Cover page AAEA09

Economic Growth and Carbon Emission Control
-A case study of power industry in China

Zhenyu Zhang * and Karina Schoengold +

Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2009 AAEA & ACCI Joint Annual Meeting, Milwaukee, WI, July 26-28, 2009.

* Correspondent, Graduate Student, Department of Agricultural Economics, University of Nebraska-Lincoln, Lincoln, NE 68583, USA. E-mail: zzy89@yahoo.com.cn.

+ Assistant Professor, Department of Agricultural Economics and School of Natural Resources, University of Nebraska-Lincoln, Lincoln, NE 68583-0922, USA. E-mail: kschoengold2@unlnotes.unl.edu.

Economic Growth and Carbon Emissions Control -A case study of power industry in China

1. Introduction

1.1 Background

Over the past decades, most developing countries, such as China (11.9%) and India (9%), have achieved moderate to rapid economic growth[1]. The continuous economic growth not only increases the national wealth, but also brings serious environmental problems: from resource depletion to global climate change. This paper tries to answer the question whether the economic development is compatible with environmental protection. The environmental issue examined in the case study is carbon emissions control within power industry of China. The carbon emissions are different from other air pollutants in several aspects: (i) carbon emissions do not impose immediate harm to the public, but have global impact on the climate change; (ii) carbon emissions are generated from rapid industrialization, involving nations at all different level of economic development; (iii) the threshold level of carbon emissions are not certain, and the cost of emissions control is pretty high.

Ideally, to keep global carbon emissions under certain threshold level requires international collaboration and careful examination of the trade off between environmental gain from regulation and economic cost of emissions control. The current international agreement on greenhouse emissions control, the Kyoto Protocol, contributes greatly to provide the comprehensively scientific reports on global climate change and its connection with human anthropogenic activity. However, the Kyoto does not make much progress on further mitigation of carbon emissions, mainly because primary emitters (including U.S. and China) disagree on the timetable of emissions control.

[1] http://en.wikipedia.org/wiki/List_of_countries_by_GDP_(real)_growth_rate

1.2 Problem Statement

We intend to understand the potential of carbon emissions control within one nation in absent of international coordination. The electricity generation sector in China[2] was chosen to demonstrate the economic impacts of emissions control on the production of power industry[3]. We focus on examining the appropriate policies that could provide firms with the 'right' incentive to abate. The important economic questions include: What could be done to stabilize the stock of carbon emissions at what price? Does taxation or subsidy work? What are the impacts of emissions control on economic growth?

To answer these questions, an endogenous growth model is built to represent a regulated power industry[4], and a Coub-Douglas production function is used to describe the joint production of electricity and carbon emissions. The modified Hamilton approach (Wossink and Swinton 2007) is employed to solve the model under three possible polices: emission fee, coal tax and abatement subsidy. The theoretical analysis suggests that firms have no incentive to abate in the absence of regulation. And it finds that the ratio of emissions to desired output is not a constant, but a function of productive capital and other parameters. The non-constant ratio provides the theoretical grounds to choose the appropriate policies for emissions control. Therefore, the sustainable growth could be achieved when appropriate environmental instruments are chosen.

Moreover, the optimal conditions derived from the model, rather than ad hoc specification, are used to examine the relationship between desired output and emissions for empirical analysis. Data comes from the China Statistical Yearbook and China Electric Power Yearbook, providing the provincial information for the period 1993-2003. Joint production function and optimal emissions fee/coal tax rate are estimated using full information maximum likelihood (FIML) method. The empirical results suggest emission fee is preferred to coal tax in the sense of social cost, if and

[2] The biggest emitter in the world (Netherlands Environmental Assessment Agency 2007)
[3] Chinese power generation accounts for 54% of national emissions and contributes to 30% of total worldwide emissions (Intergovernmental Panel of Climate Change 2007)
[4] Hereto China power generation industry.

only if the detection of emissions is not costly, and abatement technology allows removing at least 5% of total emissions at pipe end.

1.3 Organization

The paper will be organized as follows: **Section 2** presents an endogenous growth model (following the Green Solow model by Brock and Taylor 2004), to demonstrate the electricity generation sector in China. The social problem is described as utility maximization of social planner, while carbon emissions are treated as disutility factor. The private problem is described as cost minimization of private firms under the regime of regulated utility price. And the analytical equilibriums are demonstrated for the balanced growth, where the stock of emissions is stabilized and growth of desired output is non-negative. Three possible environmental instruments: emissions fee, coal tax and abatement subsidy are examined. **Section 3** reports the estimation of joint production functions, and the Full Information Maximum Likelihood (FIML) method is employed in SAS. The derived optimal conditions from the model, rather than an ad hoc specification, are used to examine the relationship between the emissions and desired output, and to compute the optimal emission fee and coal tax. **Section 4** concludes with major findings from theoretical framework and empirical analysis, discusses the implications for policy design to accommodate the balanced growth between emissions control and energy supply, and indicates the limitation of this study regarding global emissions control.

2. Model

2.1 Framework

The purpose of this study is to understand the impact of emissions control on firm's choice of allocating capital between production and abatement, and whether the sustainable growth would be achieved under what circumstance. An endogenous growth model is developed to solve for social and private optimum when production decision and emissions abatement activity are decided simultaneously. The electricity generation in China was chosen to demonstrate the model, where price of electricity is regulated and inputs markets are relatively competitive. The optimization problem is

represented by utility maximization for social planner and cost minimization for private firms respectively.

The electricity (Y) and carbon emissions flow (E) are jointly produced using capital (K) and fuel inputs (X), hereto standard coal, combining the three major fossil fuels (coal, oil fuel, gas) used in the electricity generation. While two types of capital are used to represent two possible ways for emissions reduction are considered in this framework: productive capital (K_1) is invested for improving production efficiency, abatement capital (K_2) is invested for capture and storage facility. The production function is defined as $\begin{array}{l} Y = F(K_1, X) = A^a [K_1]^\alpha [X]^{\alpha'} \\ E = G(K_1, K_2, X) = A^b [K_1]^\beta [X]^{\beta'} e^{-K_2 \gamma} \end{array}$, where A represents the technology used in electricity generation; productive capital is used in both outputs function, and marginal productivity of K_1 for both outputs are positive, i.e. $\begin{array}{l} Y_1 = \partial Y(.)/\partial K_1 > 0 \\ E_1 = \partial E(.)/\partial K_1 > 0 \end{array}$ increase in K_1 will be able to produce more electricity as long as more emissions; α, β are the parameters associated with marginal productivity of capital K_1 in joint production function; K_2 is capital used for emission abatement, the more of K_2 used, the less final emission would be released, i.e. $E_2 = \partial E(.)/\partial K_2 < 0$; γ is abatement efficiency rate of removing emission flow after it's generated when the abatement capital K_2 is used.

The major assumptions of this study are: (1) joint-production function fits the Cobb-Douglas structure and is constant return to scale in production factor only for simplicity purpose, which will be tested in empirical analysis; (2) abatement activities are narrowed down to two choices: (2a) reducing the emissions through improvement on production efficiency due to the substitution between productive capital (K1) and input standard coal (X); (2b) capturing and storing the emissions by investing on abatement capital (K2) for building facility of capture and storage; (3) carbon emissions generated at current time period is treated as a flow of pollution, the stock of which decays naturally at rate of ζ; (4) The stock of emissions is a disutility factor of social welfare, over accumulation of which has negative impact on global climate.

2.1 Social planner is assumed to maximize the discounted value of social welfare, that is a utility function of production net value (V) and pollution stock (S), subject to production constraint and environmental constraint. The marginal utility of consuming the private goods (here represented by the production net value) is positive, and marginal utility of pollution is negative, i.e. $\begin{matrix} U_1 = \partial U(.)/\partial V > 0 \\ U_2 = \partial U(.)/\partial S < 0 \end{matrix}$. The social problem could be demonstrated to maximize utility

(1) $\underset{\{X, I_1, I_2\}}{\int} U(V,S)e^{-\rho t}dt$ Subject to

(2.1) $\begin{matrix} Y = AK_1^{\alpha} X^{1-\alpha} \\ E = K_1^{\beta} X^{1-\beta} e^{-K_2 \gamma} \end{matrix}$ production technology

(2.2) $\begin{matrix} \dot{K}_1 = I_1 - \delta K_1 \\ \dot{K}_2 = I_2 - \delta K_2 \end{matrix}$ capital accumulation

(2.3) $\dot{S} = E - \zeta S$ motion of emissions stock

(2.4) $V = Y - I_1 - I_2 - WX$ production net value

where δ is capital depreciation rate, ζ is the natural decaying rate of emissions, S is the stock of emission, E is the flow of emission; W is the real price of input in term of production value; Investment on production I_1, investment on abatement I_2 and input coal X are the choice variables, productive capital K_1, abatement capital K_2 and emissions stock S are the state variables, V is the net value of production. Then current value of Hamiltonian problem could be written as:

(3)

$$H^c = U(V,S) + \lambda_{01}(I_1 - \delta K_1) + \lambda_{02}(I_2 - \delta K_2) + \lambda_{03}(E - \zeta S)$$

Where $\lambda_{01}, \lambda_{02}, \lambda_{03}$ are the co-state variable of state variables K_1, K_2, S, and represent the shadow value of productive capital, abatement capital, and pollution stock respectively. The shadow value of pollution is negative, i.e. $\lambda_{03} < 0$, because the pollution is a bad goods.

The solution of problem (3) has to satisfy the following necessary conditions:

(4) $$H_X{}^c = \frac{\partial H}{\partial X} = U_1(Y_X - W) + \lambda_{03} E_X = 0$$

(5) $$H_{I1}{}^c = \frac{\partial H}{\partial I_1} = U_1 - \lambda_1 = 0$$

(6) $$H_{I2}{}^c = \frac{\partial H}{\partial I_2} = U_1 - \lambda_{02} = 0$$

Equation (4) sets the rule for the socially optimal choice of input coal, where the social benefit of using coal inputs is equal to its market price plus the environmental cost of using coal. The environmental cost is the disutility due to the environmental damage of emissions, i.e. $U_1 Y_X = U_1 W - \lambda_{03} E_X$. Without regulation, the optimal private choice of coal inputs would be set at the point where the benefit of using coal is equal to its market price only, without considering its negative impact on environment, that is $U_1 W - \lambda_{03} E_X = U_1 Y_{X*(social)} > U_1 Y_{X*(private)} = U_1 W$. Therefore, the choice of coal inputs would be lower in the social decision than that under the private decision, i.e. $X*(social) < X*(private)$, because the social marginal utility of X is higher than the private marginal utility of X. Equations (5) - (6) set the rule for optimal social investment, where the marginal utility of private goods equals to the shadow value of capital, i.e. $U_1 = \lambda_{01} = \lambda_{02}$ solving for I_1^* and I_2^* indirectly, noticing at this point that we could not get a function for optimal investment without specifying the structure of the utility function.

2.2 Private problem

Now we look at firm's decision under three possible polices: emission fee, coal tax, abatement subsidy. To achieving the social optimum in private context, the optimal tax/subsidy rate will be

determined by comparing the optimal conditions of private problem with those of social problem. The optimization problem for firms to make production decisions is to minimize the total cost, while the price of final desired output (electricity) is regulated in China.

Obviously, without regulation, firms have no incentive to internalize the social cost of emissions into their production decision, because the shadow value of pollution is zero ($\lambda_{03} = 0$) in private context. When regulation is not in place, the market prices of coal and other factor inputs do not include the environmental damage caused by coal consumption for power generation. As a result, when firms make production decision based on the rule of setting marginal productivity of coal (X) equal to its market price, the private optimal choices would lead to more use of coal inputs X and zero abatement capital (K_2=0 when $K = K_1$) than that of the socially optimal levels. Consequently, the final production of both the desired output Y and the undesired emission E are over the social optimal levels. Therefore, government intervention is necessary.

2.2.1 Scenario #1: Emission fee

The simple and direct tool is to impose a unit fee (τ) on individual firm emissions E. The feasibility of this policy tool relies on the assumption that emissions are easily detected and measured by inspection agent. The private problem can be described as firms minimizing the discounted value of total cost subject to production technology and emissions fee as following:

(P1) Minimize

$$COST(X,K,I \mid Y,E) = \int_0^{\infty} e^{-\rho t}(WX + I_1 + I_2 + \tau E)dt$$

Subject to

(P2.1) $$\begin{aligned} Y &= AK_1^{\alpha} X^{1-\alpha} \geq Y_0 \\ E &= K_1^{\beta} X^{1-\beta} e^{-K_2\gamma} \end{aligned}$$ production technology

(P2.2) $\dot{K}_1 = I_1 - \delta\ K_1$ capital accumulation

$\dot{K}_2 = I_2 - \delta\ K_2$

where the notation of parameters are the same as in social planner's problem in Section 2.1. The constrained cost minimization problem is reformulated as unconstrained problem of maximizing the negative cost[5], and stated as a current value Hamiltonian function as follows:

(P3)

$$H^c = -(WX + I_1 + I_2 + \tau E) + \lambda_{14}(AK_1^{\ \alpha} X^{1-\alpha} - Y_0\ ) + \lambda_{11}(I_1 - \delta\ K_1) + \lambda_{12}(I_2 - \delta\ K_2)$$

Where λ_{11} the shadow value of productive capital K_1, λ_{12} is the shadow value of abatement capital K_2; λ_{14} is the marginal cost of desired output Y, emission flow E and electricity output Y are two jointly produced outputs. Assuming that appropriate conditions to guarantee the existence of solutions are satisfied, we differentiate equation (P3) with respect to the choice and state variables to obtain four conditions for optimality:

(P4) $$\frac{\partial H^C}{\partial X} = -W - \tau\frac{\partial E(.)}{\partial X} + \lambda_{14}\frac{\partial Y(.)}{\partial X} = 0 \Rightarrow W + \tau E_x = \lambda_{14} Y_X$$

(P5) $$\frac{\partial H^C}{\partial I_1} = -1 + \lambda_{11} = 0 \Rightarrow \lambda_{11} = 1$$

(P6) $$\frac{\partial H^C}{\partial I_2} = -1 + \lambda_{12} = 0 \Rightarrow \lambda_{12} = 1$$

Equation (P4) describes the rule for optimal choice of input coal in private context: when the marginal private benefit of using coal is equal to its market price plus the tax. When there is no regulation ($\tau = 0$), the marginal production of coal X is less than that when there is regulation ($\tau > 0$), because $\lambda_{14} Y_X^{\ UR} = W < W + \tau E_X = \lambda_{14} Y_X^{\ R}$. And the

[5] Wossink and Swinton (2007) Ecological Economics 64: 297-304 pp:300.

lower marginal production of coal X means more use of coal inputs X, leading to more emissions. where superscript R represents being regulated, and UR represents being unregulated. Equation (P5)-(P6) sets the rule for optimal investment on both productive and abatement capital, suggesting that the shadow value of each capital is constant and equal.

The growth rate of co-state variables (shadow value of the state variable) are zero at steady state when their optimal values are constant:

$$\text{(P14)} \quad \frac{\dot{\lambda}_{11}}{\lambda_{11}} = \rho + \delta + \frac{\tau E_1 - \lambda_{14} Y_1}{\lambda_{11}} = 0$$

$$\text{(P15)} \quad \frac{\dot{\lambda}_{12}}{\lambda_{12}} = \rho + \delta + \frac{\tau E_2}{\lambda_{12}} = 0$$

Reorganizing equation (P15) and using the emission function defined in equation (P2.2) will give the marginal emission reduction of abatement capital,

$$\text{(P16)} \quad E_2 = -(\rho + \delta)/\tau = -\gamma K_1^{\beta} X^{1-\beta} e^{-K_2 \gamma} = -\gamma E ,$$

and solve for the optimal level of emission flow at steady state for private problem:

$$\text{(P17)} \quad E^*_{private} = (\rho + \delta)/\tau\gamma \ ,$$

which will be equivalent to social optimal choice of emission flow as long as (recall the optimal level of emission flow for social problem is Equation (18) $E^*_{social} = S^* \zeta$).

And the optimal tax rate in private problem would be determined by solving the private problem subject to the optimal emission under social optimum:

$$\text{(P18)} \quad \tau^* = \frac{\rho + \delta}{S^* \zeta \ \gamma}$$

Both equation (P14) and (P15) are equal because the shadow value of each type of capital is the same, implying that the net private value of production capital is equal to the social benefit of abatement capital at optimum as following:

$$\text{(P19)} \quad \lambda_{14} Y_1 - \tau E_1 = -\tau E_2$$

Expanding Equation (P19) will get

$$\lambda_{14} A \alpha K_1^{(\alpha-1)} X^{(1-\alpha)} - \tau \beta K_1^{(\beta-1)} X^{(1-\beta)} e^{-K_2 \gamma} = \tau \gamma K_1^{\beta} X^{(1-\beta)} e^{-K_2 \gamma},$$

and reorganizing it gives the ratio of undesired output with respect to desired output,

$$\text{(P20)} \quad (\frac{E}{Y})^* = \frac{\alpha \lambda_{14}}{\tau(\beta + \gamma K_1)},$$

which provides the theoretical base for further emissions reduction without cutting back the production of desired output.

Private problem under alternative policies

Noticing the challenge for the execution of emissions fee is assuming individual emissions are is observable and easily detected. Actually, the carbon emissions have its unique characteristics, odorless, colorless, and impose long-term danger to the environment, which makes public unaware. The alternative to an unit fee on undesired output (emissions E) are taxing the dirty input (the coal X), or subsiding the investment of abatement capital K_2. The coal tax works on the source of emissions by discouraging the use of coal, while the subsidy works at the end of emissions by encouraging the activity of capture and storage.

2.2.2 Scenario#2: Input Tax

Imposing a unit tax rate $0 < \tau_1$ on the source of emissions, the dirty input X (the standard coal). The private problem becomes individual firm minimizing the production cost given the production

technology and input tax. In order to make it comparable, the social optimal level of emission flow will be incorporated into private problem as one of the constraints. Mathematically, it can be demonstrated as following:

(PP1) Minimize $COST(X, K, I \mid Y, E) = \int_0^\infty e^{-\rho t}[(W + \tau_1)X + (I_1 + I_2)]dt$

Subject to (PP2),

where the constraints include

(P2.1) Production technology

(P2.2) Evolution of capital accumulation,

(18) Social level of emission flow $E \le E^* = \xi\ S^*$

Then the current value Hamiltonian function is stated as

(PP3)

$$H^c = -[(W + \tau_1)X + (I_1 + I_2)] +$$
$$\lambda_{24}(AK_1{}^{\alpha} X^{1-\alpha} - Y_0) + \lambda_{21}(I_1 - \delta\ K_1) + \lambda_{22}(I_2 - \delta\ K_2) + \lambda_{23}(K_1{}^{\beta} X^{1-\beta} e^{-K_2\gamma} - E^*)$$

All notations are the same as that discussed in private problem under the regime of emission fee. Similarly, we obtain private optimum under the coal tax regime:

(PP4) $$\frac{\partial H^C}{\partial X} = -(W + \tau_1) + \lambda_{24}\frac{\partial Y(.)}{\partial X} + \lambda_{23}\frac{\partial E(.)}{\partial X} = 0$$
$$\Rightarrow W + \tau_1 = \lambda_{24} Y_X + \lambda_{23} E_X$$

(PP5) $$\frac{\partial H^C}{\partial I_1} = -1 + \lambda_{21} = 0 \Rightarrow \lambda_{21} = 1$$

(PP6) $$\frac{\partial H^C}{\partial I_2} = -1 + \lambda_{22} = 0 \Rightarrow \lambda_{22} = 1$$

The same strategy is used to solve for optimal input tax by comparing the private optimal conditions equation (PP4) with social optimum in equation (4) for choice of input X, the optimal coal tax rate is:

(PP13) $\tau_1 * = (\lambda_{24} Y_X + \lambda_{23} E_X) - W > 0 \;\; or \;\; < 0$

This says that a tax (subsidy) should be imposed on input coal as long as the net value of using dirty input X is greater (less) than the market price of coal, recall from equation (4) in social planner's problem, $U_1 Y_X = U_1 W - \lambda_{03} E_X$. Ideally, when the market price of coal is set to equal to the net value, i.e. $W = \dfrac{U_1 Y_X + \lambda_{03} E_X}{U_1}$, the market would be efficient in the sense that the market price of input X (mainly coal) has reflected the positive value of coal use on production and its negative impact environment. Therefore, the optimal coal tax rate should be set as the rule defined in (PP13).

2.2.3 Scenario#3: Subsidy abatement

Another alternative policy is to subsidize the investment on abatement (I_2) at the rate of $0<\tau_2<1$, which intends to induce firms to clean up the emission after generation without updating the current production technology. Same notation is applied here and the private problem under scenario#3 could be described as:

(PPP1)

$$\text{Minimize}\, COST(X, K, I \mid Y, E) = \int_0^\infty e^{-\rho t} [WX + I_1 + \tau_2 I_2)] dt$$

Subject to (PP2), the current value Hamiltonian function is stated as

(PPP3)

$$H^c = -[WX + I_1 + \tau_2 I_2)]$$
$$\lambda_{34}(AK_1{}^{\alpha} X^{1-\alpha} - Y_0) + \lambda_{31}(I_1 - \delta\, K_1) + \lambda_{32}(I_2 - \delta\, K_2) + \lambda_{33}(K_1{}^{\beta} X^{1-\beta} e^{-K_2 \gamma} - E^*)$$

Similarly, we obtain the private optimum under the policy of investment subsidy:

(PPP4) $$\frac{\partial H^C}{\partial X} = -W + \lambda_{34}\frac{\partial Y(.)}{\partial X} + \lambda_{33}\frac{\partial E(.)}{\partial X} = 0$$
$$\Rightarrow W = \lambda_{34}Y_X + \lambda_{33}E_X$$

(PPP5) $$\frac{\partial H^C}{\partial I_1} = -1 + \lambda_{31} = 0 \Rightarrow \lambda_{31} = 1$$

(PPP6) $$\frac{\partial H^C}{\partial I_2} = -\tau_2 + \lambda_{32} = 0 \Rightarrow \lambda_{32} = \tau_2$$

In the subsidy case, the rule of investment choices (I_1, I_2) is different from the coal tax case, while the shadow value of production investment ($\lambda_{31} = 1 = \lambda_{21}$) is the same as that in Scenario #2. The shadow value of abatement investment (λ_{32}) is set by the subsidy rate (τ_2), and is lower than that under Scenario #2, i.e. $\tau_2 = \lambda_{32} < \lambda_{22}$. This implies that firms are more likely to invest in abatement under the subsidy policy than that under the coal tax policy, as the lower shadow value of abatement capital is valued less under subsidy regime. In this case, the subsidy on abatement investment of Scenario #3 might provide an incentive to invest on abatement than that under coal taxation in Scenario #2.

(PPP7) $$\frac{\partial H^C}{\partial K_1} = \lambda_{34}\frac{\partial Y}{\partial K_1} - \lambda_{31}\delta + \lambda_{33}\frac{\partial E(.)}{\partial K_1} = \rho\lambda_{31} - \dot{\lambda}_{31}$$
$$\Rightarrow \frac{\dot{\lambda}_{31}}{\lambda_{31}} = (\rho + \delta) - \frac{\lambda_{34}Y_1 + \lambda_{33}E_1}{\lambda_{31}}$$

(PPP8) $$\frac{\partial H^C}{\partial K_2} = -\lambda_{32}\delta + \lambda_{33}\frac{\partial E(.)}{\partial K_2} = \rho\lambda_{32} - \dot{\lambda}_{32}$$
$$\Rightarrow \frac{\dot{\lambda}_{32}}{\lambda_{32}} = (\rho + \delta) - \frac{\lambda_{33}E_2}{\lambda_{32}}$$

Both results are exactly the same as in equations (PP7) and (PP8) of Scenario #2, where a unit input tax on X is imposed. The growth rates of the state variables and the usual transversality conditions are the same as those under coal tax regime. From equation (PPP6), we know that the

investment subsidy rate is equal to the shadow value of abatement capital $\lambda_{32} = \tau_2$. At the steady state, the growth rate of both shadow values is zero. We could then solve for λ_{32} and determine the optimal abatement subsidy rate as:

$$\text{(PPP13)} \quad 0 < \tau_2 * = \frac{\lambda_{33} E_2}{\rho + \delta} < 1$$

Notice that the subsidy rate is always positive, because the social benefit of abatement is positive. Also, in order to assure that the subsidy rate is bounded by one, the social benefit of abatement is required to be less than the sum of discount rate and depreciation rate, i.e. $\lambda_{33} E_2 < \rho + \delta$.

2.3 Private problem under both tax and subsidy

However, an input tax alone is insufficient to achieve the social optimum. When the current production technology is the most efficient one, technically, the ratio between input X and productive capital K_1 is optimal before imposing coal taxation. The cost minimization under coal taxation would induce firms to reduce the power generation using less of input X and capital K_1 by proportion. As a result, the economic growth in terms of output would be slowed down, and emission per unit of output might remain unchanged. Therefore, under regime of coal tax, the emission control could be achieved at the cost of economic growth, and the environmental protection is not compatible with economic growth.

When the current production technology is not the most efficient one, the substitution between capital K_1 and input coal X would allow firms to improve the production efficiency by investing more on K_1 and use less of input X for cost minimization under input tax. In that sense, the production efficiency is improved and emission control would be achieved from lower emission per unit of output, but such a result is not guaranteed. For efficient firms, they might stick with current technology

and choose to reduce the production under input taxation. For inefficient firms, they might choose updated production technology that requires more investment on capital and allows using less of input X to produce the same amount of output, if cost increase from investment could be compensated from cost savings from less input and increased productivity.

It is also possible for both efficient and inefficient firms to choose even less efficient and dirtier technology that requires less investment on capital K_1 and use more of input X as long as the saving from less capital is not smaller than the expenditure on purchasing input X and paying tax on input X. As a result, the emission per unit of output might be unchanged or even increased, and the goal of emission control could be achieved at the cost of slowing down the economic growth, which is not sustainable.

In the later situation, unless the cost increased by coal tax will be paid off through technology improvement, firms are not likely to invest on more efficient (clean) technology by increasing K_1. Consequently, the input tax distortion might induce firms to use less efficient (dirty) technology, and discourage further investment on cleaner technology. Therefore, subsidy on investment associated with abating (K_2) or efficient production (K_1) should be considered along with input (coal) tax, in order to achieve the goal of reducing the flow of emissions or stabilizing the stock of emissions.

Now we would examine the case of a combination of input tax with investment subsidy (referring to both capital K_1, K_2 or either one of them) would be examined in the following discussion, where the parameter less (or greater) than 1 determines the instrument imposed on investment is a subsidy (or tax).

(CP1)

Minimize

$$COST(X,K,I \mid Y,E) = \int_0^{\infty} e^{-\rho t}[(W+\tau_1)X + \tau_2(I_1+I_2)]dt$$

Subject to (CP2), which is exactly the same as (PP2), the current value Hamiltonian function is stated as

(CP3)

$$H^c = -[(W+\tau_1)X + \tau_2(I_1+I_2)]$$
$$\lambda_{C4}(AK_1^{\alpha}X^{1-\alpha} - Y_0) + \lambda_{C1}(I_1 - \delta K_1) + \lambda_{C2}(I_2 - \delta K_2) + \lambda_{C3}(K_1^{\beta}X^{1-\beta}e^{-K_2\gamma} - E^*)$$

Similarly, we obtain the private optimum under the combined policy of input tax and investment subsidy:

(CP4) $$\frac{\partial H^C}{\partial X} = -(W+\tau_1) + \lambda_{C4}\frac{\partial Y(.)}{\partial X} + \lambda_{C3}\frac{\partial E(.)}{\partial X} = 0$$
$$\Rightarrow W + \tau_1 = \lambda_{C4}Y_X + \lambda_{C3}E_X$$

(CP5) $$\frac{\partial H^C}{\partial I_1} = -\tau_2 + \lambda_{C1} = 0 \Rightarrow \lambda_{C1} = \tau_2$$

(CP6) $$\frac{\partial H^C}{\partial I_2} = -\tau_2 + \lambda_{C2} = 0 \Rightarrow \lambda_{C2} = \tau_2$$

Under the combined policy, the shadow values of investment I_1 and I_2 are the same, and also determines the subsidy rate, which implies that firms would have the same incentive to invest in either K_1 or K_2, and both ways help to achieve the social goal of zero growth of emissions stock and non-negative of output growth.

(CP7) $$\frac{\partial H^C}{\partial K_1} = \lambda_{C4}\frac{\partial Y}{\partial K_1} - \lambda_{C1}\delta + \lambda_{C3}\frac{\partial E(.)}{\partial K_1} = \rho\lambda_{C1} - \dot{\lambda}_{C1}$$
$$\Rightarrow \frac{\dot{\lambda}_{C1}}{\lambda_{C1}} = (\rho+\delta) - \frac{\lambda_{C4}Y_1 + \lambda_{C3}E_1}{\lambda_{C1}}$$

$$\text{(CP8)} \quad \begin{aligned} &\frac{\partial H^C}{\partial K_2} = -\lambda_{C2}\delta + \lambda_{C3}\frac{\partial E(.)}{\partial K_2} = \rho\lambda_{C2} - \dot{\lambda}_{C2} \\ &\Rightarrow \frac{\dot{\lambda}_{C2}}{\lambda_{C2}} = (\rho+\delta) - \frac{\lambda_{C3}E_2}{\lambda_{C2}} \end{aligned}$$

The same strategy is used to solve for optimal input tax by comparing private optimal conditions equation (CP4) with social optimum in equation (4) for choice of input X. The optimal choice of input tax rate is

$$\text{(CP13)}\ \tau_1 * = \lambda_{C4}Y_X + \lambda_{C3}E_X - W > 0 \ \ iff \ \ \lambda_{C4}Y_X + \lambda_{C3}E_X > W$$

Meanwhile, to get the optimal rate of investment subsidy, using equation (CP5~CP8) will get

$$\text{(CP14)} \quad \begin{aligned} &\tau_2 * = \frac{\lambda_{C3}E_2}{\rho+\delta} = \frac{\lambda_{C4}Y_1 + \lambda_{C3}E_1}{\rho+\delta} < 1 \\ &iff\ \lambda_{C3}E_2 = \lambda_{C4}Y_1 + \lambda_{C3}E_1 < \rho+\delta \end{aligned}$$

Both input taxation and investment subsidy together will assure the private firms achieve the same optimal flow of emission as that under the social optimum.

2.4 Comparative Static Analysis

2.4.1 Optimal emission tax rate in private problem

Equation (17) defines the rule for setting the tax rate on emissions, and the signs of the derivative of the optimal tax rate with respect to variables of interest will tell the directional impact that different factors have on the choice of emission tax rate.

$\frac{\partial \tau^*}{\partial(\rho+\delta)} = \frac{1}{S^*\zeta\gamma} > 0$ suggests that as the discount rate and depreciation rate increases, the tax rate should increase as well, because a high discount rate means that an individual is less patient and prefers consuming or producing immediately instead of saving for the future, In that case, the individual preference in the utility function would

stimulate more consumption and production, which in turn generates more emissions; in order to stabilize the stock of emission, higher tax rate is in order. Higher depreciation rate of capital would induce firms to invest more in the current period, and lead to more production and emission, which requires a higher tax rate on emission to achieve the social goal of stabilization of emission stock. $\frac{\partial \tau^*}{\partial \gamma} = -\frac{(\rho+\delta)}{S^* \zeta \gamma^2} < 0$ implies that the higher efficiency of capturing and storing emission after its generation, then a lower tax rate is required. Similarly, $\frac{\partial \tau^*}{\partial \zeta} = -\frac{(\rho+\delta)}{S^* \zeta^2 \gamma} < 0$ means that the higher natural dissipating rate of emission stock, then a lower tax rate is needed. $\frac{\partial \tau^*}{\partial S^*} = -\frac{(\rho+\delta)}{(S^*)^2 \zeta \ \gamma} < 0$ suggests that higher optimal emission stock would need a lower tax rate on emission flow, which is possible due to the fact that high stock of optimal emission results in less urgency on emission control.

2.4.2 Optimal emission factor

Equation (20) defines the relationship between two joined outputs at optimum. Taking derivatives of Equation (20) with respect to corresponding variables gives the impact and direction of each variable on the ratio. For instance, $\frac{\partial (E/Y)^*}{\partial K_1} = -\frac{\alpha \lambda_{14} \gamma}{\tau(\beta + \gamma K_1)^2} < 0$ suggests that increasing in productive capital K_1 would lower the ratio, which might explain the mechanism of reduced emission/output ratio through cleaner production technology; $\frac{\partial (E/Y)^*}{\partial \tau} = -\frac{\alpha \lambda_{14}}{\tau^2 (\beta + \gamma K_1)} < 0$ suggests that a higher tax rate on emissions will also lower the ratio, which might be explained by firms' incentive to reduce the emission from capture and storage. The second possible way of abatement, in order to avoid high

tax payment on pollution; $\frac{\partial(E/Y)^*}{\partial\gamma} = -\frac{\alpha\lambda_{14}K_1}{\tau(\beta+\gamma K_1)^2} < 0$ means that the higher of abatement efficiency on capture and storage, the second possible way of abatement, the lower the ratio would be.

$\frac{\partial(E/Y)^*}{\partial\alpha} = \frac{\lambda_{14}K_1}{\tau(\beta+\gamma K_1)} > 0$. Surprisingly, α, the share of K_1 in production function will increase the ratio. It might be because the growth of desired output is less than that of emission when the share of capital in production of desired output

increases; $\frac{\partial(E/Y)^*}{\partial\beta} = -\frac{\alpha\lambda_{14}}{\tau(\beta+\gamma K_1)^2} < 0$ indicates that β, the shard of K_1 in emission function will reduce the ratio, suggesting that the role of capital in emission function is to improve the efficiency by slowing down the growth of emission relative to that of desired output, which in turn to lowers the emission per unit of output.

2.4.3. Abatement Subsidy in Private problem

Equation (PPP13) defines the rule for optimal subsidy rate in private context to achieve equivalent social goal. Taking derivatives of subsidy rate with respect to each element explains the impact of each element on the change of it. For instance,

$\frac{\partial\tau_2}{\partial\rho} = \frac{\partial\tau_2}{\partial\delta} = -\frac{\lambda_{33}E_2}{(\rho+\delta)^2} < 0$ suggests that the higher discount rate or higher depreciation rate needs lower subsidy, because the high depreciation rate of capital would induce firms to invest more on production in the current period rather than invest in the future. An increase in capital, regardless of whether it is for production purposes or for abatement, might result in emission reduction. The result depends on the productivity of capital in both power and emission generation.

The mechanism of abatement due to increased capital is through improving the production efficiency before emissions are generated or

abatement action after emissions are generated. When the increase of productive capital (K_1) improves the emission factor (the emission per unit of output), more efficient production technology would be adopted, the less investment is required for abatement, and the lower subsidy on abatement is needed. As the same mechanism applies to how the change of consumers' preference (the discount rate), would affect the choice of subsidy rate on abatement.

$\frac{\partial \tau_2}{\partial E_2} = \frac{\lambda_{33}}{(\rho + \delta)} < 0$ implies that when abatement is more efficient, a lower subsidy is needed on abatement capital. When the abatement technology is highly efficient and easily adopted, the firms would have more incentive to do so, even without subsidy.

3. Empirical analysis

The data from China Statistical Yearbook and China Electric Power Yearbook of the time period 1993-2003 was selected for empirical analysis. The statistical information covers 26 provinces and 4 municipalities. Variables used for estimation include the final output Y, which is the total electricity generated for the current year by each province, measured in 100 million kWh; three major fuel inputs Xi (coal, oil, and gas) were used for producing the final output Y and measured in 10 thousands tons; K represents the total capital invested in production, measured in million Yuan of current year; SCC is the average production efficiency for each province, measured in gram of standard coal consumption per unit of kWh; and byproduct emission E is computed by combining each type of fuel used in power generation, times the corresponding carbon conversion factor[6], measured in million tons of CO_2, which is defined by China Development and Reform

[6] E=COAL*2.11 (ton co2/ton coal) + OIL*3.06 (ton co2/ton oil)+GAS*2.19 (ton co2/1000m3 gas),

Committee (2007)[7]. The variable description in details is summarized in Table 2.

The total 329 observations (because several variables are not available for Xizhang Province in the year of 1998) of 30 provinces and municipalities for the 11 years period have been used to estimate the joint production functions and examine the relationship between undesired output E (carbon emission) and desired output Y (electricity generation). Since the emissions and electricity are jointly produced, estimation of these two production functions requires the use of simultaneous equation techniques, as the error term in each equation is likely to be correlated. Therefore, the Full Information Maximum Likelihood (FIML) method is used for the estimation in SAS program, which is a nonlinear method equivalent to the linear equation method of Seemingly Unrelated Regression (SUR). The FIML estimation provides asymptotically efficient estimators for models that are nonlinear in parameters with normally distributed errors.

3.1 Estimation of Joint Production Function

The provincial data are used to estimate the joint production functions and the hypotheses regarding the structure of the Cobb-Douglas are tested. The results show that the joint production function could be described as

$$Y = A^{-0.027} K_1^{0.0075} X^{1.03}$$

(3.1a) $$E = A^{-0.62} K_1^{0.038} X^{1.02}$$

when no abatement activity is involved (K_2=0).

The joint production functions could be described as

$$Y = A^{-0.027} K_1^{0.0075} X^{1.03}$$

(3.1b) $$E = A^{-0.46} K_1^{0.0055} X^{1.02}$$

when abatement activity is $K_2=1/\gamma$ at zero growth of the emissions flow. The estimation results are also listed in Table 3a and Table 36. Noticing that under

[7] http://cdm.ccchina.gov.cn/WebSite/CDM/UpFile/File1364.pdf

both scenarios, the constant returns to scale in both capital and coal factor are not hold. The details about testing on the structure of the joint production function are shown in Table 4. Therefore, the general structure of Cobb-Douglas better fits the data.

The estimation of the joint production functions have three important implications: (i) At the margin, an improvement in the production technology (A) would increase the output of the byproduct (emissions) more than desired product (electricity); (ii) The productive capital (K_1) plays a small role in the joint production process. This is consistent with observations that power generation technology is mature and capital investments are gradually switching from power generation to power distribution and network construction; (iii) The marginal productivity of coal inputs (X) plays a major role in the joint production process, which reflects the fact that Chinese power generation mainly relies on burning fossil fuel, especially coal.

The estimation results imply that there are two ways for emission abatement: one is to abate emissions at the beginning of the pipe by reducing inputs (X) use; the other is to abate emissions at the end of the pipe through the use of a capture and storage system, achievable through investment in abatement capital K_2. In fact, the estimation of joint production function provides the empirical basis for choosing two possible policies for emission control, namely the input tax (τ_1) and abatement subsidy (τ_2).

3.2 Estimation of Optimal rate

Using the estimated joint production functions and derived conditions at balanced growth, we could estimate the optimal emission fee τ under different levels of abatement efficiency γ, and optimal coal tax τ_1 corresponding to different level of discount rate ρ. IPCC (2005) [8] reports that in theory, the current post-combustion and pre-combustion systems for power plants could capture 85–95 percent of the CO_2, but

[8] http://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf

the physical absorption technique for CO_2 removal is not suitable for application to exhaust gas from power plants having relatively low concentration (10 percent or less) of CO_2. Higher capture efficiencies are possible, although separation and purification devices are energy intensive. Usually, capture and compression needs roughly 10–40 percent more energy than the equivalent plant without capture, depending on the type of abating system.

3.2.1 Emission fee

The derived condition in equation (P20) describes the relationship between desired and undesired output at balanced growth, which is used to compute the optimal emission fee under different level of abatement efficiency rate (γ). Noticing that the carbon capture and storage (CCS) has not yet been applied to large (above 500 MW) fossil fuel power plants, and the overall system may not be as mature as some of its components. Technically, CSS technologies would be able to remove as much as 85 percent of emissions, but there are still long way to adopt the abatement technology in large scale. Considering the uncertainty of high technology adoption and heterogeneity of power plants in China, we intend to be conservative by choosing a much lower abatement efficiency rate (γ), such as 1, 5, and 10 percent to estimate the optimal emissions fee.

The results are consistent with the comparative analysis discussed in section 2.4, where the tax rate is decreasing as the abatement efficiency improves. Our empirical results show that the emission tax rate is pretty high, 59.78 percent as the ability of removing the carbon emission after it has been generated is as low as $\gamma = 1\%$; when the capability of capture and storage increases by five times of before, i.e. $\gamma = 5\%$. The emission tax required to achieve the same social goal would be dramatically reduced to 13.4 percent; when $\gamma = 10\%$, the emission tax rate is reduced to 6.88 percent. When the abatement method could remove all the emissions after its generation

($\gamma = 100\%$), theoretically, there is no need to impose an emission tax to curb emission due to highly efficient abatement technology. This is consistent with our estimation result where the tax rate required is relatively small, 0.787 percent, or almost zero.

3.2.2 Estimation of coal tax

Under the coal input tax (Scenario #2), the optimal choice on coal tax rate is defined and derived in equation (PP13), which gives us the theoretical basis to estimate the tax rate. First, we need to get the shadow value of output (λ_{24}) is marginal cost of desired output), and the shadow value of emission (λ_{23}). At the steady state, the growth rate of shadow value for each state variable is constant, which is derived from Hamiltonian function as $\begin{array}{l} \frac{\dot{\lambda}_{24}}{\lambda_{24}} = \rho + 1 \\ -\frac{\dot{\lambda}_{23}}{\lambda_{23}} = \rho + 1 \end{array}$, then solve for optimal value $\lambda_{24}^{*} = e^{(\rho+1)t}\lambda_{24(0)}$ where $\lambda_{24(0)}$ is the initial value of at t=0. For simplicity without loss of generality, we choose $\lambda_{24}^{*} = e^{(\rho+1)}$ for further estimation. Next, we use estimated production parameters, $a, b, \alpha, \alpha', \beta, \beta'$ with SCC, K_1, X to compute the marginal productivity of coal (Y_X) and marginal emission of coal (E_X) for each observation. Last, we compute the optimal input tax rate using equation (PP13). At different levels of the discount rate, the optimal choice on the coal tax rate will change accordingly.

According to a study by the OECD (1995), the discount rate in developing countries usually ranges from 4-8 percent. Considering the fact that Chinese have traditionally saved more than in most other developing countries, Cui et al (2002) in their study chose $\rho = 0.04$. For demonstration purpose, we choose the discount rate between 0.04 and 0.16 for computing the optimal coal tax, while the higher discount rate, the lower future value is. The estimation result shows that coal tax rate is

53.37 percent with confidence interval of 34.39 - 60.41 percent when $\rho = 0.04$; a coal tax rate of 56.13 percent with confidence interval of 36.37 - 63.44 percent when $\rho = 0.08$; a coal tax rate of 61.99 percent with confidence interval of 40.57 – 69.88 percent when $\rho = 0.16$.

The coal tax works on its source of emission by cutting the use of coal, but the coal tax alone is insufficient for achieving the sustainable growth. Under a coal tax, firms might choose to cut back the total output, or even choose dirty production technology with less capital investment, as long as the savings on capital investment plus the gain from increased output is greater than the cost of coal consumption. Therefore, a combination of input tax and abatement subsidy might work as an alternative to emission tax, but only theoretical part is demonstrated due to the unavailable data on abatement capital for empirical analysis.

The emissions fee is direct tool for emissions control and is sufficient for achieving the goal of sustainable growth. The downsides of executing the emission fee include the difficulty of regulation enforcement due to the unique characteristics of emissions and volunteered self-report. Empirical results suggest that the optimal input tax does not vary much under different levels of discount rate, while emission tax rate is relatively moderate. For instance, to achieve the same social goal, the optimal emission fee is about 13.78 percent corresponding to abatement efficiency rate of 5 percent, while the optimal coal tax is 53.37 percent for 4 percent of discount rate. Therefore, imposing coal tax is much more costly than emission fee is for stabilizing the stock of emissions at balanced growth.

4. Discussion and Conclusion

The relationship between economic growth and environmental quality has received great attention in empirical and theoretical studies. The answers to the question whether environmental improvement is compatible with continued economic growth remain unclear and require further research in a specific context. Our case study focuses on one major source of carbon emissions: the

electricity generation sector in China, the biggest emitter in the world (Netherlands Environmental Assessment Agency 2007). We intend to understand the potential of emissions control in the absence of international agreement.

The major contribution of this study is to bridge the gap between theoretical and empirical study, and provide the policy implications for emissions control within power sector of China. A theoretical model describes a regulated utility (hereto price of electricity is regulated in China), and was solved using a modified Hamiltonian approach. The optimal conditions derived from the model, have been used to perform the empirical analysis. Previously, the theoretical works had often been pursued independently from empirical testing, and empirical works often use the ad hoc specification and highly rely on the type of data (time series or panel). Our empirical findings are directly connected with the theoretical model developed earlier, and easily addressed to the current situation for the power industry of China.

The theoretical analysis is demonstrated from both social planner and private firms' perspective under three possible regulation instruments (emission fee, coal tax, abatement subsidy). Our theoretical analysis suggests that firms have no incentive to abate in the absence of regulation, because the market price of inputs does not incorporate the environmental cost of the fossil fuel consumption (mainly referred to coal) in long-run. The endogenous growth model of Chinese power generation finds that the ratio of undesired output (emissions) to desired output (electricity) is not a constant. The ratio is a function of productive capital K_1 and other parameters, involving α, β, the marginal productivity of capital K_1 in joint functions, and γ, the abatement efficiency of capital K_2 in emission function. The non-proportional relationship between power generation and its byproducts (emissions) implies the ways of further emission mitigation without cutting back the power generation.

The theoretical analysis also suggests that the emissions fee highly depends on the efficiency of abatement technology: the higher the efficiency is, the lower the tax is required to accomplish the goal; The coal tax rate hinges on

the social preference toward future value, the more people value the environment for future generation's sake, the lower the discount rate is, and the lower input tax rate is required for achieving the sustainable growth. Among three possible policies for emissions control, the emission fee is the ideal and the most direct tool. When the measurement of emissions level and enforcement of emissions fee are less costly, the emissions fee is the best choice of emissions control. But the timing of execution highly hinges on the efficiency of abatement technology. Imposing emissions fee at early stage of abatement technology (when the abatement technology only allows to remove less than 10% of total emissions) would not only discourage abatement activity, but also raise the social cost of accomplishing such a goal.

The emissions fee and coal tax are computed in the empirical analysis, while subsidy rate could not be estimated due to the lack of information on capital invested specific on abatement activity, most of which still under experiments or small scale within the power industry. For estimation of emissions fee, the improvement on abatement efficiency (γ) would largely reduce the fee approximately (τ) by 10 times, i.e. from 59.78 percent to 6.88 percent when γ is increased from 1 percent to 10 percent. Compared to emissions fee (τ), coal tax (τ_1) is more direct to impose when emissions are self-reported on voluntary base. But the coal tax alone is relatively high no matter how low the discount rate is. A decrease in the discount rate (that is individual value less about the present but more about the future) does not lower much of coal tax rate, i.e. the required coal tax rate will be reduced from 65 percent to 54 percent when ρ is decreased from 20 percent to 5 percent. It seems that emissions fee is more preferable to coal tax from the stand point of social cost, if and only if there is chance to improve abatement technology and emissions are easily measured.

Notice that policy implications discussed in the study only applicable to specific industry (power generation) of a specific country (China). First of all, For a broader or more complete policy implication regarding emissions control, more than one significant source of carbon emission is required to build a

general equilibrium. The other important factors, such changes among energy structure, other clean renewable energy sources, energy intensity changes within national economy and international cooperation/trade on abatement credit, also contribute to control the growth of emissions stock. Secondly, the steady state is the focus here for policy implication, because steady state allows simple solutions out of the system, which makes it possible to derive conditions for further estimation. Dynamic solutions, such as phase diagrams maybe better to describe the motion of control variables and state variables for the optimization problems.

In a summary, without international collaboration, within one nation the emissions stock could be stabilized with non-negative growth of economic development. In another word, the environmental improvement is compatible with economic development, as long as appropriate policy is chosen. The choice of policy instruments for emissions control relies on the source of emissions, the discount rate, preference and efficiency of abatement technology. Any policy implications derived from our models and estimations are strictly associated with emissions control in the power industry of China. The empirical results in this study suggests that emissions fee is preferable to coal tax in the sense of social cost, as emissions fee is moderate under low efficiency of abatement technology. The theoretical and empirical analysis in this study might be helpful to understand other similar industries or other stock type pollutions when it comes to the issue of how to achieve the social goal of stabilizing the growth of pollution in the private or market context.

Reference

Brock, A. W., and S. M. Taylor (2004) The Green Solow Model, Working paper 10557, National Bureau of Economic Research (NBER).

China National Statistical Yearbook 1993~2003

China Power Electric Yearbook 1993~2003

Cui, L., Z. Wang, and Y. Liu. "Modeling the Impact of CO2 Mitigation Rate on China's National Economy: a Fuzzy Equilibrium Analysis over the Uncertainty." *Journal of Safety and Environment* 2, no. 1(2002): 38-43.

Intergovernmental Panel on Climate Change (IPCC) 2007 Guidelines for National Greenhouse Gas Inventories

Netherland Environmental Assessment Agency 2007

Organization for Economic Co-Operation and Development (OECD). “The Economic Appraisal of Environmental Projects and Policies: A Practical Guide”. OECD Publishing, 1995.

Wossink, A. and S.M. Swinton. 2007. "Jointness in Production and Farmers’ Willingness to Supply Non-marketed Ecosystem Services." *Ecological Economics* 64(2): 297-304, pp:300.

Table 1 List of parameters (λ_{ij} where i=0,1,2,3,4 represents the social case, scenario#1, #2, #3, and #4, j=1,2,3,4 corresponds to K1, K2, S, Y)

Social problem	
λ_{01} Shadow value of productive capital K_1	
λ_{02} Shadow value of abatement capital K_2	
λ_{03} Shadow value of emission stock S	
Private problem	
Scenario#1: emission fee	**Scenario#2: coal tax**
λ_{11} shadow value of K_1	λ_{21} shadow value of K_1
λ_{12} shadow value of K_2	λ_{22} shadow value of K_2
Shadow value of emission stock S	λ_{23} Shadow value of emission stock S
λ_{14} Marginal cost of desired output Y	λ_{24} Marginal cost of desired output Y
Scenario#3: abatement subsidy	**Scenario#4: combined coal tax & subsidy**
λ_{31} shadow value of K_1	λ_{C1} shadow value of K_1
λ_{32} shadow value of K_2	λ_{C2} shadow value of K_2
λ_{33} Shadow value of emission stock S	λ_{C3} Shadow value of emission stock S
λ_{34} Marginal cost of desired output Y	λ_{C4} Marginal cost of desired output Y

Table 2 Description of Variables

Variable	Stand for	Measurement
Y	Electricity generation	100 million KWH
E	Carbon emission Flow	Million tons of CO2
S	Carbon emissions stock	N/A
A	Standard coal consumption	g/KWH
K_1	Investment of productive capital	Million Yuan
K_2	Investment of abatement capital	N/A
X	Standard coal, representing the factor inputs of coal, gas and oil	10,000 tons

YEAR BETWEEN 1993~2003

Source: Various China Statistical Yearbook and China Power Electric Yearbook

Table 3a Joint Production Function ($K_2 = 0$)

Parameter	Estimate	Standard error	P-value
a	-0.027 ***	0.0018	<0.0001
α	0.0075 ***	0.01015	<0.0001
α'	1.03 ***	0.01018	<0.0001
b	-0.62 ***	0.00094	<0.0001
β	0.0038 ***	0.0008	<0.0001
β'	1.02 ***	0.00098	<0.0001

Table 3b Joint Production Function ($K_2 = (\beta + \beta')/\gamma$)

Parameter	Estimate	Standard error	P-value
a	-0.027 ***	0.027	<0.0001
α	0.0075 ***	0.012	<0.0001
α'	1.03 ***	0.012	<0.0001
b	-0.46 ***	0.38	<0.0001
β	0.0055 ***	0.02	<0.0001
β'	1.02 ***	0.012	<0.0001

Total number of observations is 330

*** represents statistically significant at 1% level

** represents statistically significant at 5% level

* represents statistically significant at 10% level

Table 4 Hypothesis tests

Test	**Type**	**Pr>ChiSq**	**Conclusion**
Ho: a=1	Wald	<0.0001	Reject the null
Ho: b=0	Wald	<0.0001	Reject the null
Ho: $\alpha + \alpha' = 1$	Wald	<0.0001	Reject the null, Production function is not C.R.S
Ho: $\beta + \beta' = 1$	Wald	<0.0001	Reject the null, Emission function is not C.R.S