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Carbon Emission Control Policies within China's Power Generation Sector

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Abstract

Abstract: The paper examines the potential for emissions control policy using the example of the power generation sector in China. The analytical model is developed using a joint production function, where carbon emissions and electricity are jointly produced using capital and fossil fuel inputs. Abatement of emissions can be achieved by investment in two types of capital – production capital that improves the production efficiency, or abatement capital that removes the emissions. The analytical model shows that economic growth can be achieved while still keeping the emission stock at a stable level. The results are estimated using data from China's electricity generation sector. The results show that the level of the tax required to stabilize emissions depends greatly on the efficiency of abatement activities. As an illustration of this result, one finding shows that the required emission tax would be reduced greatly from 16 to 5 yuan per ton of emission when the abatement technology is improved from removing 10% to 30% of emissions flow.

Keywords: electricity generation, carbon emissions, carbon taxes, joint production, China

Carbon Emission Control Within the Power Generation of China

1. Introduction

Over the past several decades developed countries have generally experienced mild economic growth while many developing countries have experienced rapid economic growth. For example, in 2007 per capita Gross Domestic Product (GDP) grew by 11.4 percent in China (China Statistical Yearbook 2008)[1] and 9.2 percent in India[2] , while the United States and Japan had growth rates of 3.2 and 2.0 percent. Even under the global financial crisis, the real growth rate in 2008 was about 9 percent for China and 7.4 percent for India respectively.[3] Economic growth increases national wealth, but can also lead to environmental problems when production activities rely on non-renewable and pollution generating natural resources such as coal and petroleum. This issue is of immediate importance, as nations are trying to develop an international agreement that will effectively reduce greenhouse gas emissions while still allowing a reasonable level of pollution generation that will allow developing nations to improve their standard of living. Research that jointly models economic growth and environmental quality is informative in determining how developing countries may be impacted by emission restrictions. The question of whether economic growth is compatible with environmental protection has received great attention in the economic literature, and conclusions vary greatly.

[1] http://www.stats.gov.cn/tjsj/ndsj/2008/indexeh.htm
[2] http://www.indexmundi.com/india/gdp_real_growth_rate.html
[3] The real growth rate is -0.7 percent in Japan and 1.1 percent in US (source: CIA world fact book as of January 1, 2009)

Some find that sustainable growth can be achieved under certain conditions. With an endogenous growth model, Romer (1986) suggests that the accumulation of human capital is the driving force that makes sustainable growth feasible in the presence of environmental concern. Using an amended Green Solow model, Brock and Taylor (2004) find that the balanced growth is achievable as long as technological progress in pollution abatement is greater than the growth of production. Hartman and Kwon (2005) find that the sustainable growth is optimal when human (clean) capital grows more rapidly than physical (dirty) capital for private goods production. Economides and Philippoppoulos (2008) study the Ramsey second-best policy in a general equilibrium setting and find that the revenue of the 'right' tax and subsidy facilitate the sustainable use of natural resource.

Others suggest that continuous growth will lead to environmental deterioration and that environmental improvement can only be achieved at the cost of slowing down the economic growth. The typical Ramsey problem is applied to an economy where pollution is a disutility factor, and consumers maximize utility by choosing the level of investment, consumption and abatement activities. A seminal paper using this framework is Forster (1973), whose research was extended by Gruver (1976), Van der Ploeg and Withagen (1991), and many others. The main conclusion from these papers is that concern about environmental quality will lead to a lower growth rate, because physical capital allocated for pollution abatement crowds out investment in production for desired goods.

This paper addresses the question of whether economic development is compatible with carbon emissions control. Carbon emissions are different from other air pollutants in several aspects: (i) the flow of carbon emissions do not impose immediate harm to the public, but has a global impact via 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 is uncertain, and the cost of emissions control may be very high. A first-best solution for carbon emissions control requires international collaboration and careful examination of the trade off between environmental gain from regulation and economic cost of emissions control. The Kyoto Protocol is currently the primary current international agreement on greenhouse gas emissions control. It has been successful in raising awareness of climate change and providing the public with comprehensive scientific reports on global climate change and its connection with human anthropogenic activity. However, limited progress on further mitigation of global carbon emissions has been achieved under Kyoto, primarily because some of the major emitters (including the U.S. and China) disagree on the timetable of emissions control and have not agreed to any level of emissions reduction as of 2009.

This study examines the potential for emissions control within one major source of carbon emissions, China's power generation sector. China has been the biggest emitter of greenhouse gases in the world since 2006 (Netherlands Environmental Assessment Agency 2007),[4] and its power generation sector accounts for the majority of its carbon emissions. In 2006, China emitted 6.103 trillion metric tons of CO2, while the United States emitted 5.975 trillion of metric tons of CO_2, about 21.5 and 20.2 percent of global emissions, respectively (United Nation Millennium Development Goals Indicator database).[5] Chinese power generation accounts for 54% of its national carbon emissions, while power generation worldwide accounts for 37% of energy related carbon dioxide

[4] Netherlands Environmental Assessment Agency: http://www.pbl.nl/en/dossiers/index.html.
[5] United Nation: http://mdgs.un.org/unsd/mdg/Data.aspx,
http://unstats.un.org/unsd/environment/air_co2_emissions.htm.

and 27% of all carbon emissions (Intergovernmental Panel of Climate Change, 2007, Washington Post, 2008[6]).

Our study here is relevant to two important cases – the first case where China develops emissions control policy in the absence of any binding international agreement, and the second case where a binding international agreement exists and each nation has autonomy to reach its own emissions reduction target in the most cost-effective manner. Due to its large percentage of global carbon emissions, searching for feasible emission control instruments in China is extremely important in controlling global emissions. Recent negotiations in Copenhagen, Denmark included a proposal from China to reduce its carbon intensity by 40-45% of 2005 levels in 2020 (BBC, 2009).[7] Carbon intensity, China's preferred measurement, is the amount of carbon dioxide emitted per unit of GDP.

In this paper, we focus on examining appropriate policies that provide firms the incentive to achieve a social goal of emissions control. In most previous studies, theoretical modeling and empirical analysis have been done independently. The model is often built in an abstract context, with ad hoc specification used for most of the empirical testing. This study develops a theoretical model, which describes the characteristics of the electricity generation industry. In particular, the different roles of the flow and stock of emissions is recognized. During the process of electricity generation, the flow of emissions is generated at firm level, while the accumulation of its stock is defined as a disutility factor in social welfare. Also, the firm's optimization choice is represented as a cost-minimization problem as opposed to profit maximization, reflecting the semi-regulated nature of China's power industry. In addition, the empirical analysis is

[6] http://www.washingtonpost.com/wp-dyn/content/article/2008/08/26/AR2008082603096.html.
[7] BBC News, November 26, 2009.

connected with theoretical modeling through the optimal conditions derived directly from the model, which are used to examine and compute the policy instrument for emissions control.

The paper will be organized as follows: **Section 2** presents a model describing China's regulated power generation sector. Both the social and private problems are examined to determine if the social goal can be achieved under appropriate policy instruments. We derive the emission fee that is required to achieve balanced growth, where the stock of emissions is stabilized and growth of desired output is non-negative. **Section 3** develops the empirical analysis using the derived conditions from the analytical model. Provincial level power sector data from China is used to compute the optimal tax rate that allows sustainable growth. The Full Information Maximum Likelihood (FIML) method is employed to estimate the joint production function. The estimated production parameters, derived optimal conditions, and data from the China Power Electric Yearbook are used to compute the emission tax. **Section 4** concludes with a discussion of the major findings from the theoretical and empirical analyses, the implications for policy choice that accommodate the balanced growth between emissions control and electricity generation, and the limitations corresponding to global emissions control.

2. Model

The purpose of this study is to provide insight on the potential for carbon emission control in the absence of an effective international agreement. The question we will answer is whether sustainable economic growth can be achieved under appropriate carbon regulation tools.

2.1 Joint Production Model

To provide tractable analytical results, a Cobb-Douglas production function is used to describe the process of power generation, where the desired and undesired outputs (i.e., electricity and emissions) are jointly produced. A modified Hamiltonian approach is employed to solve for the social and private optimum when production and emissions abatement are decided simultaneously. The modeling set-up is developed to capture the most important characteristics of the electricity generation sector in China, where the price of electricity is regulated and input markets are relatively competitive. Therefore, the optimization problem is described as utility maximization for social planner and cost minimization for private firms.

The Cobb-Douglas joint production function is defined as following:

$$\begin{aligned} Y &= F(K_1, X) = A^a [K_1]^\alpha [X]^{\alpha'} \\ E &= G(K_1, K_2, X) = A^b [K_1]^\beta [X]^{\beta'} e^{-K_2 \gamma} \end{aligned} \quad (1),$$

where electricity Y and carbon emissions E are jointly produced using inputs of capital investment K_1, K_2, and fossil fuel X. Fuel consumption X is measured in units of standard coal, a measure that combines information on the three major fossil fuels (coal, oil fuel, and gas) used in electricity generation. Two types of capital are used to reflect investment in alternative methods of emission reduction: improved energy efficiency and end of the pipe treatment. K_1 represents investment in production efficiency that can reduce emissions per unit of electricity generated, while K_2 is investment in capture and storage technology that allows for abating emission after generation. The major parameters in this joint function include: A represents the technology used in electricity generation; α and β are associated with marginal productivity of capital K_1 in the production of output and emissions, respectively; and γ is the abatement efficiency rate of removing emission flows after electricity generation. The Cobb-Douglas function implies that the marginal productivity of K_1 for both outputs is positive, i.e. $Y_1 = \partial Y(.) / \partial K_1 > 0$ and $E_1 = \partial E(.) / \partial K_1 > 0$. We also assume that the marginal productivity of K_2 in emissions is negative, or that $E_2 = \partial E(.) / \partial K_2 < 0$.

Estimation of a production function is central to a large body of empirical analysis in economics, especially for measurement of technological efficiency. The Cobb-Douglas function, first proposed by Cobb-Douglas in 1927-1928, has been widely used due to its simple structure. The commonly used least square method[8] suffers from the problems caused by data aggregation or data used in estimation are in monetary values. The major concern in this literature is the possible endogeneity bias as a result of correlation between input factor and error term.[9] Instrumental variable (IV) estimator is the main approach used to deal with bias in the presence of such correlation.

For estimating a production function using firm-level panel data, Olley and Pakes (1996) showed under certain assumptions, investment can be used as a proxy variable for unobserved time-varying productivity. Levinsohn and Petrin (2003) proposed a modification of Olley and Parks approach to address the problem of lumpy investment, suggesting using intermediate inputs to proxy for unobserved productivity. Felipe et al (2008) argued that the endogeneity problem is simply the result of omitted variable bias due to poor approximation to an accounting identity, and they believe that the problem has no econometric solution. They question the recent attempts to solve such problem by

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[8] Examples: Bronfenbrenner and Douglas (1939) at JPolitEcon 47:761-785; Douglas and Gunn (1941) at AER. 31: 67-80; Douglas, Daly and Olson (1943) at JPolitEcon 51:61-65.

[9] See details in Marschak and Andrew (1944) at Econometrica 12: 143-205.

developing new estimators, and showed that the only possible way to estimate technological productivity of production function is by using physical quantities instead of expenditures.

Our work differs from previous studies when using production function estimation in several ways: 1) we use measures based on physical quantities, which might reduce the problems associated with the major concerns discussed in previous literature; 2) we test for possible correlation within each equation and across two equations; 3) we are interested in determining the optimal emission tax that would allow non-negative production growth in this set up, not in measuring the productivity. We find insignificant correlation between inputs and the error term for each equation, and slightly significant correlation between the two error terms across the two equations, which provides justification for estimating the two equations simultaneously.

The major assumptions used in this study are: (i) emissions and electricity production can be represented using a Cobb-Douglas joint-production function; (ii) abatement activities are narrowed down to two choices: (ii-1) reducing emissions through improvements in production efficiency due to substitution between productive capital and standard coal inputs; (ii-2) investing in abatement capital to build capture and storage facilities; (iii) the stock of emissions is a disutility factor in the social welfare function. We model carbon emissions generated in the current time period as a flow of pollution, the stock of which has a natural decay rate.

2.1 Social Problem

The social planner is assumed to maximize the discounted value of social welfare in continuous time, which is defined in a utility function of production net value (V) and pollution stock (S), subject to constraints on production technology and the absorptive capacity of the environment. The marginal utility of private good consumption (here represented by the production net value) is positive, and marginal utility of pollution is negative. These conditions are represented by the following:

$$\begin{aligned} U_1 &= \partial U(.)/\partial V > 0 \\ U_2 &= \partial U(.)/\partial S < 0 \end{aligned} \tag{2}$$

The social planner's problem is to maximize the discounted value of utility over time, where ρ_0 is the social discount rate,

(3) $\underset{\{X,I_1,I_2\}}{Max} \int U(V,S)e^{-\rho_0 t}dt$ Subject to

(4) $Y = AK_1^{\alpha} X^{\alpha'}$, $E = K_1^{\beta} X^{\beta'} e^{-K_2\gamma}$ Joint production function

(5) $\dot{K}_1 = I_1 - \delta K_1$, $\dot{K}_2 = I_2 - \delta K_2$ Capital accumulation

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

(7) $V = Y - I_1 - I_2 - WX$ Production net value.

Where δ is the depreciation rate of capital, ζ is the natural decay rate of the stock of carbon emissions, *S* is the stock of emission; *W* is the real price of input in term of production value. The choice variables are investment on production I_1, investment on abatement I_2 and coal inputs *X*, while the state variables are productive capital K_1, abatement capital K_2 and emissions stock *S*. *V* is the net value of production, where the price of output is normalized to one. The current value of Hamiltonian problem can be written as:

(8) $H^c = U(V,S) + \lambda_{s1}(I_1 - \delta K_1) + \lambda_{s2}(I_2 - \delta K_2) + \lambda_{s3}(E - \zeta S)$,

where $\lambda_{s1}, \lambda_{s2}, \lambda_{s3}$ 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 *s* subscript refers to the social optimum. Since pollution is a bad, its shadow value is negative, i.e. $\lambda_{s3} < 0$. Solving Equation (8) gives the following necessary conditions:

$$(9) \qquad H_X{}^c = \frac{\partial H}{\partial X} = U_1(Y_X - W) + \lambda_{s3} E_X = 0$$

$$(10) \qquad H_{I1}{}^c = \frac{\partial H}{\partial I_1} = U_1 \frac{\partial V}{\partial I_1} + \lambda_{s1} = 0 \Rightarrow U_1 = \lambda_{s1}$$

$$(11) \qquad H_{I2}{}^c = \frac{\partial H}{\partial I_2} = U_1 \frac{\partial V}{\partial I_2} + \lambda_{s2} = 0 \Rightarrow U_1 = \lambda_{s2}$$

Equation (9) sets the rule for the socially optimal choice of coal inputs, where the social benefit of using coal equals its social cost, i.e. market price plus the environmental cost of using coal. The environmental cost is the disutility due to the environmental damage of emissions, i.e. $U_1 Y_X = U_1 W - \lambda_{s3} E_X$. Without regulation, the optimal private choice of coal inputs would be set at the point where the marginal benefit of using coal is equal to its market price only. This corresponds to a market outcome where the shadow value of emission is zero, i.e. $\lambda_{s3} = 0$. Equations (10) and (11) set the rule for optimal social investment, i.e. $U_1 = \lambda_{s1} = \lambda_{s2}$, where the marginal utility of private goods equals to the shadow value of investment for both production and abatement. The optimal investment I_1^* and I_2^* cannot be solved directly without specification of utility function.

2.2 Private Firm Problem

The private problem is examined under the emission tax, which will be imposed on the flow generated at the firm level when emissions exceed the socially optimal level. To achieve the social optimum, the optimal tax rate will be derived by comparing the first-order conditions of the private problem under an emissions tax with those of social problem. In the context of China's electricity generation sector, economic reform of output markets was proposed in 2003, but due to various reasons, it has never taken effect. Therefore, the optimization problem for firms is described as a cost minimization problem, since the electricity price is regulated in China while input markets are competitive.

Without regulation firms have no incentive to internalize the social cost of emissions (its negative impact on the environment) into their production decision. They choose to set $Y_{X*(private)} = W$, a rule that sets the marginal private benefit equal to the marginal private cost. Under regulation, firms have to reset the production plan upon the rule deviated from the socially optimal condition on input *X*, where $U_1 W - \lambda_{s3} E_X = U_1 Y_{X*(social)}$. Since $\lambda_{s3} < 0$, the firm will use more coal inputs (*X*) under the private optimum than that under social problem, i.e., $X*(social) < X*(private)$. With no regulation, firms have no incentive to invest in abatement capital ($K_2 = 0$ and $K = K_1$). Moreover, we show in the next section that final production of both the desired output *Y* and the undesired emission *E* would exceed the social optimal levels without regulation. Therefore, government intervention is necessary.

A simple and direct tool is to impose a unit fee (τ) on individual firm emissions E when it exceeds the optimal level E^* in order to achieve the socially optimal outcome and require firms to internalize the external cost of emissions. While much of the previous literature imposes a tax on all emissions, Holterman (1976) shows that setting the tax on all emissions or only on emissions above the socially optimal level achieve the same result.

In the long run at a steady state, the optimal level of aggregate emissions for private firms could be defined as $E^* = S^*\xi$. The feasibility of this policy tool relies on the assumption that emissions can be detected and measured by an inspection agent, and that the fine associated with non-compliance is large enough to induce compliant behavior by firms. Therefore, the corresponding private problem can be described as firms minimizing the discounted value of total cost subject to current production technology, and the long-run policy goal of stabilized emission stock levels as follows:

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

Subject to

(13.1) $\begin{array}{l} Y = AK_1^{\alpha} X^{\alpha'} \geq Y_0 \\ E = K_1^{\beta} X^{\beta'} e^{-K_2 \gamma} \end{array}$ Joint production

(13.2) $\begin{array}{l} \dot{K}_1 = I_1 - \delta\ K_1 \\ \dot{K}_2 = I_2 - \delta\ K_2 \end{array}$ Capital accumulation

(13.3) $E^* = \xi S^*$ Socially optimal emission flow,

where the notation is the same as that in social problem in Section 2.1.

The constrained cost minimization problem is reformulated as an unconstrained problem by maximizing the negative cost (Wossink and Swinton 2007). The current value Hamiltonian function is stated as follows:

$$(14)\quad \begin{aligned} &H^{c} = -(WX + I_1 + I_2 + \tau(E - E^{*})) + \lambda_{\mathrm{p}1}\ (\mathrm{I}_1 - \delta K_1\ ) \\ &+\lambda_{\mathrm{p}2}\ (\mathrm{I}_2 - \delta K_2) + \lambda_{p3}(AK_1^{\ \alpha} X^{\alpha'} - Y_0\ ) \end{aligned} ,$$

where λ_{p1} is the shadow value of productive capital K_1, λ_{p2} is the shadow value of abatement capital K_2; λ_{p3} is the shadow value of desired output *Y*; emission flow *E* and electricity output *Y* are two jointly produced outputs. The *p* subscript refers to the private optimization problem. Assuming that appropriate conditions that guarantee the existence of solutions are satisfied, we differentiate Equation (14) with respect to the choice and state variables to obtain conditions for optimality:

$$(15)\quad \frac{\partial H^{C}}{\partial X} = -W - \tau\frac{\partial E(.)}{\partial X} + \lambda_{p3}\frac{\partial Y(.)}{\partial X} = 0 \Rightarrow W + \tau E_x = \lambda_{p3} Y_X$$

Equation (15) describes the rule for the optimal choice of coal inputs for electricity producers: 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 ($\tau > 0$). Letting the superscript *UR* denotes the unrestricted outcome and *R* denotes the restricted (with tax) outcome, this conclusion follows because $\lambda_{p3} Y_X^{UR} = W$ and $\lambda_{p3} Y_x^{R} = W + \tau E_X$ or that $Y_X^{UR} < Y_x^{R}$. Since $Y_{XX} < 0$, it follows that $Y^{UR} > Y^{R}$, and that the output produced under no regulation will be greater than under the emission regulation.

(16) $$\frac{\partial H^C}{\partial I_1} = -1 + \lambda_{p1} = 0 \Rightarrow \lambda_{p1} = 1$$

(17) $$\frac{\partial H^C}{\partial I_2} = -1 + \lambda_{p2} = 0 \Rightarrow \lambda_{p2} = 1$$

Equations (16) - (17) set the conditions for optimal investment in both productive and abatement capital, and show that the shadow value of each type of capital is constant and equal.

Equations (18) – (19) show the condition for the growth rate of the co-state variables, which are zero at an optimal steady state:

(18) $$\frac{\dot{\lambda}_{p1}}{\lambda_{p1}} = \rho + \delta + \frac{\tau E_{K1} - \lambda_{p3} Y_{K1}}{\lambda_{p1}} = 0$$

(19) $$\frac{\dot{\lambda}_{p2}}{\lambda_{p2}} = \rho + \delta + \frac{\tau E_{K2}}{\lambda_{p2}} = 0$$

Reorganizing equation (19) and using the emission function defined in equation (13.3) will give the marginal emission reduction of abatement capital,

(20) $$E_{K2} = -(\rho + \delta) / \tau = -\gamma K_1^{\beta} X^{\beta'} e^{-K_2 \gamma} = -\gamma E \; .$$

We can use this to solve for the optimal level of emission flow at a steady state for a private producer:

(21) $$E^*_{private} = (\rho + \delta) / \tau\gamma \; ,$$

which will be equal to the socially optimal emission flow as long as the tax rate is set according to the following condition:

$$(22)\qquad \tau^* = \frac{\rho+\delta}{S^*\zeta\,\gamma}.$$

When the social constraint is binding in the private problem, $E^*_{private} = (\rho+\delta)/\tau\gamma = E^*_{social} = S^*\xi$ solves for optimal tax rate. While the functional form in Equation (22) cannot be used for our empirical analysis, it is useful for providing an economic interpretation of the optimal outcome. For instance, a higher efficiency rate for abatement technology (γ) reduces the necessary emission tax. This is because lower investment in abatement capital is necessary to achieve emission reductions. A higher individual discount rate (ρ) requires a higher emission tax, since an individual has little motivation to reduce emissions in the absence of regulation. A lower level of emission stock at the social optimal (*S**), or a lower of absorptive capability (ξ) of atmosphere requires a higher tax rate to control the emission. That is because achieving a socially optimal level of emission stock that is low requires a larger amount of emission flows to be removed; and a lower absorptive capacity of the atmosphere accelerates the accumulation of emissions, which requires a higher tax to stabilize.

Because the shadow value of each type of capital is a constant, the growth rate of capital will be zero. As a result, Equation (18) and (19) are equal at the steady state, and we can derive the relationship between marginal value of production capital and abatement capital as following:

$$(23)\qquad \lambda_{p3}Y_{K1} - \tau E_{K1} = -\tau E_{K2}$$

Equation (23) implies that the marginal net value of production capital to the firm is equal to the marginal social benefit of abatement capital at the optimum, where production capital plays the roles in both generation of desired output and emission. The left-hand side of the equation shows the two impacts of increasing productive capital (K_1). On one hand, an increase in K_1 increases the desired outputs that bring firms the benefit from output value. On the other hand, it also increases the undesired emissions, which firms have to pay for through the tax.

Expanding Equation (23) with the parameters from Equation (1) gives the following,

$\lambda_{p3} A\alpha K_1^{(\alpha-1)} X^{\alpha'} - \tau\beta K_1^{(\beta-1)} X^{\beta'} e^{-K_2\gamma} = \tau\gamma K_1^{\beta} X^{\beta'} e^{-K_2\gamma}$, which can be solved to get the optimal ratio of emissions to output,

$$(24) \quad (\frac{E}{Y})^* = \frac{\alpha\lambda_{p3}}{\tau(\beta+\gamma K_1)},$$

where $\lambda_{p3} = \frac{w+\tau E_X}{Y_X}$ from equation (15). Equation (24) provides the theoretical basis to show that further emissions reduction can be achieved without cutting back the production of desired output. In the case of emission control, this ratio is referred to as the emission factor. Much of the previous literature which models endogenous growth assumes that emissions are proportional to the final production (e.g., Van der Ploeg and Withagen 1991, Michel and Rotillon 1995) or the emission per unit of output is a constant. Others model the pollution process as a function of technological progress in abatement (Brock and Taylor 2004), production technology (Stokey 1998), and abatement knowledge accumulation (Xepapadeas 1997).

One main result from previous work, which assumes a fixed emissions factor, implies that the only way to reduce emissions is to reduce production. In this study, modeling a joint production function without assuming a fixed emissions factor opens the possibility that the abatement of pollution (hereto emissions) does not necessarily require cutting back production (hereto power generation). Using a joint production function in the model rather than a single production function or the assumption that pollution is proportional to output (ex. Michel and Rotillon 1995), we find that the emission factor is a function of production capital. Previous research that used single production function often treat pollution as an input in the economic model. The main concerns about using a single production function are: a) emissions are a byproduct of electricity generation, therefore the use of single production function in modeling is inconsistent with the power generation process; b) the underlying assumption of using a single production function is that the emissions are a fixed proportion of electricity. Our framework allows us to test for this result, but does not assume that it holds. The theoretical findings in our study (Equation 24) suggest that several factors could change the ratio of emissions to electricity, and provide insight into the feasibility of emission reduction without slowing economic development. Either improving production efficiency from investment in K_1, or abatement investment in K_2 could change the emissions per unit of output, implying that emission abatement is compatible with economic development under circumstances. These findings can be used as a theoretical base for identifying under what circumstances environmental protection is compatible with continuing economic growth.

Rewriting equation (24) to solve for optimal emission tax as:

$$(25)\ \tau^* = \frac{\alpha XW}{E(\alpha'(\beta + \gamma K_1) - \alpha\beta')}$$

Comparing the optimal conditions in the private and social problems for demand for coal *X*, we can also derive the optimal emission tax that allows achieving the social optimal conditions in term of utility function:

$$Y_X - \frac{\lambda_{s3} E_X}{U_1} = \lambda_{p3} Y_X - \tau E_X$$
$$\Rightarrow \tau^* = (\lambda_{p3} - 1)\frac{Y_X}{E_X} + \frac{\lambda_{s3}}{U_1}$$

where $\lambda_{p3} = \dfrac{\tau(E_1 - E_2)}{Y_1}$ and $\lambda_{s3} = \dfrac{U_2}{\rho_0 + \zeta - g(\lambda_{s3})}$

Reorganizing the term will get the emission tax that is connected with social utility function:

$$(26)\ \ \tau^* = \left(\frac{\alpha' Y}{\beta' E} - \frac{U_1}{U_2 L}\right)/(M-1)$$

where $L = \rho_0 + \zeta - g(\lambda_{s3}) > 0$ and $M = \dfrac{(\beta + \gamma K_1)\alpha'}{\alpha\beta'} > 1$. Theoretically, Equations (25) and (26) are equivalent. Due to data availability, Equation (25) will be used for computation of policy rate in empirical analysis in section 3.2.

2.3 Comparative Static Analysis

In this section we will examine the effect of changes in various parameters on the emission tax policy. For example, we show how an increase or decrease in the discount or depreciation rate affects the optimal tax rate. This could be important in determining the impact of technological improvements that increase the life of capital or a shift in perceptions about the relative importance of current generations versus future generations.

2.3.1 Optimal emission tax rate

Equation (22) defines the emission tax rate when the private optimal emission flow equals to the social level. The signs of its derivative will tell the impact of different factors on the emission tax. Examining the discount and depreciation rates shows that $\frac{\partial \tau^*}{\partial(\rho+\delta)} = \frac{1}{S^*\zeta\gamma} > 0$, suggesting that as the private discount rate and depreciation rate increases, the tax rate should increase as well. This is because a high discount rate means that an individual places a greater value on current consumption or production compared to the future. Letting $D = \alpha'(\beta + \gamma K_1) - \alpha\beta'$, we show that the derivative of Eq. (P14) with respect to productive capital $K_{1,}$ is negative, or that $\frac{\partial \tau^*}{\partial K_1} = \frac{\alpha XW}{E(-D^2)}\alpha'\gamma + \frac{\alpha XW}{D(-E^2)}E_1 < 0$. This indicates that when the efficiency of production technology increases, a lower tax rate is required for stabilizing the emission stock. The derivative of Equation (26) with respect to the social discount rate, $\frac{\partial \tau^*}{\partial \rho_0} = \frac{1}{U_1}\frac{-U_2}{(\rho_0 + \zeta - g(\lambda_{s3}))^2} > 0$ suggests the higher social discount rate in the utility function would stimulate more consumption and production, which in turn generates more emissions, and requires a higher emission tax rate to stabilize the stock of emissions. In considering the impact of abatement technology efficiency, we find that $\frac{\partial \tau^*}{\partial \gamma} = -\frac{(\rho+\delta)}{S^*\zeta\gamma^2} < 0$, implying that more efficient abatement technology, the 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 to stabilize the stock.

2.3.2 Optimal emission factor

Equation (13) defines the relationship between two joint outputs at the optimum. Taking the derivative of Equation (13) with respect to corresponding variables gives the impact and direction of each variable on the ratio. For instance, $\frac{\partial (E/Y)^*}{\partial K_1} = -\frac{\alpha \lambda_{p3} \gamma}{\tau(\beta + \gamma K_1)^2} < 0$, suggesting that increasing in productive capital K_1 would lower the ratio, which explains the mechanism of reduced emission/output ratio through cleaner production technology. The impact of a change in the tax rate can be examined by looking at $\frac{\partial (E/Y)^*}{\partial \tau} = -\frac{\alpha \lambda_{p3}}{\tau^2(\beta + \gamma K_1)} < 0$, which might be explained by firms' incentive to reduce the emission from capture and storage under higher emission tax rates. In considering the possibility of investment in pollution abatement technology, we find that $\frac{\partial (E/Y)^*}{\partial \gamma} = -\frac{\alpha \lambda_{p3} K_1}{\tau(\beta + \gamma K_1)^2} < 0$, meaning that the higher of abatement efficiency on capture and storage, the second possible way of abatement, the lower the ratio. One somewhat surprising result is the impact of changes in α, the share of K_1 in the production function. We find that $\frac{\partial (E/Y)^*}{\partial \alpha} = \frac{\lambda_{p3} K_1}{\tau(\beta + \gamma K_1)} > 0$, meaning that a larger share of K_1 in production function will increase the ratio. This result might be due to the fact that the growth of the desired output is lower than the growth in emissions when the share of capital in the production function increases. In considering the emissions generation function, we find that $\frac{\partial (E/Y)^*}{\partial \beta} = -\frac{\alpha \lambda_{p3}}{\tau(\beta + \gamma K_1)^2} < 0$ indicating that β, the share of K_1 in emission function will reduce the ratio. This suggests that the role of productive capital in the 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.

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 power industry information covers 26 provinces and 4 municipalities. Variables used for calculating the emission tax rate include final output *Y*, the total electricity generated for the current year by each province, measured in 100 million kWh; three major fuel inputs *X* (coal, oil, and gas) consumption are measured in 10 thousands tons; *K* is the electricity generation capacity measured in million Yuan of current year, representing the stock of production capital; and byproduct emission *E* is measured in million tons of carbon[10] by converting fossil fuel consumption into carbon emission using the corresponding emission factor, which is defined by China Development and Reform Committee (2007)[11]. The summary statistics are presented in Table 1.

The data includes a total of 326 observations[12] of 30 provinces and municipalities for an 11-year period. This has been used to estimate the joint production functions and examine the relationship between the undesired output *E* (carbon emissions) 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

[10] E=COAL*2.11 (ton co2/ton coal) + OIL*3.06 (ton co2/ton oil)+GAS*2.19 (ton co2/1000m3 gas)
[11] http://cdm.ccchina.gov.cn/WebSite/CDM/UpFile/File1364.pdf and Intergovernmental Panel on Climate Change (IPCC) 2007 Guidelines for National Greenhouse Gas Inventories.
[12] Due to the missing values in several variables, Xizhang Province in the year of 1998 is not use for estimation.

techniques, as the error term in each equation is likely to be correlated. We use Full Information Maximum Likelihood (FIML) to take care of possible correlation problem in a system of nonlinear equations. This method is analogous to the linear equation method of Seemingly Unrelated Regression (SUR). In addition, as no appropriate data is available to represent the technology *A*, the production function will be estimated without a technology term as follows: $\begin{matrix} Y = b_1 K_1^{\alpha} X^{\alpha'} \\ E = b_2 K_1^{\beta} X^{\beta'} \end{matrix}$, where b_1 and b_2 are the multipliers that correct for the potential econometric problem of heterogeneity across provinces. Therefore, implementing the Full Information Maximum Likelihood (FIML) method provides estimates that are efficient and asymptotically consistent.

3.1 Estimation of Joint Production Function

The estimation results are shown in Table 2. When no abatement activity is included (K_2=0), the joint production function could be described as $\begin{matrix} Y = 0.211 K_1^{0.0989} X^{0.942} \\ E = 0.0498 K_1^{-0.0395} X^{0.966} \end{matrix}$. We test for correlation between the explanatory variables and the error term in each equation using the Pearson method. The results are reported in the Table 3. The results from the Pearson test suggest that the FIML method is appropriate for getting consistent and approximately efficient estimation, since the correlation between the error terms across the two equations is statistically significant at the 5% level, while the correlations between the explanatory variable and error term within each equation are insignificant. We test the joint production function for constant returns to scale, and the results are shown in Table 4. We find that technology does not exhibit the constant returns to scale in both capital and coal factor inputs in the joint production of electricity and emission. Therefore, the general structure of Cobb-Douglas is appropriate for fitting the data.

The results from the estimation of the joint production functions have three important implications: (i) the input coal (*X*) is the primary input in the joint production; (ii) productive capital (K_1) plays a small role in the electricity generation process, compared to that of input coal; (iii) the productive capital intends to reduce the marginal productivity of emission. The second implication is consistent with the reality that power generation technology is mature and capital investments are gradually switching from the stage of power generation to the stages of power distribution and transmission network (often referred to 'grid') construction. The third implication reflects the fact that Chinese power generation heavily relies on the coal consumption, while the coal-fired power plants provided 81.5 percent of electric supply (China National Statistical Bureau 2007).

3.2 Computation of Optimal Emission Tax

The derived condition in equation (25) defines the optimal tax rate for emission control. Using the estimated parameters from the joint production function and derived conditions at balanced growth from the model, we compute the optimal emission tax rate τ under different levels of abatement efficiency γ. The IPCC (2005) [13] report suggests that the current post-combustion and pre-combustion systems for power plants could capture 85–95 percent of the CO_2 in theory. However, 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 are energy intensive activities. Currently

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

available methods for capture and compression technology require approximately 10–40 percent more energy than the equivalent generation level without capture. As capture and storage (CCS) has not yet been applied to large (above 500 MW) fossil fuel power plants, the overall system results may be different than with initial results in smaller plants. Considering the uncertainty of abatement technology adoption and heterogeneity of power plants in production efficiency, we consider a range of abatement efficiency rates (γ) from 10 to 100 percent in calculating the optimal emission tax.

The results shown in Table 5 are consistent with the comparative analysis discussed in Section 2.3, where the emission tax rate is decreasing as the abatement efficiency improves. The calculation shows that the tax is 16.16 yuan per ton of emissions when the ability to remove carbon emissions is as low as $\gamma = 10\%$. The emission tax could be reduced dramatically to 5.35 yuan per ton, once the capability of capture and storage has been increased to $\gamma = 30\%$. In theory, if the abatement method could remove all the emissions after its generation ($\gamma = 100\%$), the required tax rate is very small, 0.787 yuan per ton.

4. Discussion and Conclusion

Previous literature has shown that determining whether environmental improvement is compatible with continued economic growth remains unclear and requires 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 according to the Netherlands Environmental Assessment Agency 2007). Our results provide policy implications for emissions control within the power sector of China, for cases when there is no international agreement or when an international agreement allows individual countries to choose their preferred method to control carbon emissions.

A theoretical model is developed to describe a regulated sector in China, and a modified Hamiltonian approach is used to demonstrate the optimal conditions that accommodate the policy of emission control in a private context. The optimal conditions derived from the model have been used to perform the empirical analysis. The 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).

The theoretical model finds that the ratio of undesired output (emissions) to desired output (electricity) for Chinese power generation is not a constant, but a function of inputs and production parameters. The ratio would be affected by the quantity and marginal productivity of productive capital, input coal prices, and the efficiency of abatement capital. This variable relationship between power generation and its byproducts (emissions) implies that there are multiple methods for further emission mitigation: improvement of production efficiency through an increase in the stock of productive capital, or improvement of the abatement efficiency.

The theoretical analysis suggests that the optimal emissions tax depends largely on the efficiency of abatement technology: the higher the efficiency is, the lower the tax is required to accomplish the goal. The empirical testing using the power sector data at provincial level is consistent with the theoretical results. The required emission tax would be reduced greatly from 16 to 5 yuan per ton of emission when the abatement technology is improved from removing 10% to 30% of emissions flow.

While the conclusions of this study are based on a single industry, results are informative in comparing emission control policies for different nations. For example, a nation with more efficient abatement technology would require a lower emission tax to achieve stable pollution levels. However, there are some limitations to our results. This study uses a partial equilibrium framework that looks at a single sector, while the stock of pollutants generated locally from a variety of different sources often involve more than one industrial sector. Therefore, the results do not consider the interaction across different sectors. Other important factors, such as a change of energy structure, alternative energy sources, energy intensity changes within national economy and international cooperation/trade on abatement credit, also contribute to controlling the growth of emissions stock. Secondly, the derived conditions used for the empirical analysis and policy interpretation are at the steady state. Dynamic solutions, such as phase diagrams could be useful for describing the evolution of state and control variables over time.

In summary, we find that environmental improvement is compatible with economic development, as long as appropriate policy is chosen. The choice of emission tax rates for emission control is determined by the productivity of capital, productivity of coal and efficiency of abatement technology. The computation in this study suggests that the optimal emission tax rate is moderate when abatement technology allows removing at least 30% of newly generated emissions. The theoretical and empirical analysis in this study could be used to understand other industries, nations, or stock pollutions when it comes to the issue of how to achieve the social goal of stabilizing the pollution levels in private context.

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Table 1: Summary Statistics

Variable	Definition	Unit	Mean	Std Dev	Minimum	Maximum
YC	Electricity of fossil fuel power	100 million kilowatt hour	343.84	283.40	15.17	1449.20
EC	Carbon emissions from fossil fuel consumption	Million tons of CO_2	28.69	1.18	139.72	
K1	Capacity of generation	10,000 kilowatt	735.83	590.58	33.85	3920.20
X	Standard coal	10,000 tons	1265.93	1007.73	71.60	5037.69
W	Price of coal	Yuan per ton of coal	143.28	14.70	120.26	180.89

Year between 1993~2003

Source: Various China Statistical Yearbook and China Power Electric Yearbook

Table 2: Joint Production Function ($K_2 = 0$)

$$YC = b_1 K_1^{\alpha} XC^{\alpha'} + \varepsilon_1$$
$$EC = b_2 K_1^{\beta} XC^{\beta'} + \varepsilon_2$$

Parameter	**FIML Estimate**	**Approx. Std Err**	**P-value**
b_1	0.211593 ***	0.00762	<0.0001
α	0.098873 ***	0.00909	0.0009
α'	0.941999 ***	0.00927	<0.0001
b_2	0.049743***	0.00619	<0.0001
β	-0.0395	-0.0314	0.2092
β'	0.966443 ***	0.0349	<0.0001

Table 3: Pearson Correlation Coefficients

Prob>|r| under Ho: Rho=0

correlation (p-value)	ε_1	XC	ε_2	K_1
ε_1	1	.02647 (0.6340)	0.11150 (0.0442)**	0.03830 (0.4907)
XC		1	-0.04071 (0.4638)	0.94794 (<0.0001)***
ε_2			1	-0.04261 (0.4433)
K_1				1

Total number of observations is 326

***, ** and * represents statistical significance at 1%, 5% level and 10% level

Table 4: Hypothesis testing for joint production structure

Test	Wald **Test Statistics**	**Pr>ChiSq**	**Conclusion**
Ho: $\alpha + \alpha' = 1$	78.15	<0.0001	Reject the null, Production function is not C.R.S
Ho: $\beta + \beta' = 1$	21.27	<0.0001	Reject the null, Emission function is not C.R.S

Table 5: Computation of The Optimal Emission Tax Rate (τ)

Abatement efficiency rate (γ)	(a) Calculated emission tax	(b) Calculated emission tax
10%	16.15	16.10
20%	8.03	8.02
30%	5.34	5.33
40%	4.00	4.00
50%	3.20	3.20
60%	2.66	2.66
70%	2.28	2.28
80%	1.99	1.99
90%	1.77	1.77
100%	1.59	1.59

(a): tax is computed under estimated parameters $\hat{\alpha} = 0.0988, \hat{\alpha}' = 0.942, \hat{\beta} - 0.0395, \hat{\beta}' = 0.966$

(b): tax is computed under estimated parameters $\hat{\alpha} = 0.0988, \hat{\alpha}' = 0.942, \hat{\beta} = 0, \hat{\beta}' = 0.966$,

because the coefficient of $\hat{\beta}$ is insignificant.