13133	0.071022	0.071022	0.379496
Hydropower and Subcritical Technology Power Supply	0.00000	1031.99974	0.058476	0.058476	0.401152
Production and Supply of Gas	0.00000	287866.72772	0.041121	0.041121	0.329688
Mining and Washing of Coal	0.00000	3145.77519	0.106606	0.106606	0.575383
Manufacture of Raw Chemical Materials and Products	0.00000	484944.07131	0.071555	0.071555	0.35866
Manufacture of Non-metallic Mineral Products	0.00000	89741.84481	0.061219	0.061219	0.352016
Smelting and Pressing of Ferrous Metals	0.00000	60451.23377	0.054497	0.054497	0.256036