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Quantifying the effects of air pollution control policies: A case of Shanxi province in China

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ABSTRACT

With a rapid growth rate of economic development in China, air pollution has attained to an extremely high level. Consequently, air pollution has become a pressing challenge facing Chinese authorities. To control air pollution, a variety of economic instruments (such as Pigou tax and Coase means) as well as command and control means (such as environmental regulation, etc.) have been adopted. As one of China's important energy resources bases, Shanxi Province is also one of the most polluted regions. Therefore, the adapted air pollution control policies and its influence in Shanxi Province is representative for China. With this regard, a dynamic computable general equilibrium (CGE) model is constructed to evaluate the effects of air pollution control tools including SO_2 taxation, clean technical progress (CTP) and energy efficient (EE) improvement, etc. and their socioeconomic impacts on Shanxi province. The results indicate that, in a variety of scenarios, SO_2 taxation combining with technical progress can effectively control air pollution, improve energy consumption structure, and do not exert remarkable negative impact on economic performance. Additionally, significant synergistic effects of CO_2 and $PM_{2.5}$ emission reduction and energy rebound effect are found as well.

1. Introduction

Rapid economic growth is often accompanied by massive energy consumption and severe environmental degradation (Zhang et al., 2012), which is a common phenomenon during the development process of countries all over the world. Energy consumption will continue to grow. According to EIA's International Energy Outlook 2017, the global energy consumption will increase by 28% between 2015 and 2040, while the energy-related carbon dioxide emissions is expected to approach to 40 billion metric tons in 2040.[1] China is presently the largest energy consumer and emitter of air pollution (Li et al., 2015), in which Shanxi,[2] as an important energy resources base (Zang et al., 2017), is a typical epitome of regional environmental pollution. Over the past decade, China's persistent environmental pollution has been highly concerned by researchers. Environmental pollution has posed a threat to the health and survival of local human beings, which seriously hinders the sustainable development of economy. The primary environmental issues present complex relationships with water shortages, serious soil erosion, air pollution, dust contamination, noise pollution, solid waste pollution, ecological damage and other serious problems.

Among all these issues, air pollution in urban areas is responsible for the majority of environmental problems and associated losses.[3] In 2014, only eight of the 74 cities in China that have been carrying out air quality monitoring met the National Clean Air Standard. The severe air pollution in those cities was in part caused by SO_2 emission during the process of coal mining, processing and utilization. In particular, inferior coal with high sulfur content bears relatively lower utilizing cost, and the application of efficient clean coal technology is often overlooked, resulting in inadequate utilization of inferior coal in China.

At present, coal is the main energy resource of China (Pandey et al., 2014; Burke and Liao, 2015). Shanxi accounts for about one-third of the entire country's proven coal reserves and constitute nearly a quarter of the coal production in China (Zhang et al., 2011). The proportion of coal consumption in primary energy use was maintained at more than 90% over the past three decades in this area. The long-term and high-intensity exploitation of coal resources and the high degree of centralised industrial structure in this region are the main causes of excessive SO_2 emission. As a typical representative of regional air

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[1] https://www.eia.gov/outlooks/ieo/.
[2] Shan province is one administrative region of China. The “province” in China is similar to the “state” in the U.S..
[3] https://www.iea.org/publications/freepublications/publication/WorldEnergyOutlookSpecialReport2016EnergyandAirPollution.pdf.

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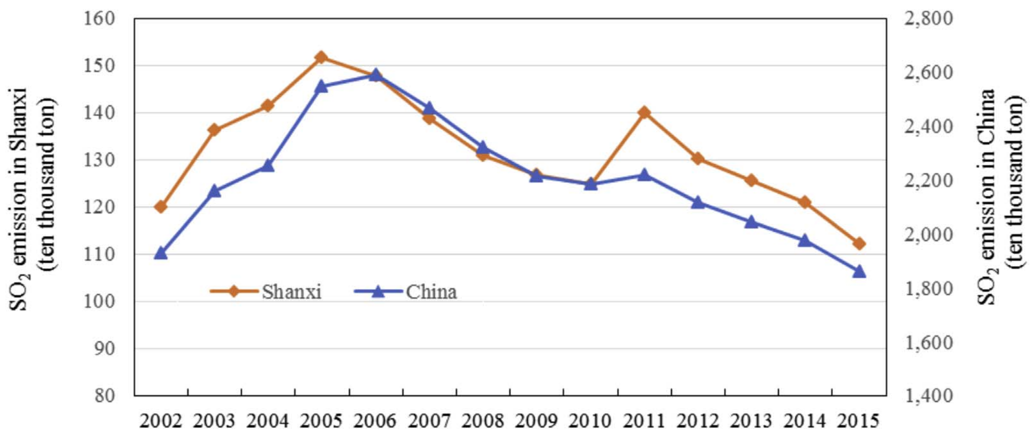

Fig. 1. SO_2 emission in Shanxi and China over the period 2002–2015.

pollution, Shanxi's SO_2 emission in 2015 is 7.15 tons per square kilometers, which is more than four times the Chinese average level.[4] From 2002 to 2015, for Shanxi province, the proportion of SO_2 emission nationwide has been maintained at more than 5%. As illustrated in Fig. 1, the trend of SO_2 emission in Shanxi is basically consistent with that of the whole country. In addition, the coal-dominated energy structure in Shanxi is difficult to change in the short term. To sum up, air pollution in this region is highly associated with the coal economic cycle, which leads to endlessly unmanageable environmental issues. Therefore, the key point to reduce SO_2 emission and related air pollution is to decrease the use of fossil energy, especially the coal.

In the related successful practice of environment governance in developed countries, the market-oriented mechanism is generally taken as a basis for air pollution management (Pizer, 2002). Relevant policy tools can be broadly divided into two categories: one is the price scheme, such as the collection of sulfur tax (Xu and Masui, 2009; Nam et al., 2013; Garcia-Gusano et al., 2015), carbon tax (Eichner and Pethig, 2009; Kim et al., 2011; Calderon et al., 2016; Filippini and Heimsch, 2016) or resource tax (Eisenack et al., 2012; Liu et al., 2017); another is the quantity control, for example, emission trading permits (Kollenberg and Taschini, 2016; Milt and Armsworth, 2017) for air pollutants. Even though Shinkuma and Sugeta (2016) have argued that emission trading instrument is superior to tax scheme under free market entry, we will follow Weitzman (1974) who selected the tax scheme as the instrument of air pollution control owing to administrative intervention still exists widely in China.

As for economic techniques, CGE model is widely recognized as a standard instrument for the estimation of environmental policies' effects (Nestor and Pasurka, 1995; Xie and Saltzman, 2000; Nugent and Sarma, 2002; Gerlagh et al., 2004; Wier et al., 2005; Liang et al., 2007; Garcia-Gusano et al., 2015; Calderon et al., 2016; Zhang et al., 2017). Compared with the researches on CO_2 emission, the issues of controlling SO_2 emission under the CGE model framework has received relatively less concern, such as the studies on developed countries (Bergman, 2005; Nam et al., 2010; Weisbach, 2012) and developing countries (Kiuila, 2003; O'Ryan et al., 2005), especially for China (Xu and Masui, 2009; Nam et al., 2013; Liu et al., 2016).

The main contributions of this paper are as follows: First, different from possibly similar studies in Utgikar and Scott (2006), Feng and Zhang (2012), and Aydin et al. (2016) using different forecasting methods, our constructed CGE model contains more variables and makes predictions more accurate under the framework of general equilibrium. Second, studies on air pollution in China or other countries are mainly concentrated on greenhouse gas emission reduction, whereas the investigation on SO_2 is relatively limited. Despite there have been literature on SO_2 emission in China (Xu and Masui, 2009), SO_2 pollution is more of a regional problem in virtue of the vast size of China. In other words, China's environmental pollution is often concentrated in several key areas. Although some literature has studied the regional environmental pollution issues for China (Zhao et al., 2013; Huang et al., 2015; Han et al., 2016), issues of serious air pollution in local region like Shanxi have not been specifically researched. Third, existing literature mostly ignore the technological progress in contexts of natural economic growth while taxing air pollutants. This paper extended the study of Xu and Masui (2009). Our input-output data is the latest and particularly the development goal of renewable energy to 2030 has been added according to the latest policy documents to make this study more detailed. Furthermore, the production structure of this model is more flexible, because it follows a nested constant substitution elasticity (CES) function, which allows for the substitution between intermediate inputs and non-intermediate inputs. Fourth, as air pollutants, such as SO_2, CO_2 and $PM_{2.5}$, are stemmed from coal to some extent, most of the studies does not take the potential co-benefits brought by some specific air pollutant reduction on others into account when using the instruments of environmental pollution control. Fifth, energy rebound effect might emerge as energy efficiency increases, previous related literature rarely considers this effect, and our paper seeks to replenish it.

The remainder of the paper is organized as follows. Section 2 summarizes the key features of a dynamic CGE model and briefly describes the model's parameterization. Section 3 presents the data source and the seven simulation scenarios. Section 4 discusses the results. The last section involves a brief conclusion and related implications.

2. A dynamic CGE model

In this paper, a dynamic recursive CGE model following PEP (Decaluwé et al., 2010) is specifically established, which consists of modules of production, income and expenditure, dynamic recursion etc.. Based on this prototype, a series of important innovation is initiated: appending the environmental pollution module, treating energy as a factor of production process, embedding sulfur tax into the production side, merging the sectors and adding technological progress module. The following context briefly introduces the main modules of each part. Fig. 2 presents a schematic diagram of the model.

2.1. Production

Overall, the production function consists of three layers of nested CES structure. The top layer is a CES function of the energy composition, the value added, and other intermediate inputs. In contrast to conventional CGE model, intermediate inputs are non-energy intermediate inputs and exclude all kinds of energy. The structure pattern of energy inputs in this paper follows the ORANI-G model (a generic

[4] It is estimated by the author. The related data is derived from the National Bureau of Statistics (NBS).

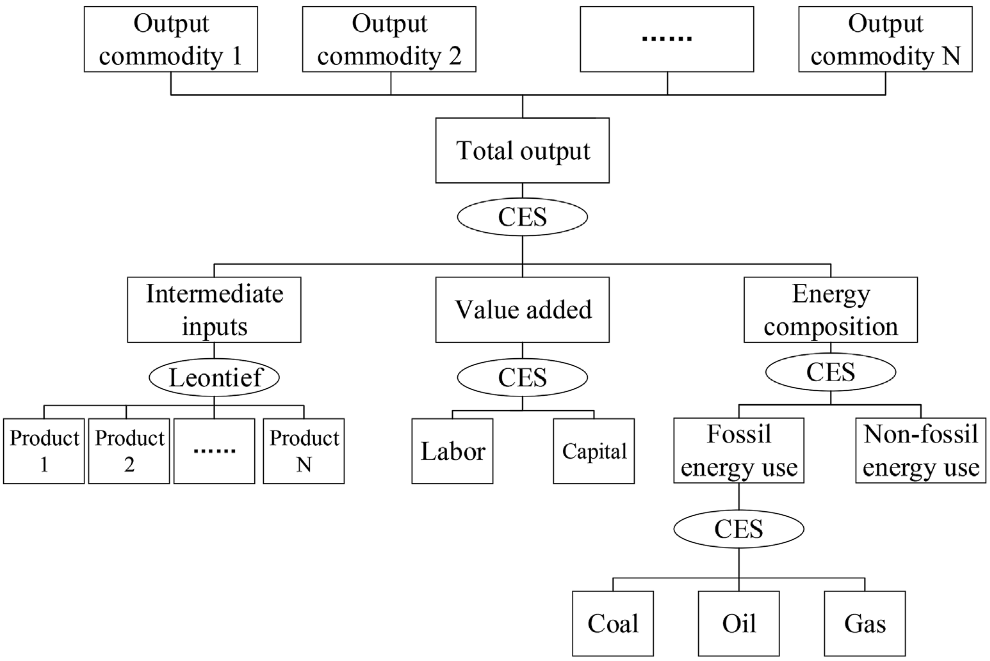

Fig. 2. The dynamic CGE model structure.

single-country CGE model for Australia) regarding the governance of electricity sector (Meng, 2014). On the second level, value added is a CES function of the composition of labor and capital, while energy is disaggregated into fossil energy and non-fossil energy (electricity) with the same CES nested pattern. The bottom level is a CES composition of coal, oil, and natural gas. All intermediate inputs are strictly complementary, and are composited by a Leontief function. The main production equations are described below:

$$XT_{j,t} = B_j^{XT}\left[\beta_j^{CI}*CI_{j,t}^{-\rho_j^{XT}} + \beta_j^{VA}*VA_{j,t}^{-\rho_j^{XT}} + \left(1-\beta_j^{CI}-\beta_j^{VA}\right)*EC_{j,t}^{-\rho_j^{XT}}\right]^{-1/\rho_j^{XT}}$$

$$VA_{j,t} = B_j^{VA}\left(\beta_j^{L}*LAB_{j,t}^{-\rho_j^{VA}} + \beta_j^{K}*CAP_{j,t}^{-\rho_j^{VA}}\right)^{-1/\rho_j^{VA}}$$

$$EC_{j,t} = B_j^{EC}\left(\beta_j^{F}*FOS_{j,t}^{-\rho_j^{EC}} + \beta_j^{EL}*ELE_{j,t}^{-\rho_j^{EC}}\right)^{-1/\rho_j^{EC}}$$

$$FOS_{j,t} = B_j^{F}\left[\beta_j^{COA}*COA_{j,t}^{-\rho_j^{F}} + \beta_j^{OIL}*OIL_{j,t}^{-\rho_j^{F}} + \left(1-\beta_j^{COA}-\beta_j^{OIL}\right)*GAS_{j,t}^{-\rho_j^{F}}\right]^{-1/\rho_j^{F}}$$

where $XT_{j,t}$ is the total final output produced by sector j at time t; $CI_{j,t}$, $VA_{j,t}$, and $EC_{j,t}$ are the non-energy intermediate inputs, the primary factors composites, and the energy composites, respectively; $LAB_{j,t}$ and $CAP_{j,t}$ denote the labor and the capital; $FOS_{j,t}$, $ELE_{j,t}$, $COA_{j,t}$, $OIL_{j,t}$, and are the fossil energy, the electricity, the coal, the oil, and the natural gas, respectively; B_j is the scale parameters; β_j is the share parameters; and ρ_j is the elasticity parameters.

2.2. Income and expenditure

Three agents (households, enterprises, and government) and their related sources of income and expenditure are described in detail. For residents' consumption, Stone-Geary utility function is used to explain how residents distribute income given the disposable income, which is obtained by deduction of the personal income tax.

$$PM_{i,t}*X_{i,h,t} = PM_{i,t}*X_{i,h,t}^{\min} + \gamma_{i,h}^{LES}\left(I_{h,t} - \sum_{ij=1}^{n} PM_{ij,t}*X_{i,h,t}^{\min}\right) \quad (5)$$

where $PM_{i,t}$, $X_{i,h,t}$, and $X_{i,h,t}^{\min}$ are the commodity price by type h household at time t, the actual consumption amount and the minimum consumption for the commodity i by type h household at time t, respectively; $I_{h,t}$ is the disposable income and $\gamma_{h,t}^{LES}$ is the marginal propensity of commodity i; This equation is subject to the conditions of $X_{i,h,t} > X_{i,h,t}^{\min}$ and $0 < \gamma_{h,t}^{LES} < 1$.

Household income is primarily derived from the labour force and the capital use, and the remainder is derived from transfer payments from other agents. Government revenue is primarily derived from income taxation on residents and enterprises (in this paper, it is assumed that the imposed SO_2 taxation is part of the government's revenue). Firms acquire their revenue from capital investments and government transfer payments, with part of the revenue used to pay income tax and be transferred to residents, and the remainder allotted to savings.

2.3. The recursive dynamic module

The specification of dynamic recursive module of this paper is following Lemelin and Decaluwé (2007), where it allows the capital at the current period to be linked with the next. The current capital accumulation is equal to the capital stock in previous period minus depreciation, plus the investment over the same time (see Eq. (6)). Eq. (7) implies that the new capital price is assumed to be related to the quantity of the commodity, and Eq. (8) shows that the new capital investment is constrained by the given investment price. Following Jung and Thorbecke (2003), we modified the investment demand, as shown in Eq. (9). According to Tobin's Q theory, capital depends on price, depreciation rate and interest rate of the new capital (Eq. (10)).

$$KD_{j,t+1} = KD_{j,t}(1-\delta_j) + IND_{j,t} \quad (6)$$

$$IT_t = PK_t \sum_j IND_{j,t} \quad (7)$$

$$PK_t = (1/A^K)\prod_i \left(PC_{i,t}/\gamma_i^{INV}\right)^{\gamma_i^{INV}} \quad (8)$$

$$IND_{j,t} = \phi_{j,t}(R_{j,t}/U_{j,t})^{\sigma_j^{INV}} KD_{j,t} \quad (9)$$

$$U_{j,t} = PK_t(\delta_j + IR_t) \tag{10}$$

where $KD_{j,t+1}$ and $KD_{j,t}$ represent the capital demand by industry j in periods $t+1$ and t, respectively; δ_j is the depreciation rate; $IND_{j,t}$, IT_t, PK_t are the new capital investment, total capital investment and the new capital price, respectively; A^K is the size of the coefficient; $PC_{i,t}$ is the producer price; γ_i^{INV} is the total investment demand in the share of goods; $\phi_{j,t}$ is the size of the parameters (assigned to the sector's investment); $R_{j,t}$ is the rental rates; $U_{j,t}$ is the cost of capital use; σ_j^{INV} and IR_t are the elasticity of investment demand relative to Tobin's q and interest rate, respectively.

2.4. Environment module

To effectively mitigate SO_2 emission in particular industries, the module of SO_2 emission control is added to the production process. It is assumed that the demand for this element is equal to the total amount of SO_2 generated by the consumption of fossil energy. The module constitutes energy-related SO_2 emission, which is written as follows:

$$SE_{j,t} = \left(\sum_s QF_{j,s,t} * EF_s\right) \tag{11}$$

where $SE_{j,t}$ stands for the SO_2 emission by industry j in period t, $QF_{j,s,t}$ represents the input of fossil energy s by industry j, EF_s is the SO_2 emission factor for fossil energy s, and TC_t denotes the clean technical progress (CTP) that cuts SO_2 pollution. Since the clean technological progress (TC_t) is a prominent way of controlling for SO_2 emission, in order to describe the impact of TC_t on pollution reduction, it is joined into Eq. (11).

$$SE_{j,t} = \left(\sum_s QF_{j,s,t} * EF_s\right) / TC_t \tag{12}$$

The way of imposing sulfur taxation can be divided into two components: the first one is collecting SO_2 taxation from the consumption side, namely, fossil energy users; and the second is to collect it from the production process. Both of the two means have advantages and drawbacks. The former helps curb the demand for fossil energy, with a wider range compared with the latter. This paper adopts the latter pattern. The governance object is focused on the polluted industries. In what follows, SO_2 tax rate is set as endogenous in the scenario of SO_2 emission control to achieve the goals set, and its tax rate increases progressively as the emission reduction cost rises.

$$PP_{j,t} * OUT_{j,t} = OT_{j,t} + SE_{j,t} * TS_t \tag{13}$$

$$\sum_j SE_{j,t} = TQ_t \tag{14}$$

where $PP_{j,t}$ is the producer price of industry in period t; $OUT_{j,t}$ is the total output; TS_t is the SO_2 taxation rate; TQ_t is the aggregate SO_2 emission.

Since sulfur oxides, nitrogen oxides and others caused by fossil fuels and wastes combustion will ultimately be converted into $PM_{2.5}$, it is assumed in this paper that SO_2 emission is highly correlated with $PM_{2.5}$ concentration. To validate it, a monthly panel data about $PM_{2.5}$ and SO_2 over the period 2014–2016 in 179 typically polluted cities of China is used to capture the intercorrelation. Econometric result shows that the correlation coefficient between $PM_{2.5}$ and SO_2 is greatly significant, with a value of 0.6.[5] Relevant supporting comments can further be found in Zheng et al. (2005). Therefore, there is a good reason to make the deduction that reducing SO_2 emission will help lower $PM_{2.5}$.[6] According to the "Bulletin of the State of Environment of Shanxi Province in 2015", the average concentration of $PM_{2.5}$ in 11 major cities of Shanxi in 2015 is 56 μg/m^3, and the total SO_2 emission is 1.12 million tons throughout the year.[7] Thus, in this paper, it is supposed that the ratio of SO_2 emission to $PM_{2.5}$ is generally kept constant.

3. Data source and scenarios setting

3.1. Data source

The base data used for this study is obtained from the latest 2012 input-output table for Shanxi that covers 42 sectors. All of the sectors are aggregated into ten categories: agriculture, coal, oil, natural gas, electricity, light industry, heavy industry, construction, transportation and service. The remainder data for the Social Accounting Matrix (SAM) of Shanxi are compiled from the Shanxi Statistical Yearbook, China Finance Yearbook and the NBS. The GAMS technique is applied to build CGE model.

The initial data of the SAM table is presented in terms of value quantity rather than physical quantity. However, energy consumption and pollutant data are more appropriate to be calculated in physical quantity. It is assumed in this paper that SO_2 and CO_2 emissions are derived from fossil fuel combustion. Detailed pollutant emission data need to be evaluated separately according to the related emission factors. In detail, the calculation of SO_2 emission is by the conversion of standard physical quantity (unit: tsce) to physical quantity (unit of coal and oil is measured by ton while natural gas is m^3) in the light of the standard conversion coefficients of various fossil energy sources in the China Energy Statistical Yearbook. The quantity of CO_2 emission is obtained by estimating the standard amount of the consumption by each type of energy based on the same method as SO_2, and then evaluating it according to the CO_2 emission factors, which is derived from Meng and Niu (2011).

The population growth rate is obtained from the United Nations population prospects (2015) for China.[8] The GDP growth rate between 2016 and 2030 refers to the EIU database.[9] With respect to energy efficiency, according to the National Development and Reform Commission (NDRC) of China, the annual predicted improvement in energy efficiency is 3% from 2003 to 2020. Against this background, following the study of Xu and Masui (2009), annual energy efficiency improvement rates were conservatively established in different periods, with 2.5% from 2016 to 2020 and 1.5% from 2021 to 2030. In addition, by calculating the intensity of SO_2 emission from 2002 to 2015 in Shanxi (a decrease in the SO_2 emission intensity can be considered as equivalent to CTP), it is found that annual rate of CTP on average in Shanxi held at a rate of 14.31%.[10] In view of the fact that China is under the 'new normal' state, the slowdown of economic growth will inevitably lead to a decrease in the growth rate of CTP. In this context, we establish that annual CTP increases by 7% from 2012 to 2020, and 5% from 2021 to 2030. In particular, according to the China's 13th Five-Year Plan, its renewable energy share in total energy consumption in 2030 will target to 20%, considering the goal of its development. However, a large proportion of coal use in Shanxi suggests that the adjustment of coal-dominated consumption structure to a green one may take years. Particularly, conservative forecasts for the target of

[5] Data details are available upon request.

[6] See Zheng et al. (2005). Coal combustion is a major source of $PM_{2.5}$. For example, in Beijing, the coal use accounts for 40% of $PM_{2.5}$ (http://tech.qq.com/a/20120224/000460.htm). Therefore, it seems that $PM_{2.5}$ and SO_2 are partly derived from the same source.

[7] http://www.sxhb.gov.cn/cmsContent.action?articleId=9f94fd50-aeff-4851-88a9-f6088fe472af.

[8] We cannot find a specific population forecast data for Shanxi Province, as Shanxi is geographically and economically located in the middle part of China. That is to say, its economic development level is similar to the overall level of china, thus the data for China's population growth rate forecast by UN is adopted. https://esa.un.org/unpd/wpp/publications/files/key_findings_wpp_2015.pdf.

[9] https://eiu.bvdep.com/version2017510/cgi/template.dll?product=101&user=ipaddress&dummy_forcingloginisapi=1.

[10] It is calculated by the author and the original data comes from the NBS.

Table 1
Scenarios setting.

Scenarios	Brief description
BAU	Business-as-usual scenario. No policy constraints on sulfur emission.
T11	Annual energy efficiency improvement: 2.5% in 2012–2020; 1.5% in 2021–2030. Annual CTP: 7% in 2012–2020; 5% in 2021–2030. SO_2 emission cap: 10%. SO_2 price is endogenous.
T12	Annual energy efficiency improvement: 2.5% in 2012–2020; 1.5% in 2021–2030. Annual CTP: 7% in 2012–2020; 5% in 2021–2030. SO_2 emission cap: 20%. SO_2 price is endogenous.
T13	Annual energy efficiency improvement: 2.5% in 2012–2020; 1.5% in 2021–2030. Annual CTP: 7% in 2012–2020; 5% in 2021–2030. SO_2 emission cap: 30%. SO_2 price is endogenous.
T21	Annual energy efficiency improvement: 2.5% in 2012–2020; 1.5% in 2021–2030. Annual CTP: 7% in 2012–2020; 5% in 2021–2030.
T22	Annual energy efficiency improvement: 2.5% in 2012–2020; 1.5% in 2021–2030. Annual SO_2 efficiency improvement: 7% in 2012–2020; 5% in 2021–2030. Energy intensity decreases 25% in 2012–2030.
T3	Annual energy efficiency improvement: 2.5% in 2012–2020; 1.5% in 2021–2030. SO_2 tax rate: 630 yuan/t in 2012–2030 (initiated by China's NDRC since 2005)

renewable energy in primary energy use are 10% in 2020 and 15% in 2030. As for capital accumulation, annual depreciation rate for capital on average in Shanxi is assumed to be 5% (Hsieh and Klenow, 2009).

3.2. Scenarios setting

To estimate potential impacts of SO_2 emission reduction, seven scenarios were established in this CGE model (see Table 1), including a business-as-usual (BAU) scenario (reference scenario) and six other counterfactual scenarios. The BAU scenario was characterized by no further SO_2 pollution control. The first three out of the six simulation scenarios are SO_2 control cap scenarios under the condition of endogenous SO_2 tax, technical progress and EE improvement. Specifically, green technical progress is supposed to increase annually on average of 7% between 2012 and 2020 and 5% from 2021 to 2030, while energy efficiency is annually improved by 2.5% from 2012 to 2020 and 1.5% from 2021 to 2030. T11, T12 and T13 achieve a specific stringent cap on SO_2 emission with a quantity reduction of 10%, 20% and 30%, respectively. Accordingly, the required SO_2 tax rate is treated as endogenous. The fifth scenario T21 merely enforces technical progress and EE improvement to explore whether there is energy round effect caused by them. Energy intensity control is given increasingly great concern by authorities (Fischer and Springborn, 2011). In the light of the scenario T21, energy intensity control, with a quantity decrease by 25% from 2012 to 2030, is considered. The objective of the final scenario T3 is to explore the influence of a SO_2 tax rate of 630 yuan per ton initiated in 2007 by the NDRC of China. The forecast period starts at 2017 for all scenarios.

4. Simulation results

4.1. SO_2 emission and additional benefits

In general, in a laissez-faire economy without policy intervention, there would be excessive environmental pollution due to negative externalities, which is called market failure. Fig. 3 delineates that SO_2 emission shifts steadily upward without policy restriction, reaching to the level of 1.58 million tons in 2030, increasing by 0.28 million tons compared to the level of 2012. In the T3 scenario, the trajectory of SO_2 emission is very closely correlated with that of the BAU scenario, indicating that imposing SO_2 taxation with a low rate generates a negligible impact on sulfur pollution. Only green technology progress and EE improvement in scenario T21 do not frustrate SO_2 emission, but instead lead to a rise in it. This result shows that single policy of technological progress improves energy efficiency as a result of a lack of incentives from environmental taxation, resulting in more energy consumption with higher sulfur content. On the other hand, under the scenario of controlling for energy intensity, the rate of SO_2 emission reduction performs the fastest decline, presenting a steeper downward slope, and its effect of SO_2 emission reduction is very close to the T13 scenario in 2030. Therefore, lowering energy intensity is a vital approach to achieve the goal of SO_2 governance. Policy makers, in the process of implementing air pollution related policies, should pay due attention to energy intensity.

Under more stringent targets for pollution control, the required SO_2 tax rate increases step by step, which is reflected in the scenarios of T11, T12 and T13. For example, SO_2 tax rate in the T13 scenario gradually increases from 6278.07 yuan in 2017–17442.36 yuan in 2030 (Fig. 4), which provides a reference for policy makers to achieve the specific target of SO_2 emission reduction. Under the cap in T13, a significant fall of $PM_{2.5}$ concentration is observed (see Table 2). For scenarios where SO_2 reduction targets are set up, as demonstrated in Table 2, the decrease in $PM_{2.5}$ concentration relative to the reference scenario ranges from 37.7% to 48.76%. Moreover, it is worth noting that $PM_{2.5}$ under the scenario T21 does not fall significantly. The improvement of energy efficiency makes energy price slow down relative to other factor inputs and increases energy consumption, leading to higher $PM_{2.5}$ concentration.

Unlike the case for SO_2, as displayed in Fig. 5, the trajectory of CO_2 emission in all scenarios follows a steady upward trend. In contrast to the baseline, the instruments under most of scenarios contribute to a decrease in CO_2 significantly, except the T3 scenario. For example, in the T12 scenario (20% reduction of SO_2 emission), carbon emission reduction is close to 30% in 2030 relative to the baseline scenario. Similar to the case of $PM_{2.5}$, a rise in CO_2 emission is found under T21. From this point of view, the control for sulfur will also trigger a synergistic effect on greenhouse gas emission reduction (except T21). Therefore, policy makers should consider the positive impact of SO_2 taxation on other pollutant reduction in the process of environmental governance.

4.2. GDP changes

As shown in Table 3, real GDP loss is found in almost all scenarios. With the regulation intensifying, a negative impact of pollution control on GDP gradually increases. However, compared to the larger emission reduction targets, the negative impact of sulfur reduction on GDP is relatively weak, less than 0.25% (see Table 3). Thus, pollutant emission can be reduced without negatively impacting economic growth rate via reasonable collocation of regulation policies. Because the influence of various sulfur reduction measures on the economy is mainly structural. Such regulation policies put a burden on the development of highly energy-intensive sectors while vigorously facilitating other clean energy industries, such as using coal-clearing technologies, constructing natural gas power facilities, and applying environmental monitoring systems.

4.3. Energy consumption

Although energy consumption in each scenario continues to maintain a stable growth, the establishment of SO_2 regulatory policies in most of the simulation scenarios will contribute to reducing fossil energy consumption in Shanxi (except T21). With respect to different energy sources, as reported in Table 4, the largest decline emerges in the consumption of coal, followed by natural gas and oil, and by 2030,

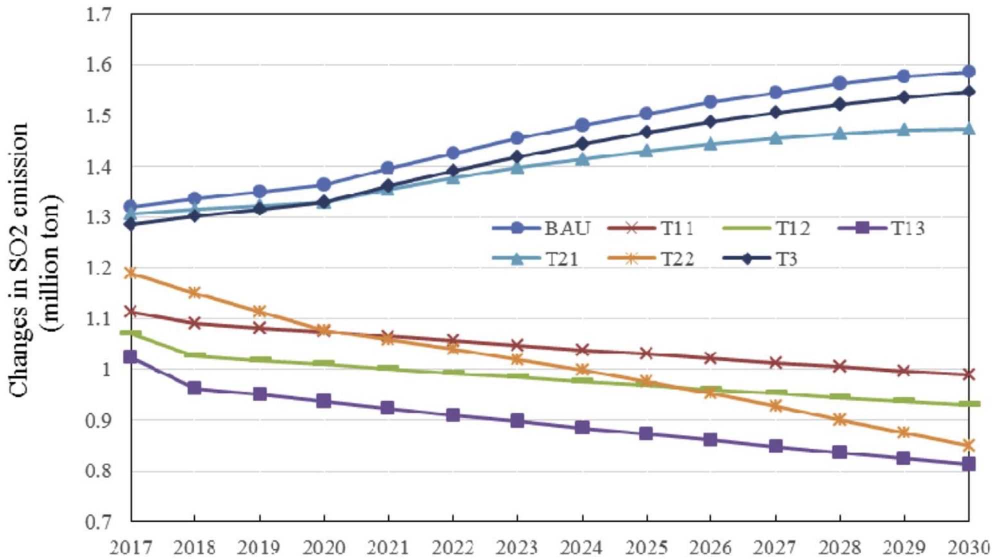

Fig. 3. Changes in SO_2 emission from 2017 to 2030.

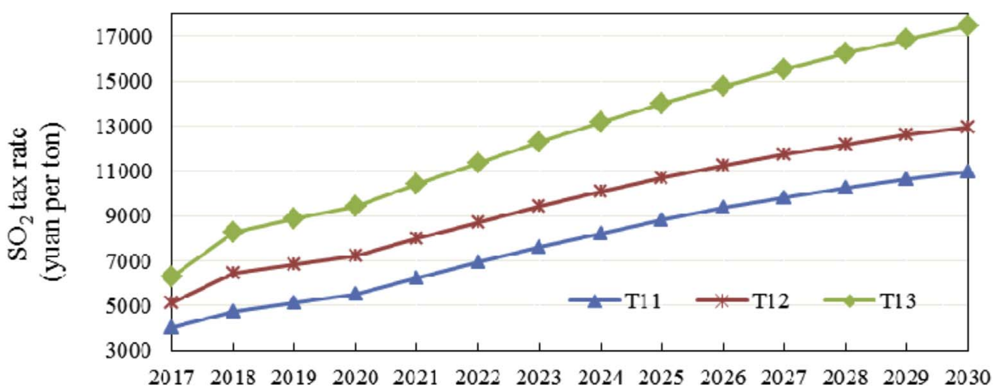

Fig. 4. SO_2 tax rate in three cap scenarios.

Table 2
Changes in PM2.5 compared to BAU (%).

Year	T11	T12	T13	T21	T22	T3
2017	−15.620	−19.030	−22.369	−1.026	−9.909	−2.559
2020	−21.297	−26.019	−31.358	−2.495	−21.141	−2.540
2025	−31.517	−35.626	−41.998	−4.883	−35.124	−2.517
2030	−37.698	−41.436	−48.758	−7.095	−46.495	−2.496

Table 3
Change in real GDP (%).

Year	T11	T12	T13	T21	T22	T3
2017	−0.050	−0.062	−0.073	−0.001	−0.031	−0.009
2020	−0.075	−0.093	−0.113	−0.001	−0.074	−0.010
2025	−0.129	−0.148	−0.176	−0.004	−0.145	−0.011
2030	−0.175	−0.195	−0.234	−0.006	−0.222	−0.012

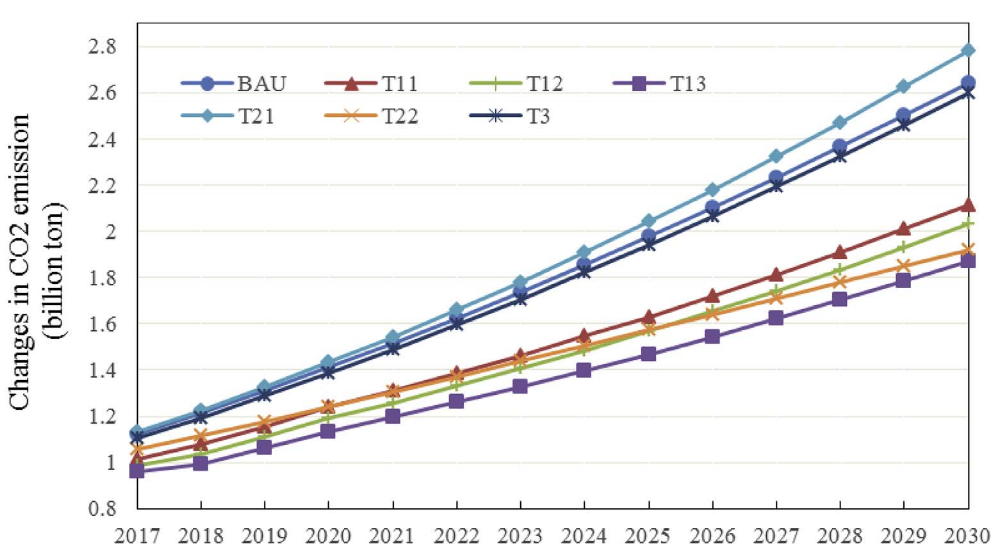

Fig. 5. Changes in CO2 emission.

Table 4
Change in each energy consumption (%).

Sector	Year	T11	T12	T13	T21	T22	T3
Coal	2017	−14.525	−18.109	−21.616	0.008	−8.502	−2.646
	2020	−18.183	−23.280	−29.036	0.021	−17.977	−2.626
	2025	−25.681	−30.321	−37.506	0.045	−29.689	−2.601
	2030	−29.302	−33.721	−42.361	0.070	−39.601	−2.579
Oil	2017	−5.596	−7.177	−8.760	0.008	−3.304	−1.061
	2020	−6.714	−9.097	−11.894	0.021	−7.254	−1.075
	2025	−9.417	−11.786	−15.625	0.044	−12.572	−1.087
	2030	−10.456	−12.856	−17.804	0.069	−17.741	−1.101
Natural gas	2017	−5.743	−7.392	−9.045	0.009	−4.115	−1.101
	2020	−6.750	−9.227	−12.137	0.024	−8.988	−1.108
	2025	−9.296	−11.750	−15.737	0.049	−15.473	−1.114
	2030	−10.088	−12.567	−17.690	0.077	−21.649	−1.120

these three fuels decrease by 42.36% (T13), 17.8% (T13) and 21.65% (T22), respectively. It seems possible that rising production cost associated with sulfur regulation in firms with high energy consumption depresses energy use, particularly the usage for "dirty" energy - coal. This result also indicates that by substituting fossil energies for a clean one, the energy consumption structure dominated by coal in Shanxi will be transformed into a green one.

In addition, the result in T21 shows that single policy to improve energy efficiency and CTP will increase the demand for the three fuels, which confirms the finding as aforementioned. Technological progress could generate energy rebound effect (Greening et al., 2000; Brännlund et al., 2007; Zhang et al., 2015; Lin and Zhao, 2016). An important reason for the energy rebound is that the energy price mechanism in China is imperfect (Lin and Liu, 2013; Li and Lin, 2015), indicating that the energy price and its pricing mechanism in Shanxi are not completely market-oriented.

4.4. Sectors' output

The outcome from each sector differs among scenarios. In contexts of exogenous CTP and endogenous SO_2 tax rate, the effect of various industries caused by environmental instruments is enhanced as the efforts of SO_2 emission reduction are strengthened, characterized by certain nonlinearity. For example, Table 5 shows that coal output in the T11, T12, and T13 scenarios, relative to the reference scenario, decreases by 3.24%, 3.63% and 4.38%, respectively. The maximal negative shock is observed in coal and petroleum sectors where their sulfur content is relatively higher. This result may be explained by the fact that in the process of implementing various measures to control for air pollution, the income and substitution effects in the consumption of coal and oil are negative, yielding sharp falls in production for the two sectors. By comparison, production in other sectors increases in varying degrees. It is noteworthy that natural gas industry performs the best, with a positive level of 9.31% in 2030 over the benchmark scenario. This consequence reflects the substitution of clean energy for dirty energy. In terms of income effect, the consumption for natural gas and coal tends to increase the producers' cost because of the relatively high sulfur content in the two sectors, and thus the induced income effect is negative. However, as for substitution effect, sulfur content in natural gas is much lower than that in coal. The cost of natural gas, as a result of environmental measures, such as sulfur taxes, rises far below that of coal. As a consequence, enterprises will consume more natural gas instead of coal, and the substitution effect between them is positive. Finally, from the perspective of benefit, the positive substitution effect exceeds the negative income effect, thus the combined effect is positive. However, in the case of T21, the fossil energy sectors will be exceptionally benefited, while the output from clean energy sector will be suppressed. Moreover, the production from most of non-energy sectors is obviously found to be reduced. This result implies that policies that only consist of EE improvements and CTP may be counterproductive because of lack of incentives produced by sulfur tax.

Table 5
Change in sectors' output in 2030 compared to BAU (%).

Sector	T11	T12	T13	T21	T22	T3
Agriculture	0.559	0.577	0.591	0.237	0.582	0.030
Coal	−3.235	−3.625	−4.376	0.055	−4.108	−0.243
Oil	−2.617	−3.437	−5.276	2.009	−4.664	−0.258
Natural gas	5.588	6.763	9.309	−1.954	6.167	0.483
Electricity	0.431	0.450	0.477	0.210	0.449	0.018
Transportation	0.476	0.590	0.826	−0.342	0.789	0.053
Heavy industry	2.287	2.653	3.381	−0.583	3.273	0.204
Light industry	1.049	1.198	1.490	−0.148	1.397	0.085
Service	0.287	0.298	0.312	0.143	0.265	0.013
Construction	4.148	4.677	5.702	−0.291	5.580	0.329

4.5. Energy prices

Higher fossil energy prices occur in the cases where SO_2 taxation is endogenous. For instance, as shown in Table 6, in the T13 scenario, coal price rises by 48.79% in 2030, followed by oil, and natural gas. With the SO_2 cap lifting, fossil energy prices rise accordingly. The reason is that the collection of SO_2 taxation directly increases the cost of coal, cutting down the demand for coal and enhancing the use of its alternatives - natural gas. Unlike other scenarios, change in energy prices in the T21 scenario is opposite. This inconsistency may be due to that the energy inputs for firms are more accessible to non-energy types, pushing the energy prices down. In terms of different energy types, the price of natural gas falls even more, for example, with a level of 2.97% in 2030 compared to the baseline scenario.

4.6. Employment

The result in Table 7 demonstrates that labor force in the main

Table 6
Change of energy price (2030) (%).

Sector	Year	T11	T12	T13	T21	T22	T3
Coal	2017	11.337	14.532	17.915	−0.007	6.357	1.743
	2020	15.352	20.342	26.752	−0.023	14.860	1.711
	2025	24.315	29.719	39.504	−0.057	28.327	1.677
	2030	29.931	35.559	48.786	−0.107	43.182	1.644
Oil	2017	2.778	3.551	4.346	−0.167	1.674	0.472
	2020	3.677	4.894	6.386	−0.448	3.903	0.485
	2025	5.692	6.987	9.206	−0.969	7.328	0.497
	2030	6.933	8.300	11.313	−1.569	11.095	0.511
Natural gas	2017	3.051	3.972	4.928	−0.380	3.406	0.546
	2020	3.687	5.102	6.859	−0.963	7.910	0.544
	2025	5.293	6.761	9.312	−1.956	14.854	0.542
	2030	5.910	7.410	10.764	−2.973	22.518	0.540

Table 7
Change in sectors' employment in 2030 (%).

Sector	T11	T12	T13	T21	T22	T3
Agriculture	0.802	0.828	0.849	2.051	0.835	0.043
Coal	−5.555	−6.216	−7.482	−0.318	−7.032	−0.422
Oil	−3.774	−4.948	−7.562	−1.684	−6.695	−0.374
Natural gas	8.209	9.960	13.785	−1.984	9.070	0.702
Electricity	1.973	2.060	2.188	4.250	2.056	0.082
Transportation	1.135	1.408	1.974	2.494	1.884	0.126
Heavy industry	2.161	2.470	3.078	2.162	2.884	0.175
Light industry	4.407	5.119	6.546	1.982	6.333	0.390
Service	0.581	0.603	0.631	−1.071	0.536	0.027
Construction	6.627	7.484	9.150	0.014	8.951	0.520

energy sectors, such as coal sector, declines the most while labor demand in clean energy sector, such as natural gas, increases the most. Similar to the analysis for output, the usage of coal and oil generates more cost for users as a result of the associated environmental regulations. Employers in the two sectors will cut down the labor employed. Furthermore, looking into the differences in employment between the two fossil energy sectors, in most counterfactual simulations (Such as T11 and T12), labor demand in the coal industry is slightly lower than that in the oil sector. As the intensity of sulfur emission regulation increases to a certain extent (T13), employment in the petroleum sector slows down slightly more than that in the coal sector. With respect to the whole industry, labor demand in other sectors rises in varying extents. Specifically, labor force in the light industry raises much more than in the heavy industry. The possible interpretation may be linked to the discrepancy between the substitution and income effects of labor. SO_2 control policies increase the production costs of enterprises and make the substitution from labor to capital, and the substitution effect between labor and capital is greater than the income effect of labor. Consequently, labor force in the two industries increases. Interestingly, the increase in employment in the light industry is higher than that in the heavy industry in the T21 scenario. This observation suggests that the clean technology and energy efficiency tend to ameliorate the employment structure of light industry.

4.7. Marginal reduction cost of SO_2 emission

In this paper, SO_2 abatement cost is defined as the loss of GDP relative to the BAU scenario divided by SO_2 emission reduction as compared to the baseline. It can be regarded as SO_2 shadow price (Lee and Zhang, 2012; Molinos-Senante et al., 2015). With continuous development of economy and the decline of CTP rate, the trend of rising emission reduction costs occurs in all the scenarios. As shown in Table 8, the reduction cost of SO_2 emission in the T21 scenario in 2030 is 80.61 thousand yuan per ton, while the cost in other scenarios ranges from 464.8 to 496.63 thousand yuan per ton. By contrast, it is not difficult to find that the SO_2 abatement cost pushed by cleaner technology and higher energy efficiency seems to be much lower than the cost of SO_2 regulation. In terms of the cost, we tend to recommend the SO_2 tax rate in T12 scenario, because in that case it will not yield high abatement cost while ensuring a moderate amount of SO_2 emission.

Table 8
Marginal reduction cost of SO_2 emission (thousands yuan per ton).

Year	T11	T12	T13	T21	T22	T3
2017	322.687	325.009	326.144	48.730	311.972	340.095
2020	351.689	357.223	360.549	58.081	350.339	379.930
2025	408.640	414.385	419.887	72.215	412.898	439.961
2030	464.804	471.741	480.739	80.607	477.863	496.631

5. Conclusions and implications

Based on the latest 2012 input-output data of Shanxi province, this paper undertakes a quantitative analysis of the long-term impact of SO_2 reduction on local economy by using a dynamic CGE model. Specifically, on the basis of the PEP dynamic CGE model, a series of salient innovations are launched, such as adding the environmental pollution module, modifying the production structure to make it more flexible, embedding SO_2 tax into the production side, amalgamating the sectors and incorporating clean technological progress into the environmental module, and taking into account the target of renewable energy development. The main conclusions are summarized as follows.

With the improvement of clean technology and energy efficiency, the required sulfur tax rate rises correspondingly with the increasing intensity of sulfur regulation. A non-linear characteristic between SO_2 emission tax rate and its regulation target is quite evident. Specifically, to achieve the target of 30% reduction of SO_2 emission relative to the BAU scenario, it is required to impose a SO_2 tax rate of 6278.07 yuan per ton in 2017 and 17442.36 yuan per ton in 2030, respectively. One striking observation is that regulating SO_2 emission will contribute to depressing other air pollutants, such as CO_2 and $PM_{2.5}$, because they stem from the same source to some extent, such as coal usage (Pei et al., 2016). Lowering energy intensity is also an important approach to SO_2 emission abatement, which seems to be more effective in the long run compared with other policies. In addition, it is noteworthy that present SO_2 tax rate of 630 yuan per ton is far from adequate to effectively cutting down SO_2 emission in this region. The results above imply that using the economic instruments to control for the air pollution in Shanxi is reasonable and feasible. In the formulation of related SO_2 emission control policies, the measures persistence and adequate time should be given full consideration to allow full play to their latent role. It also implies that more attention ought to be paid to enforce the environmental organizations management, which contributes to making an integrated analysis of natural resources, biodiversity, and climate change (Jabbour et al., 2012; Gunasekaran et al., 2014).

As for the pivotal macroeconomic indicators, there is a explicitly negative impact on real GDP for all scenarios. With the SO_2 pollution control intensifying, the negative effects on GDP are enhanced accordingly. Nevertheless, compared to the larger extent of SO_2 emission reduction, GDP loss is quite minor, less than 0.25% for all scenarios relative to BAU. One implicit point is that the local government can support environmental enforcement without worrying the loss of GDP as a result of establishing the relevant policies. The energy consumption structure will be effectively improved by tax. The fossil energy demand, especially the coal, is effectively inhibited, while the demand for clean energy is encouraged. These changes impel Shanxi to be progressively transformed into a green economy.

From a sectoral perspective, the impact of cutting SO_2 emission on production is different across sectors. Overall, the output in fossil energy sectors will be curbed while the production in other sectors boosted. Within the energy sectors, output in the oil sector decreases more than that in the coal sector as the target of reducing SO_2 emission reaches 30% compared to the baseline scenario. Thus, if policies are designed to reduce SO_2 discharge mainly by restricting coal consumption, it is essential for policy makers to seriously consider the air pollution control target. This is because too high intensity of regulating SO_2 may incur a tremendous negative impact on other sectors, which baffles the overall industrial development. In addition, the clean energy and construction sectors will benefit the most from output. The improvement of clean technology and energy efficiency increases the employment for the light industry.

In the long run, technical progress is a fundamental way of energy saving and environmental protection, because of lower marginal abatement cost of sulfur discharge under technological advances. The regulators should engage in improving and popularizing clean energy technology, heightening the installation rate for desulfurization and denitrification equipment and shutting down the small scale and inefficient thermal power plant to promote industrial integration and upgrading as well as strengthen the development of relevant laws and regulations. For instance, coal consumption in Germany dropped by close to 40% between 1990 and 2014, while SO_2 emission fell by 92.8% during the period.[11] The reason for this is the rapid development of energy conservation technologies in Germany during this period, with the typical desulfurization technology represented by thermal power plants. At present, the desulfurization equipment installed rate for coal-fired enterprises in Shanxi is relatively low, there is still much space for technical progress. In addition, local government should offer financial support for enterprises' independent innovation. However, as a result of the energy rebound effect, technological innovation and energy efficiency improvement must not be taken as the single means to achieve the goal of energy saving and environmental quality improvement in Shanxi. More attention needs to be paid to the role of market-oriented mechanism on SO_2 mitigation. Pricing mechanism should be fetched into the energy sector to further deepen the reform for energy price system, and exploit the basic role of the market mechanism for energy price. To sum up, to fulfill energy conservation or solve the issues associated with energy and environmental constraints in the local economic development, it is necessary to incorporate a series of market-oriented approaches, such as energy price and environmental tax.

The object of this paper mentioned above is a typical epitome of China's environmental pollution, which also provides insights for other BRICs (Brazil, Russia, India and China) to formulate sustainable development policies. The BRICs have been in the forefront of economic sustainable development strategy in the world, and at the same time been accompanied by some negative impact on their environments. For example, the atmospheric environment in most of cities in India presently fails to reach the national standard, while air pollution annually causes 1.2 million deaths in India.[12] As such, this paper implies the following policy implications for other BRICs. First, due to the local nature on environmental pollution, the central government should strengthen environmental organization management (Jabbour et al., 2012; Gunasekaran et al., 2014) and suit one's measures to local conditions. Second, differentiated environmental pollution control objectives should be set for specific areas. Third, efforts should be made to formulate higher standards for pollutant discharge. Fourth, increasing financial support for renewable energy such as solar and wind power generations is another effective way for air pollution abatement. Last but not least, imposition of environmental taxes is necessary,[13] which can be used to support the development for clean energy technologies.

Indeed, this study, due to the data unavailability, does not take into account the NO_X pollutants when implementing SO_2 reduction related policies, which could be a potential line of future research.

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[11] The data is originated from the OECD database.

[12] https://timesofindia.indiatimes.com/india/air-pollution-causes-12-lakh-deaths-in-india-annually-delhi-most-polluted-greenpeace-report/articleshow/56478622.cms.

[13] According to World Bank, although environmental strategies are costly in the short term, the long-term benefits are more significant. http://siteresources.worldbank.org/INTUWM/Resources/340232-1205330656272/CitiesandClimateChange.pdf.

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