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Reform of the Coal Sector in an Open Economy: The Case of China

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Abstract

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JEL Classification C7, H2, H32, L5, Q38, Q48

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Abstract

Cheap, abundant and easy to transport and store, coal has been produced and consumed to meet people's energy needs. The last decade's growth in global coal use has been driven mainly by developing economies like China, whose phenomenal economic growth has been powered by coal-fired electricity and promoted by the export of manufactured goods. A recent reform focus in China's coal sector is on coal taxation. The paper develops a game-theoretic model tailored to the context of China where coal taxation reform takes place against the background of privatisation of coal firms and an open economy. It finds that the adoption of special coal taxes is optimal for social welfare under most circumstances, but may induce coal firms to commit opportunistic behaviour in the process of privatisation. The paper also cautions about potential resistance to the reform from consumers, coal firms and government officials.

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1. Introduction

As the second source of primary energy after oil and the first source of fuel for electricity generation in the world, coal remains a crucial part of the energy mix, in particular in emerging economies. The surge in global coal consumption over the last decade has been driven primarily by developing economies, mainly China and India (IEA, 2012). Cheap and abundant, coal has fuelled China's economy. Coal and coal-fired electricity are used as intermediate consumption, mostly by firms, many of which now compete internationally in final product markets. Given the role of manufactured exports as the main driver of China's economic growth, policies and reforms adopted in the coal sector will impact not only on how coal will be produced and used domestically but also on the competitiveness of downstream, exporting manufacturing firms, and in turn national competitiveness. It is therefore important for policy makers to take a broader view when designing and implementing coal policies, going beyond the boundary of the sector and taking into consideration possible impact on other parts of the economy.

China's coal industry has undergone various reforms since the late 1970s as central planning was gradually dismantled and market mechanism introduced. Coal prices were liberalised from the mid 1990s for all but the power generation and agriculture sectors, and from 2002 officially all prices were supposed to be market-determined (Peng, 2011). However, given coal's dominance in electricity generation and strictly regulated electricity tariffs, prices for thermal coal are still subjective to government intervention (Lin and Jiang, 2011).[1] In the sector, corporatisation started from the late 1990s, accompanied by partial or full transfer of state ownership to private investors in some coalmines. The experience of other transition economies shows that, due to slacks in regulation and corporate governance, a restructuring process involving both corporatisation and privatisation may lead to opportunistic behaviour such as asset stripping, undervalued and under-priced state assets, insider control and managerial entrenchment, and de-capitalisation – all attempted for private gains at the expense of social welfare (Frydman, *et al*, 1990; Lipton and Sachs, 1990; Winiecki, 1990; Milanovic, 1991; Newbery, 1991; Bolton, *et al*, 1992; Alexeev, 1999; Frydman, *et al*, 1999; Black, *et al*, 2000; Richter, 2002; Filatotchev, *et al*, 2003). It is therefore important to understand whether coal firms undergoing privatisation will engage in such behaviour, in reaction to coal reforms and policies adopted.

One of the most recent debates on China's coal industry is the reform of coal taxation. Chinese coalmines are subject to two types of taxes – general taxes mainly in the form of value added tax, business tax and income tax; and special taxes such as coal resource tax and environment-related taxes. In addition, coal firms are required to transfer part of their profits (if any) to the government, a practice which can be traced back to the early years of economic reform in China when state-owned firms started

[1] In China, there are two sets of electricity prices – on-grid tariffs and end-use rates – both regulated by the government. More detailed discussion on electricity prices and the political economy of setting them can be found in Zhang (2013).

sharing their profit with the government under a profit-retention scheme.[2] Having since then undergone various amendments, such charges used for coal firms now take the form of lump-sum fees, primarily for the purpose of equalising the profits of the coal and other industries (Li and Zhang, 2012). With regards to coal tax reform, there have been calls for revamping the special taxes and streamlining unreasonable fees or levies, in order to encourage sustainable usage of this non-renewable resource. It can be expected that such reforms will not only impact on the behaviour of coal firms but also have important implications for downstream, coal- and electricity-intensive, export-oriented manufacturing firms.

One debated issue is whether the above-mentioned lump-sum fees should be scrapped and coal firms be only subject to coal specific taxes (apart from general taxes).[3] It has been argued that these fees – a legacy of central planning– have become ill-suited in the emerging market economy of China and that more reliance should be placed on the use of well-designed coal-specific taxes to induce firms to achieve sustainable development of the industry (Zeng and Li, 2013). To policy makers, this is not an easy task and many issues need to be considered. Is the use of the lump-sum fees now unjustified? Will the reform increase social welfare in China where both energy and manufactured exports are important for economic growth? Will corporatised coal firms become more prone to engage in opportunistic behaviour in the process of privatisation? Will there be potential resistance from interest groups? Addressing these questions requires an analysis which takes into consideration the interests of the three entities – the government, coal firms, and downstream, export-oriented manufacturing firms.[4] The present study develops a game-theoretical model tailored to the context of China where coal tax reform takes place against the background of privatisation of coal firms and an open economy. The model depicts and compares between what would happen when the lump-sum fees are levied and the scenario in which coal firms are only subject to coal-specific taxes, alongside a baseline case of 'no taxation at all'.[5]

The contribution of this paper is two-folded. First, it joins the discourse on China's coal industry and presents a timely analysis which takes a broader view of coal tax reform. Second, in doing so, it contributes to the literature by linking privatisation and taxation in the coal industry with downstream manufacturing sectors in open economies.

Following the seminal work of Hotelling (1931), important contribution to economics of non-renewable resources has been made by studies such as Dasgupta and Heal (1974), Stiglitz (1976), Pindyck (1980), Livernois and Uhler (1987) and Krautkraemer (1998). There are studies which model the effects of taxes and subsidies in extractive industries and their optimal levels (e.g., Barness, 1976; Sweeney, 1977; Dasgupta, *et al*, 1980; Conrad and Hool, 1981; Heaps, 1985; Slade,

[2] Economic reform started in China in 1979. In the mid 1980s, a profit retention scheme was introduced for industrial firms, in which they would submit a given percentage of their profits to government authorities and retain the rest.
[3] Another debated issue is whether the coal resource tax should be calculated based on sales value or production volume. A reform plan for the adoption of sales-value-based taxes has been made and is expected to take effect soon.
[4] Electricity generating firms are not explicitly considered in the analysis for reasons stated in Section 2.
[5] General taxes, which are not a major concern of coal tax reform, are not incorporated in the model.

1986). In the privatisation literature, models theorising the political economy and the consequences of privatising state-owned firms are presented in studies like Boycko, *et al* (1994) and Shleifer and Vishny (1994). Mixed oligopoly models have often been used to analyse the effects of privatisation (e.g., Cremer, *et al*, 1989, 1991; DeFraja and Delbono, 1989; Fershtman, 1990; George and La Manna, 1996; Fjell and Pal, 1996; White, 1996; Matsumura, 1998). Among studies of open economies, most attention has been on the role of trade or/and industrial policy in promoting domestic firms in international competition (e.g., Spencer and Brander, 1983; Brander and Spencer, 1985; Eaton and Grossman, 1986; Maggi, 1996; Bagwell and Staiger, 1999; Neary and Leahy, 2000).

Although literature is growing in each of the above areas – economics and taxation of non-replenishable natural resources, privatisation, and trade/industrial policy in an open economy, not many attempts have been made to incorporate more than one of these aspects. Pal and White (1998), Fjell and Heywood (2002), Chang (2005), and Chao and Yu (2006) are among the few studies which investigate the effects of privatisation when domestic firms face international competition. Dasgupta, *et al* (1978), Aarrestad, (1978), Brander and Djajic (1983) and Hillman and Long (1983) analyse depletion policies against the background of open economies, but the focus is on their effects on the exports of the exhaustible resources in concern. There is a gap in the literature to integrate the above three areas. This paper attempts to fill in the gap by presenting a model in which the analysis of coal policies incorporates coal firm privatisation and related opportunistic behaviour, and extends to export-oriented manufacturing sectors of an open economy – China.

The paper is organised as follows. The next section outlines the game theoretical model and related assumptions, followed by the solution to the game in Section 3. Section 4 compares the scenarios of different tax regimes with regard to social welfare, the extent of privatisation of coal firms and related opportunistic behaviour, consumer surplus, profits of coal firms, and government tax revenues. Section 5 presents a numerical case study to which the model is applied. The last section concludes.

2. The Methodology and Model

This section describes the configuration of the model.

2.1 Three-stage Theoretical Game

Coal-fired power is the largest user of coal in China, accounting for around 50% of the total coal consumption and producing about 80% of the total electricity supply (IEA, 2000; 2012). Industries have been the largest electricity consumer, and the share of manufacturing sectors in total industrial electricity consumption has been growing. For simplicity, we only consider coal consumption by power generation, assuming that all the coal supplied is used for producing electricity, and that all electricity generated is consumed by downstream manufacturing sectors.[6] We also exclude from the analysis imports and exports of coal and electricity, which have so far accounted for a relatively small part of their respective total supplies.[7]

There are three players in the game: (i) the government, (ii) coal firms,[8] and (iii) electricity-intensive, manufacturing firms which compete with foreign firms in the market of final products. In the model, electricity generating firms that consume coal and supply electricity to manufacturing sectors are not considered as a separate player, based on the observation in China. Despite continuous conflicts between coal firms and coal-fired power companies, which have been intensified after the coal price liberalisation, the government has often used administrative intervention in both industries to ensure the coal supply for electricity generation, coupled by schemes such as the coal-electricity price co-movement policy that allows adjustments in on-grid and end-user electricity tariffs in the event of a rise of 5% or more in coal prices (Ma and Oxley, 2010). In general, facing strictly regulated electricity prices and pre-defined output quotas, power companies are not allowed to supply large industrial users directly and, generally, cannot decide on how much electricity to produce, at what price, and for whom.[9] Thus, excluding coal-fired electricity producers from the game will simplify the model without compromising the analysis.[10]

In order to cast light on the debate of whether to scrap the lump-sum fees and subject coal firms only to special taxes, we develop a three-stage game (see Figure 1). In the first stage, the government chooses among three tax regimes – the lump-sum fees, coal-specific taxes, or no taxation at all, with the objective of maximising social welfare.[11] We assume that coal-specific taxes are levied to correct for the losses in social welfare when welfare-maximising state-owned firms are privatised. In the coal industry, privatisation is likely to lead to social welfare reduction in the form of negative externalities - environmental, inter-generational, etc.. Such welfare losses can be partially compensated by levying resource and environment-related taxes. We also assume that the lump-sum fees are levied in such a way as to equalise the profits of the coal industry and downstream manufacturing sectors. For simplicity, we use

[6] Considerable volume of coal may also be consumed directly by manufacturing firms. The analysis presented in the paper will not change even if such coal consumption is considered, given the three main players involved in the model.

[7] China has witnessed a rise in its coal imports since 2009, with Indonesia and Australian being its largest overseas coal suppliers. However, the amount of coal imported in comparison to the county's total coal consumption is still small (e.g. 126 v.s. 2985 Mt in 2009).

[8] In the model, we consider national or 'key' state-owned coal firms – the term used in Tu (2011) – which accounted for half of the national coal output in 2009.

[9] See Zhang (2013) for more details on electricity prices and the quota-based dispatch system in China.

[10] Electricity companies, in particular those that are centrally state-owned, have a strong bargaining power with government agencies (Zhang, 2013). Nonetheless, their influence falls, arguably, outside the loop of the game, in particular when the model is mainly concerned with the government's choice of coal taxation regime.

[11] The literature debates whether governments are social-welfare or private-interest maximisers. We assume that the government is benevolent, as many existing studies do (e.g., Mujumdar and Pal, 1998; Pal and White, 1998; Leahy and Neary, 2001). In addition, we distinguish between government and government officials, emphasising the former's role as the policy maker while recognising the latter's self-interested and rent-seeking nature.

‘fees’ to refer to the lump-sum fees and ‘taxes’ to coal-specific taxes in the rest of the text.[12]

In stage two, having observed the chosen coal taxation regime, coal firms will make their decision. Unlike most existing studies, we don’t assume that coal firms can choose their output levels in order to maximise their objective function, because the government often intervenes in big energy firms’ decisions over investment and production to ensure adequate energy supply for economic growth, a practice likely to continue in the coal industry in the foreseeable future.[13] Instead, we assume that coal firms influence the extent of privatisation and whether to engage in opportunistic behaviour. Although some existing studies see the degree of privatisation as exogenous while others are ambiguous about whose decision it is to privatise,[14] we assume explicitly in the model that privatisation is coal firm’s decision, for reasons discussed below.

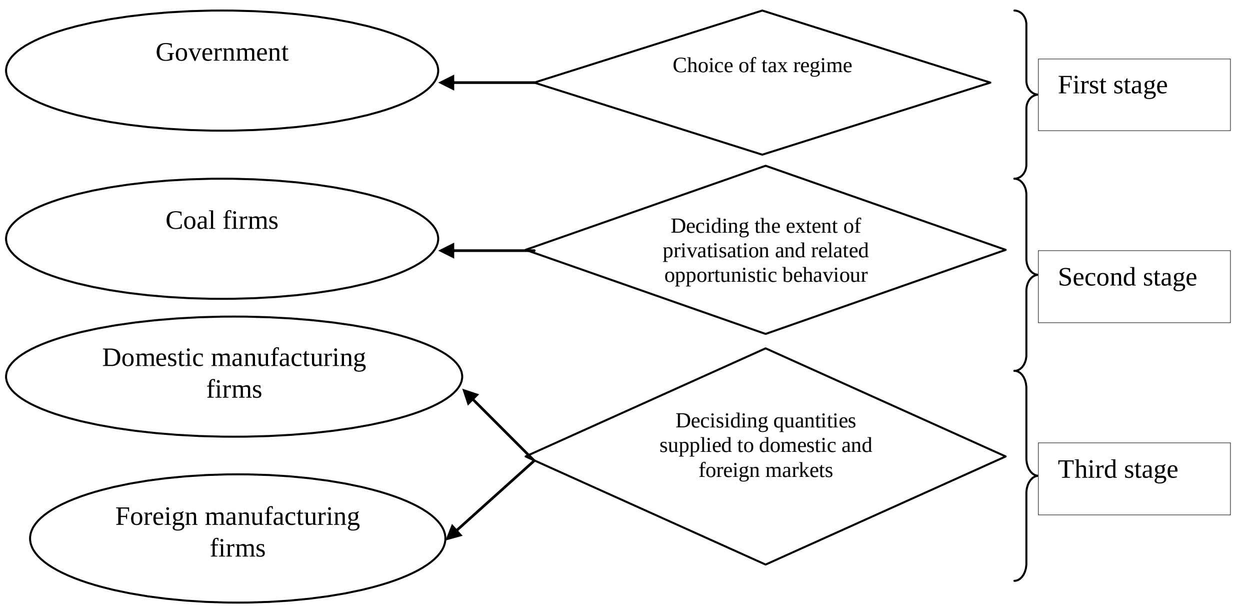

Figure 1. Flowchart of the Three-stage Theoretical Game

Firstly, a general observation in China is that large energy companies are influential in their relations with government agencies (Xu, 2008). Senior managers of major state-owned coal firms have administrative ranks no lower than that of the governing agencies, and have close political ties with top leadership of the government. Therefore, treating privatisation as a decision by coal-firms is justified as their managers will be part of the decision-making body over issues such as

[12] These terms are used for simplicity and do not match those used in taxation literature.
[13] See Zhang (2013) and Peng (2011) for examples of government intervention in coal and electricity industries.
[14] For instance, the degree of privatisation is taken as exogenous in Chao and Yu (2006) and Matsumura (1998). Section V in Shleifer and Vishny (1994) provides an interesting discussion that the decision to privatise is the outcome of bargaining between politicians, the Treasury and taxpayers. Laffont (2005) develops a model in which the incentives for privatisation are a function of various exogenous variables and ownership affects the ability of governments to extract rents.

privatisation, or at least will have influence on the direction of policy. This view holds some applicability to other transition and developing economies where energy firms are controlled by the ruling elite which can influence or even have the outright control over government agencies (Banerjee and Munger, 2004). Secondly, this approach allows us to shed light on an interesting question. That is, if the managers of coal firms could influence the issue of privatisation, which is likely given their influence over and presence in key government bureaucracy, would they attempt to privatise their companies in response to coal tax reform and what implications would this have for downstream manufacturing sectors? Thirdly, original to the literature, the paper incorporates opportunistic behaviour in the analysis of privatisation. Arguably, it will be at the discretion of large coal firms whether to engage in social-welfare detrimental practices.

Following Matsumura (1998) and Chao and Yu (2006), we employ a mixed oligopoly model to formulate the objective function of coal firms, in which they are assumed to maximise the weighted average of social welfare and their own profits, with the weights associated with the extent of privatisation.

In the third stage of the game, after knowing the choice of the government and the decision of coal firms, domestic manufacturing firms choose their output levels to maximise profits, in competition with foreign firms that decide over their own supply quantities in pursuit of profit maximisation. For simplicity, we do not take into account tariffs and other trade barriers for the final products. This assumption is justifiable when regional and international trade agreements have increasingly called for removal of such barriers.

We solve the game by backward induction and begin with the third-stage subgame.

2.2 Subgame of Downstream Manufacturing Firms

We assume that home and foreign firms produce a homogeneous product, competing in both home and foreign markets. They choose their output levels *à la* the Cournot equilibrium in both the markets to maximise their respective aggregate profits. We define q_d as the output of domestic firms and β as the share of total output which is exported. Similarly, q_f is the output of foreign firms' and γ their share of output used for exporting to China. Therefore, the total supply quantity (Q) is $(1-\beta)\times q_d + \gamma\times q_f$ on Chinese domestic market and $\beta\times q_d + (1-\gamma)\times q_f$ on the foreign market, where β、$\gamma \in [0, 1]$. Generally speaking, the price of the product, p, can be derived by taking the inverse demand function, i.e. $p=a-Q$, with a as market size (or total market demand). Thus, prices in the domestic and foreign markets are given, by $p_d= a-(1-\beta)\times q_d-\gamma\times q_f$ and $p_f= a-\beta\times q_d-(1-\gamma)\times q_f$ respectively. The marginal costs of domestic and foreign firms are c_d and c_f respectively. Because of lack of further information on their cost structures, we follow the literature assuming that the two groups of firms employ identical technologies and thus face the same marginal cost. That is, $c_d=c_f=c$. Like most existing studies, we assume fixed costs are 0. Thus, the profit of domestic and foreign firms – π_d and π_f–are written respectively as

$$\pi_d(q_d,q_f)=\beta\times[a-\beta\times q_d-(1-\gamma)\times q_f-c]\times q_d+(1-\beta)\times[a-(1-\beta)\times q_d-\gamma\times q_f-c]\times q_d, \quad (1)$$

$$\pi_f(q_d,q_f)=\gamma\times[a-(1-\beta)\times q_d-\gamma\times q_f-c]\times q_f+(1-\gamma)\times[a-\beta\times q_d-(1-\gamma)\times q_f-c]\times q_f. \quad (2)$$

By solving simultaneously the first order conditions of equations (1) and (2), we can obtain the equilibrium outputs of domestic and foreign firms, q_{d*}, q_{f*}, which are the function of β and γ. Based on Hessian Matrices of π_d and π_f (see Appendix 2), their leading principal minors are negative and positive, indicating that they are both strictly concave and the solutions are local maxima. Expanded algebraic expressions of q_{d*}, q_{f*} are shown in Appendix 1. Accordingly, we could obtain the equilibrium profit of domestic firms, π_{d*}, again as a function of β and γ (see equation A2 in Appendix 1 for the expanded expression).

2.3 Subgame of Coal Firms

In the second stage of the game, coal firms make a decision about privatisation to maximise their objective function, which, following Matsumura (1998) and Chao and Yu (2006), is given by $\Pi=\alpha\times\pi+(1-\alpha)\times W$, where π is the profit of coal firms and W social welfare. α – the weight associated with profit – is interpreted in the literature as the shares controlled by private owners, with a value between 0 and 1. In our model, however, we relax the constraint, allowing α to take a value bigger than 1. This is to take into consideration opportunistic behaviour of privatised firms, prevalent in developing and transition economies due to institutional weaknesses and slacks in corporate governance (Dewatripont and Roland, 1992; Estache and Wren-Lewis, 2009). α exceeds the value of 1 if a fully-privatised coal firm engages in such behaviour. In this way, we are able to model the decision of coal firms over the issue of privatisation and their motivation to engage in opportunistic practices, in response to the government's choice of taxation regime.

Taxes are levied to compensate partly for the loss of welfare caused by privatisation. State-owned firms maximise social welfare and in this process negative externalities, which takes the form of a quadratic cost function in most existing literature, is fully internalised. When privatised, firms deviate from the objective of welfare maximising, in proportion to the share of private ownership. In such cases, negative externalities are only internalised in proportion to the share of state ownership. The remaining externalities can be partially compensated by levying taxes, to the amount of α *t *[output of coal], where t represents the tax rate.[15]

When we take the measure unit of coal output and that of the manufactured goods in such a way that one unit of coal produces one unit of the final product, the marginal cost faced by coal firms can be set equal to the marginal cost of downstream firms, c. Thus, the coal price - as given by the inverse demand function of coal - can be written as $p=a-Q$, identical in algebraic expression to the price function of the final product. In the rest of the paper, we use the subscripts T, F and N to denote the regime of taxes, fees and no taxation, respectively. Coal firms' profit under taxes, π_T, is given by

[15] In the model, we don't distinguish explicitly between inter-generational and environmental externalities. Instead, they are modelled together as $q_d^{*2}/2$ in the analysis. The taxes used to compensate for the externalities include both coal resource taxes and environment-related taxes.

π_T=[a-q_d^*-α×t-c]×q_d^*-(1-α)×q_d^{*2}/2 (3)

where q_{d*} is the equilibrium output of domestic manufacturing firms. q_d^{*2}/2 in Equation (3) is the negative externalities, given in the form of a quadratic cost function.

Fees are levied with the effect of equalising profit levels across industries. Thus, coal firms' profit under fees, π_F, is set as

$\pi_F \equiv \pi_d^*$ (4)

where π_{d*} is the profit of domestic manufacturing firms when producing the equilibrium output.

As a baseline scenario, no taxation is levied. Coal firms' profit π_N is expressed as

$\pi_N \equiv \pi_{\{T|t=0\}}$ (5)

Let consumer surplus in the domestic market be

CS=[(1-β)×q_d^*+γ×q_f^*]^2/2-α×q_d^{*2}/2 (6)

where q_d* and q_f* are equilibrium outputs of domestic and foreign manufacturing firms.

2.4 Subgame of the Government

Maximising social welfare is the objective of the government in the first stage of the game. The following equations give the algebraic expressions of social welfare under taxes, fees and no taxation at all, respectively.

W_T=CS_T+π_d^*+π_T , (7)
W_F=CS_F+π_d^*+π_F, (8)
W_N=CS_N+π_d^*+π_N. (9)

3. Solving the Game

Backward induction applied to finite games is used here to solve the model. In this section, the solutions under the three taxation regimes are discussed.

3.1 The Regime of Taxes

By substituting q_{d*} into Equation (6), we obtain consumer surplus under taxes, CS_T(α; β, γ), as a function of α.Similarly, we obtain from q_{d*} and Equation (3) the coal firms' profit after tax, π_T(α; β, γ). The objective function of coal firms is given by Π_T(α; β, γ)= α×π_T(α; β, γ)+(1−α)×W_T=α×π_T(α; β, γ)+(1−α)×[π_{d*}+CS_T(α; β, γ)+ π_T(α; β, γ)]. When ∂Π_T(α; β, γ)/∂α=0, Π

$_T(\alpha;\ \beta,\ \gamma)$ is maximised with respect to α, giving the sub-game equilibrium extent of privatisation, $\alpha_T(t;\ \beta,\ \gamma)$. Substituting $\alpha_T(t;\ \beta,\ \gamma)$, π_{d*}, $CS_T(\alpha;\ \beta,\ \gamma)$ and $\pi_T(\alpha;\ \beta,\ \gamma)$ into Equation (7), and making $\partial W_T(t;\ \beta,\ \gamma)/\partial t=0$, we obtain the optimal tax rate, t, as a function of β and γ (see equation A3 as the algebraic expression)

By substituting the optimal tax rate – $t(\beta,\ \gamma)$ – into $\alpha_T(t;\ \beta,\ \gamma)$, we obtain the equilibrium extent of privatisation, $\alpha_T(\beta,\ \gamma)$, whose algebraic form is given by equation A?. In turn, the equilibrium profit of coal firms (π_T) and consumer surplus (CS_T), both as functions of β and γ, can be derived. Up to now, we have obtained all the elements in Equation (7) to compute the equilibrium social welfare under the regime of taxes (see Equation A7 for the expanded algebraic expression).

3.2 The Regime of Fees

When fees are collected, coal firms' profit expressed as a function of α is, by assumption, set equal to that of manufacturing firms. That is, $\pi_F(\alpha;\ \beta,\ \gamma)\equiv\pi_{d*}$. The objective function of coal firms can be expressed in terms α, as $\Pi_F(\alpha;\ \beta,\gamma)$. We then maximise $\Pi_F(\alpha;\ \beta,\ \gamma)$ with respect to α to obtain the sub-game equilibrium extent of privatisation, α_T, whose algebraic expression is given in A4.

Under this taxation regime, government revenues are the fees levied on coal firms – $G_F=\ \pi_T|_{\{t=0,\ \alpha=\alpha_F(\beta,\gamma)\}}-\ \pi_F(\alpha;\ \beta,\ \gamma)$, where the first term is given by Equation (3) and the second term equals π_{d*}. Social welfare under fees is $W_F=\pi_{d*}+CS_F(\alpha;\ \beta,\ \gamma)+\pi_F(\alpha;\ \beta,\ \gamma)$. Note that so far G_F and W_F have been expressed as a function of α. By simply substituting α_T into the two equations, we can obtain G_F and W_F in the form of a function of β and γ. (see equations A13 and A8 for the algebraic expressions).

3.3 The Case of no Taxation

When the government chooses not to levy taxes or fees, coal firms' profit π_N is given by Equation (5) or Equation (3) with $t=0$, as a function of α. We write the objective function of coal firms Π_N in terms of α, and obtain the sub-game equilibrium extent of privatisation, $\alpha_N(\beta,\ \gamma)$, by maximising Π_N through making $\partial\Pi_N(\alpha;\ \beta,\ \gamma)/\partial\alpha=0$. Substituting $\alpha_N(\beta,\ \gamma)$ into Equation (9) gives the equilibrium social welfare when no taxation is levied, expressed as a function of β and γ (see A9 as the algebraic form)

4. Comparison of the Taxation Regimes

Based on the solutions to the model, this section compares the three regimes along the dimensions of social welfare, the extent of privatisation of coal firms and the likelihood for them to commit opportunistic behaviour, consumer surplus, coal firms' profit, and government tax revenues. Given the complex mathematic transformation used to derive these variables as a function of β and γ and their cumbersome algebra expressions as shown in the appendix, we use graphs produced by the software Mathematica 5.0 to make visual comparison of the taxation regimes

The purpose is to see which regime is optimal in terms of social welfare, and, if adopted, whether coal firms will engage in opportunistic behaviour and whether the reform will face resistance from coal firms, consumers and/or government officials.

4.1 Comparison with regard to Social Welfare

Figures 2-a, 2-b and 2-c illustrate, in a pair-wise way, the difference in the equilibrium social welfare between the taxation regimes. Axes x and y represent γ and β respectively. The vertical axis is $\triangle W$, the difference in social welfare between the regimes in comparison, with $(a-c)^2$ as the measure unit. In the bracket of each figure's title are the two taxation regimes to be compared, with the first one represented by the plain plot surface and the second by the checked plot surface. Figure 2-a shows that, in most cases, social welfare under taxes is higher than that under fees. The probability of this occurrence is 94.82%, which is calculated by subtracting from 1 the area of the plain surface when it is below the checked surface.[16] Figure 2-b compares levying taxes with no taxation, showing that social welfare under taxes is always higher than the case of no taxation at all. When the regime of fees is compared with levying nothing (see Figure 2-c), the probability of the former producing higher social welfare than the latter is as small as 0.1532, occurring only when a moderate β is combined with either a very high or very low γ.

In order to get a better idea about which regime and under what circumstance will produce superior results in terms of social welfare, Figure 2-d is constructed, which divides the two-dimensional space into four areas according to the values of β and γ. Area I represents the situation in which domestic manufacturing firms' export share is moderate ($0.3583<\beta<0.7507$) while foreign firms' export share γ is high, above 0.81, corresponding to the upper part of the plain surface above the checked one in Figure 2-c. This is an area in which the equilibrium social welfare under taxes is higher than that under fees, which is in turn higher than no taxation at all. Thus, when there is on the domestic market a large quantity of products exported by foreign firms but domestic firms are only able to export a moderate portion of their output to the foreign market, the optimal taxation regime is levying taxes. Area II denotes the cases in which foreign firms' export share is in the middle range, corresponding to the area where the plain surface goes beneath the checked one in Figure 2-c. With the equilibrium social welfare under taxes being the highest and that under fees the lowest, the optimal regime in Area II is levying taxes. When domestic firms export a moderate share of their output ($0.334<\beta<0.7057$) while foreign firms export a very low share ($\gamma<0.1998$), as depicted by Area IV in Figure 2-d and the area of the plain surface which goes below the checked surface in Figure 2-a, the optimal regime is levying fees. Taking Areas I, II, and IV out of the two-dimensional space of Figure 2-d gives Area III, where domestic firms' export share is moderate ($0.2328<\beta<0.7488$) and foreign firms export a relatively smaller share ($0.1998<\gamma<0.2926$) of their output. The optimal taxation regime in this area is tax.

[16] The Monte Carlo simulation method is used to calculate the probability here and those in the later part of the section, in which an interval of length 0.001 within [0, 1] is used for the inputs β and γ, resulting in 1 million trial runs.

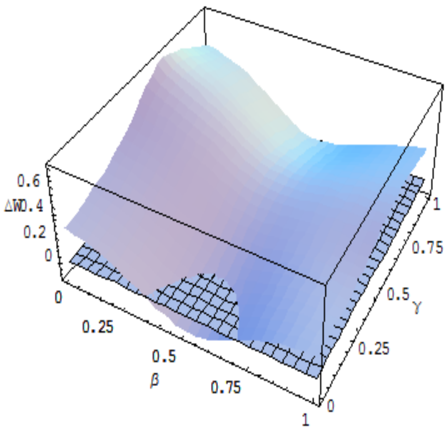

Figure 2-a. Social Welfare (taxes v.s. fees)

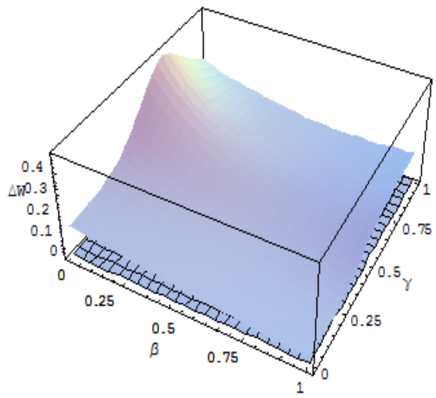

Figure 2-b. Social Welfare (taxes v.s. no taxation)

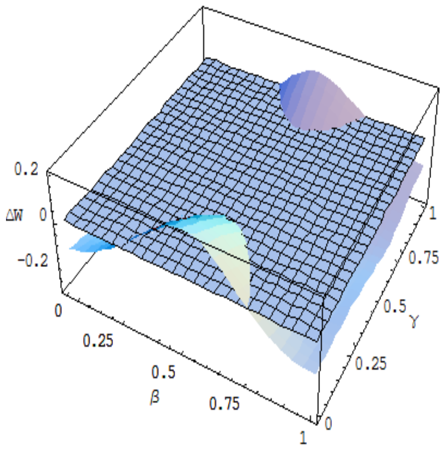

Figure 2-c. Social Welfare (fees v.s. no taxation)

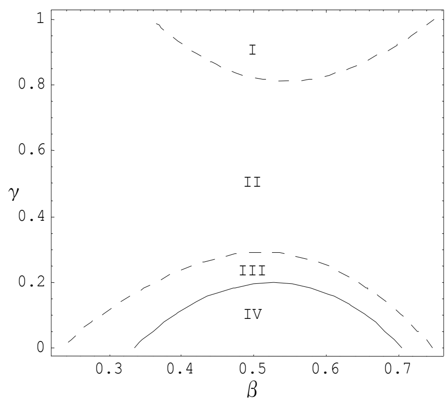

Figure 2-d. Comparison of Social Welfare

The comparison indicates that levying neither taxes nor fees is always an inferior policy option and that the optimal regime in most cases is tax. This result is generally in line with the theoretical prediction that, for nonrenewable resources like coal, which is an important energy source and whose extraction and consumption is associated with substantial externalities, the use of special taxes as an economic instrument tend to have the effect of altering the behaviour of coal firms over coal extraction and production (e.g. Garnaut and Ross, 1975; Robinson, 1983; Fraser and Kingwell, 1997; Bosquet, 2002; Lund, 2002; Schoeb, 2003; Bretschger and Valente, 2010). Going a step further, our result suggests that the use of such taxes is, under most circumstances, associated with higher social welfare in the context of an open economy when downstream manufacturing sectors is incorporated into the analysis. The superiority of taxes to fees in most of the cases implies that taxes will do a better job at correcting for the deviation of coal firms from social welfare maximisation when they are privatised. This is because the social welfare loss associated with market failure, in particular the failure of internalising externalities under private ownership, can be partly compensated for by levying taxes from privatized firms. Based on the above discussion, we can obtain the following result.

Result 1: Under most circumstances, the optimal taxation regime is to levy taxes. Levying fees is optimal only when domestic firms export a moderate share of their output and foreign firms export a small share.

4.2 Comparison with regard to Privatisation and Opportunistic Behaviour

When privatised, firms may have incentive to engage in opportunistic behaviour which reduces social welfare. This is more likely in developing and transition economies where institutions are weak and corporate governance mechanisms are less effective or simply not in place to control such practices. In the model, we allow the parameter α to take values bigger than 1 to account for such behaviour. Thus, α is larger than 1 when coal firms commit opportunistic practices, making the weight attached to social welfare in their objective function ($\Pi = \alpha \times \pi + (1-\alpha) \times W$) negative. As pure profit maximisers, coal firms with full private ownership would no longer care about social welfare in their objective function. Rather, by engaging in opportunistic behaviour, they would maximise their private gains at the expense of social welfare.

Figures 3-a and 3-b are constructed to illustrate coal firms' tendency to commit opportunistic practices under fees and taxes respectively. For the comparison purpose, Figure 3-c illustrates the scenario in which the government chooses to levy neither fees nor taxes, although it is clear from the last sub-section that this regime is not optimal under any circumstances.

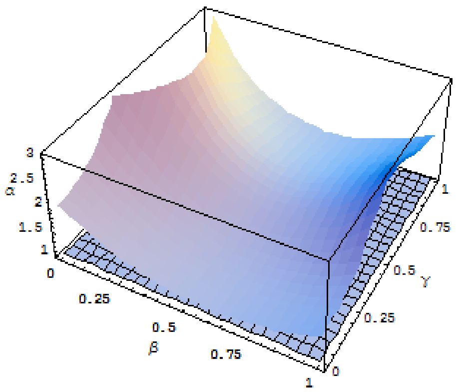

Figure 3-a. Privatisation and Opportunistic Behaviour (fees)

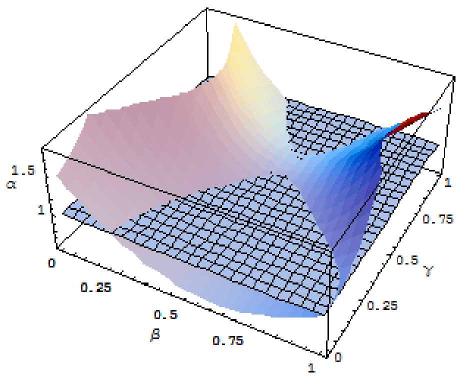

Figure 3-b. Privatisation and Opportunistic Behaviour (taxes)

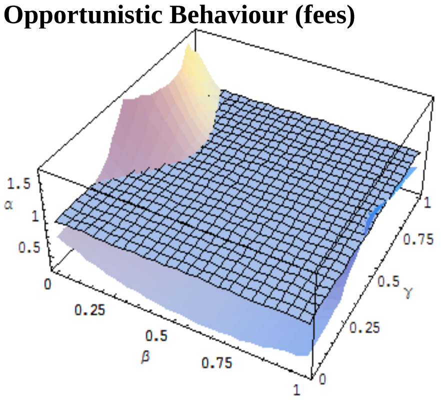

Figure 3-c. Privatisation and Opportunistic Behaviour (no taxation)

Figure 3-a indicates that coal firms would always engage in opportunistic behaviour under fees. This is in line with intuition that, once their profit is set equal to that of the manufacturing sectors, coal firms under privatization would resort to practices such as asset stripping, under-pricing state assets, de-capitalisation, etc., in order to enlarge their private gain. Note that levying fees is the optimal regime in the cases depicted in Area IV in Figure 2-d. Thus, we can obtain the following result.

Result 2: when the export share of domestic firms is moderate and that of foreign firms is small, the adoption of levying fees as the optimal taxation regime to maximise social welfare will induce privatised coal firms to commit opportunistic behaviour.

If the government chooses the regime of taxes, as shown in Figure 3-b, the extent of privatisation decided by coal firms would be smaller compared with the other two regimes. There are two circumstances in which opportunistic behaviour would occur. One is when domestic firms export a small share of their output while foreign firms export around or above half of their output, corresponding to a probability of 0.1306. The other is when domestic firms export nearly all their output while the export share of foreign firms stays in the middle range, with an approximate probability of 0.0053. In other words, the probability of coal firms deciding not to engage in opportunistic practices is 0.8642. Overall, levying taxes is associated with the lowest probability of opportunistic behaviour among the three taxation regimes. A possible explanation is that, when part of their profit is taken away in the form taxes and thereby their objective function diverges from their profit function, coal firms have to make a balance between the private gains from opportunistic behavior and the amount of profit submitted as taxes, thus becoming less tempted to commit these practices.

The following result can be obtained.

Result 3: under circumstances other than the ones in Result 2, levying taxes as the optimal regime for social welfare maximisation will not induce coal firms to commit opportunistic behaviour, except for the cases where β is low and γ is from moderate to high, or when β is nearly 1 and γ moderate.

In the cases referred to as exceptions in Results 3 (as illustrated in the two areas where the plain surface is above the checked plane in Figure 3-b), opportunistic behaviour would occur. However, a close look at the figures reveals that the extent of such behaviour under taxes would be smaller than that under either of the other two regimes. In other words, when it is adopted as the optimal regime for social welfare, levying taxes is also optimal for reducing the severity of opportunistic practices.

It is clear from the discussion that, when the optimal taxation regime is adopted for the purpose of maximising social welfare, coal firms may choose to behave opportunistically when privatised. The government needs to anticipate such behaviour and find ways to mitigate its detrimental effects. One option is to reduce the output of domestic firms – q_d – to reduce negative externalities formulated as $q_d^{*2}/2$, so that the part of the externalities which is not internalised (in the magnitude of $(1-\alpha)\times q_{d2}/2)$) can be reduced. Another option relates to the deployment of cleaner coal-fired electricity generation technologies.[17] Which is more desirable depends on the circumstances in question and policy makers' priorities. If the priority lies in promoting economic growth and the development of manufacturing sectors, the second option can be pursued. If the economy is shifting from extensive to intensive growth and more weight is given to sustainable development, the two options can be combined.

4.3 Comparison with regard to Consumer Surplus

In order to compare consumer surplus under different taxation regimes, Figures 4-a, 4-b and 4-c are constructed in a similar way to Figures 2-a to 2-c. The vertical axis represents consumer surplus (CS), with $(a-c)^2$ as the measure unit. The figures show consumer surplus is highest under taxes and lowest under fees. An elaborate explanation to the result has to do with the way in which the model is constructed, where the magnitude of the negative externalities borne by consumers – $\alpha \times q_{d2}/2$ – varies under different taxation regimes according to α, which is in turn a function of β and γ, whose equilibrium levels are both affected by the government's choice of taxation regime. Intuition can be useful to understand the result. As shown in Equation (8), there are two terms in the calculation of consumer surplus. The first term increases when the supply of the final product on the domestic market rises and the price falls as a result. The second term capturers the negative externalities borne by consumers, which is associated positively with the extent of privatisation and related opportunistic behaviour. It is clear from the last sub-section the equilibrium α is lowest under taxes and highest under fees (see Figures 3-a to 3-c), resulting in the second term in the consumer surplus equation being the largest under fees and lowest under taxes. Therefore, levying taxes produces, ceteris paribus, the highest consumer surplus, followed by no taxation at all and then levying fees.

It should be noted that consumer surplus is not always positive, even under taxes. When taxes are levied as the optimal regime, consumer surplus is below zero in the cases represented by the area denoted as 'c-' in Figure 4-d. According to Result 1, the government will choose taxes to maximise social welfare in the cases other than Area IV in Figure 2-d. In Area IV where levying fees is adopted as the optimal regime, consumer surplus is below zero. Thus, when the optimal tax regime is chosen to maximise social welfare, consumer surplus will become negative for any combination of β and γ in the union of Area IV in Figure 2-d and the area 'c-' in Figure 4-d.

[17] Note that the deployment of clean generation technologies in the electricity sector is not easy. A discussion of the issue from a political economy perspective can be found in Zhang (2013).

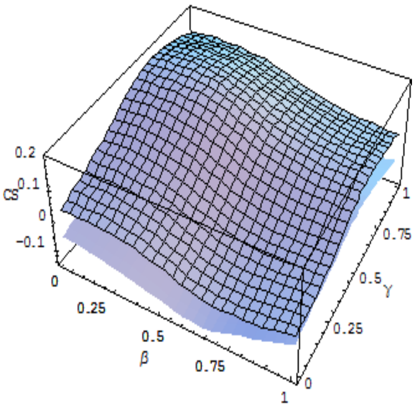

Figure 4-a. Consumer Surplus (taxes vs no taxation)

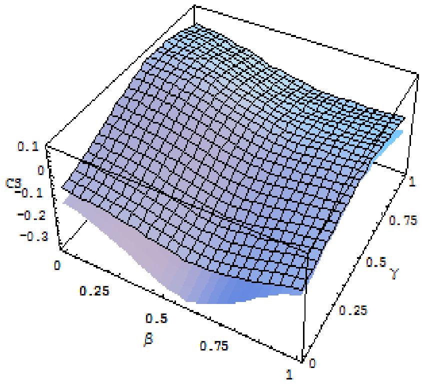

Figure 4-b. Consumer Surplus (no taxation vs fees)

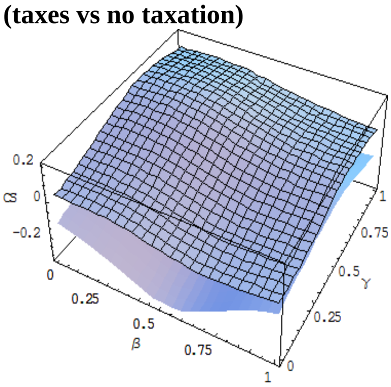

Figure 4-c Consumer Surplus (taxes vs fees

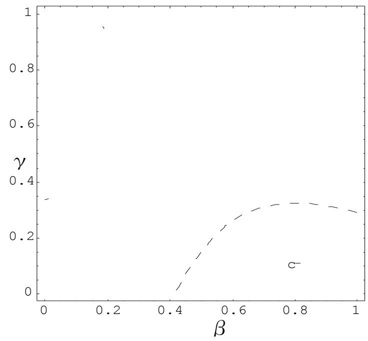

Figure 4-d. Comparison of Consumer Surplus

Result 4. When the export share of foreign firms is low but that of domestic firms is from moderate to high, the equilibrium consumer surplus under the optimal taxation regime is below zero.

This result indicates that the adoption of taxation regime with social welfare maximisation as the objective may not always bring about positive consumer surplus, and that the optimal taxation regime can be sub-optimal for consumer surplus under some circumstances. Policy makers need to be aware of potential resistance from consumers when implementing coal taxation reform; measures may need to be put in place to compensate consumers. Such measure may be particularly important when changes in the circumstances of downstream manufacturing sectors require a shift of the optimal taxation regime from taxes to fees, resulting in a further reduction of consumer surplus. If the direction of reform is to scrap the fees and subject coal firms to special taxes as discussed in the introduction section, reduced resistance from consumers can be expected because they would be better off under taxes.

4.4 Comparison with regard to Coal Firms' Profit

Coal firms may resist and even obstruct coal tax reform if their profits will be adversely affected. In addition, government officials (both central and local) may be hesitant to adopt the optimal regime if tax revenues from coal firms will be reduced. This and the next sub-sections examine, respectively, coal firm's profit and government tax revenue, in order to shed light on potential challenges faced in the reform.

Coal firms' profit can be calculated based on Equations (5), (6) and (7) and the algebraic expressions can be found in the appendix. In Figures 5-a to 5-c, coal firms' profit represented by the plain plot surface is compared with the checked plane which denotes zero profit. It is clear that coal firms can always make profit under fees. Under taxes, they will make a loss when the export share of foreign manufacturing firms is either very low or very high. In the other cases, profit can be made. Profit under taxes will be higher than that under fees when γ is moderate and β falls outside the middle range.

According to Result 1, levying fees is optimal in Area IV of Figure 2-d. It can be expected that the adoption of the optimal regime in that area will not face resistance from coal firms because their profit there will be highest under fees. Outside Area IV when taxies are levied as the optimal regime, coal firms will support the reform if γ is from moderate to high and β is low or when γ is moderate and β is high. However, they will become resistant if their profit is reduced, in particular when they start making a loss instead of profit. This is a potential obstacle to the reform move of scraping the fees, given the stronghold of major state-owned or -controlled coal companies.

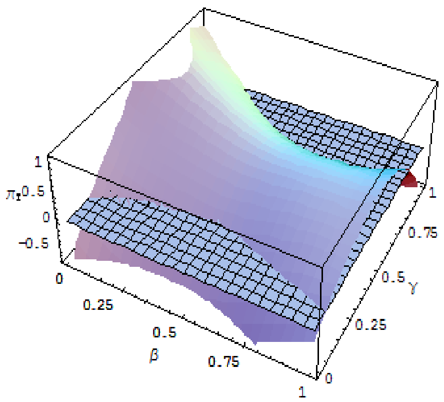

Figure 5-a. Coal Firms' Profit (taxes)

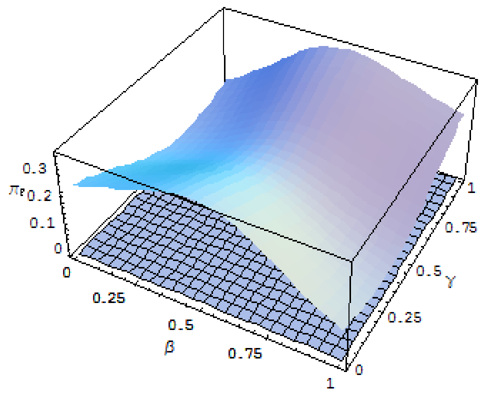

Figure 5-b. Coal Firms' Profit (fees)

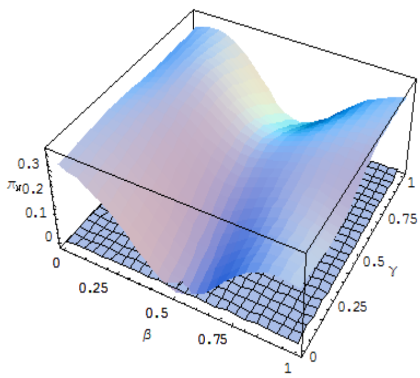

Figure 5-c. Coal Firms' Profit (no taxation)

4.5 Comparison with regard to Government Revenue

While taxes and fees are levied in the coal industry, the government quite often subsidise coal firms, partly for the purpose of attracting and encouraging investment in the sector. When comparing between coal taxation regimes, we take account of both fiscal revenue collected in the form of taxes and fees and government spending in the form of subsidies to coal firms.

When no taxation is levied, government tax revenue is zero. Tax revenue under fees is given in Equation (A13) and that under taxes is $G_T = t \times \pi_d^*$ (see the appendix for the algebraic expression). Constructed in a similar way to the figures in subsections 4.1 and 4.3, Figures 6-a to 6-c compare government revenue between the different regimes.

Government revenue under taxes is always below zero, indicating the government is in fact subsidising coal firms. If fees are levied, government revenue is negative in two areas. One is when domestic firms' export share (β) is around 0.5 and that of foreign firms (γ) is high. The other is when β is moderate and γ is low, the cases which fall within Area IV in Figure 2-d. If levying fees is adopted as the optimal taxation regime in this area and levying taxes in other circumstances, the government will have to face worsening fiscal situation. This finding is in line with the conclusion of Collier and Hoeffler (2005), Gupta and Sen (2007) and Moore (2007), which find resource rich countries are usually associated with poor fiscal performance and warn of increasing rent-seeking behaviour of government officials.

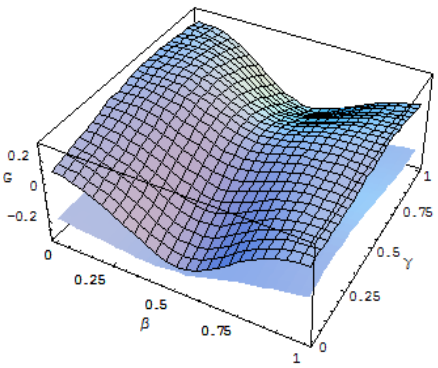

Figure 6-a. Government Revenue (fees vs taxes)

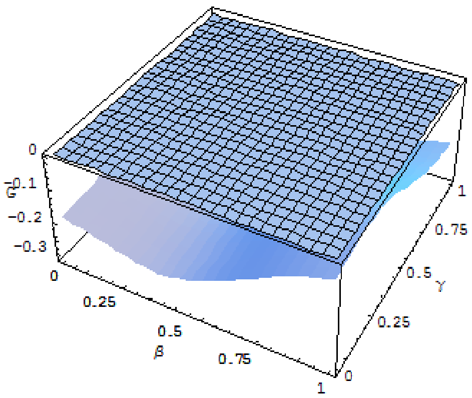

Figure 6-b. Government Revenue (no taxation vs taxes)

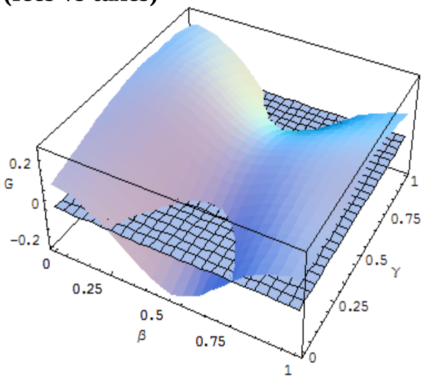

Figure 6-c. Government Revenue (fees vs no taxation)

Coming back to our results, the danger is that government officials may simply choose to oppose the adoption of the optimal taxation regime. It's not clear whether the fiscal deficit can be covered by other sources of government revenue such as tax revenue from downstream manufacturing firms.[18] Even if it is possible, given the fact that the provinces in which coal mines concentrate are not those where most export-oriented manufacturing firms locate, the adoption of the optimal taxation regime will create huge fiscal imbalance between the regions with rich coal reserves and those in which manufacturing firms cluster. With difficulty in inter-province fiscal transfers in the context of China's fiscal decentralisation, officials in coal-abundant provinces would endeavour to block coal taxation reform. If the optimal taxation regime is adopted by the central government in a top-down approach, local officials in coal-rich provinces will tend to commit rent-seeking and corrupt practices or/and create difficulty in enforcement.[19]

5. Case Study – The Policilicon Sector

This section presents a numerical case study to illustrate what would be the optimal coal taxation regime if policy makers took a broader view – taking into consideration the implications for downstream firms. In other words, policy makers' choice of taxation regime for maximising social welfare and coal firms' decision on privatisation can be expressed as the functions of the circumstances in downstream manufacturing sectors – more precisely, β and γ. An ideal case study in point is to base the analysis on the situation of electricity-intensive, export-oriented manufacturing sectors as a whole. However, this approach suffers from potential difficulty in interpreting β and γ aggregated from industries which are heterogeneous in the two parameters. For simplicity, we choose to focus on one typical industry for the illustrative purpose. The caveat is that the government's choice of coal taxation regime should, by no means, be made on the basis of the situation in this industry or any other individual industries.

The downstream industry we choose to look at is China's polysilicon sector, an industry in which the capacity of domestic firms has increased rapidly since 2008 and now a significant share of domestic output is exported. China-based polysilicon firms currently have 30% of the world market share (China Silicon Industry, 2013). There have been intensified trade frictions and increasing cases of major trading countries accusing each other of 'dumping'. This is also an energy-intensive industry, especially so in China where the dominant technology is the 'Siemens' process, a method consuming more electricity than alternative processes. Thus, it is an industry for which policies and reforms adopted in energy such as the coal sector may have important implications. Producing polysilicon by the 'Siemens' method is also very polluting, creating substantial negative externalities. For all these reasons, this industry is chosen for the numerical application of the model.

[18] This is an interesting question, but no answer can be obtained from the model presented in the paper. Future research effort could be made to establish a model incorporating the issue.
[19] Poor enforcement at local levels of rules and regulations issued by central government is discussed in literature such as Williams and Kahrl (2008), Xu (2011) and Zhang (2013).

In the illustrative case study, we use the data for the years from 2009 to 2012, a period in which China-based polysilicon firms grew rapidly and China started to become the target of dumping and anti-dumping strategies of other countries. Table 1 shows the outputs of China and other major trading countries, with the measures of industry concentration presented in the last three rows. The annual export share of Chinese firms, β, is calculated based on data from *Silicon China*. Using the data from the same source on China's import of polysilicon and the total production of other major trading countries presented in Table 1, the annual export share of foreign firms, γ, is calculated.[20] Table 2 presents the values of β and γ, the corresponding optimal regime of coal taxation, and the signs of the variables discussed in the last sections. [21]

Table 1. Output of Polysilicon in Main Trading Countries

Countries	2009 Output	2010 Output	2011 Output	2012 Output
China	18823	52880	79041	110744
Taiwan, China	740	2080	3109	4356
Korea	8000	17200	33900	50500
USA	25100	37801	44300	47000
German	12300	31100	32700	35800
Japan	16200	22900	24100	27200
Norway	9000	13000	16000	17000
Italy	0	1000	2500	3500
Holland	200	1800	1800	2800
Russia	600	1600	1800	2000
UK	153	1000	1200	1500
Canada	50	200	200	n.a.
World Total	91166	182561	240650	302400
CR_4	0.7944	0.7925	0.7893	0.807
CR_{10}	0.9995	0.9934	0.9942	0.995
HHI	1857.74	1858.43	1949.36	2119.22

Source: http://www.sxgxt.gov.cn/0/1/16/91/9982.htm;
the industry concentration indicators are calculated by authors).

[20] An accurate calculation of γ needs data on the output of all the other countries than China, which we did not have. Instead, we calculated the aggregate output of other major trading countries and used it in the computation of γ. This would not be a major problem, given the high CR10.

[21] In a pure application of the theoretical model, β and γ are decided by downstream firms after observing policy maker's choice of the taxation regime and coal firms' decision on privatisation. However, there are no real data that could be used to calculate such parameters, given the imaginary nature of the three scenarios depicted in the model. What the numerical case study does is to illustrate what the optimal taxation regime would be if the equilibrium export shares of downstream firms were as given by the data for the period.

Table 2. Application of the Model to the Polysilicon Industry: Optimal Coal Taxation Regime

Year	(β, γ)	Optimal taxation mode	π	CS	α	G
2009	(0.76, 0.299)	taxes	$\pi T>0$	$CST<0$	$\alpha T<1$	$GT<0$
2010	(0.42, 0.366)	taxes	$\pi T>0$	$CST>0$	$\alpha T<1$	$GT<0$
2011	(0.16, 0.4)	taxes	$\pi T>0$	$CST>0$	$\alpha T<1$	$GT<0$
2012	(0.12, 0.279)	taxes	$\pi T>0$	$CST>0$	$\alpha T<1$	$GT<0$

Sources: constructed by authors based on data from http://www.siliconchina.org/duojinggui/tongji/2.html and http://www.sxgxt.gov.cn/0/1/16/91/9982.htm.

As shown in Table 2, over the time period studied, the optimal taxation regime for welfare maximisation would be levying taxes. With the adoption of this regime, consumer surplus would be positive in all the years but 2009, in which it would be just below zero. Nonetheless, it seems less likely that consumers would resist the reform of coal taxation towards levying taxes, if adopted. Levying taxes as the optimal regime would incur negative government revenue, however. A closer look at the combinations of β and γ presented in the table reveals that government would always enjoy fiscal surplus under fees, implying that government officials would likely seek to obstruct the reform moving away from levying fees towards levying taxes.

Would coal firms welcome the adoption of the optimal taxation regime and would they engage in opportunistic behaviour in privatisation? The combinations of β and γ in these years all fell within the area in which coal firms would enjoy profit under taxes, and it is therefore less likely that they would resist the adoption of taxes. Under this regime, they would not engage in opportunistic practices.

6. Conclusions

Taxation of non-renewable extractive energy resources such as coal is important for the inter-generational and environmental dimensions of sustainable development. It has significant implications for not only firms in the coal sector but also for the downstream manufacturing industries. In an open economy like China whose rapid economic growth has been fuelled by coal or coal-based energy and depended to a great extent on the export of manufacturing goods, it is necessary for policy makers to take a broader view when reforming coal taxation and take into consideration the linkages between the sector and other part of the economy. The paper develops a model of three-stage game, tailored to the context of China where the coal taxation reform takes place against the background of privatisation of coal firms and an open economy.

The findings of this paper show that levying coal-specific taxes is optimal for social welfare under most circumstances. Also, this tax regime will not encourage coal firms to engage in opportunistic behaviour in most cases. In the cases it does, the extent of such behaviour will be less severe compared with the other regimes. When domestic manufacturing firms export a moderate share of their output and foreign firms export a small share, levying the lump-sum fees is optimal for social welfare. However, this will make coal firms more willing to engage in opportunistic practices in the process of privatisation.

We also showed that the adoption of optimal taxation regime will not always be associated with positive consumer surplus. Resistance from consumers when they become the loser presents a potential challenge to the reform. Under some circumstances, the use of optimal taxation regime will reduce coal firms' profit and even causes losses for them, thus making them resistant to reform. Similarly, with negative government tax revenues as the result of adopting the optimal taxation regime, government officials would likely try to block the reform or, if unsuccessful, seek to engage in rent-seeking behaviour and create difficulties in enforcement.

Several policy implications can be drawn. Firstly, it is important for policy makers to look beyond the boundary of the coal industry when designing and implementing coal tax reform. Secondly, it is advisable to scrape the lump-sum fees, which have long been imposed on coal firms, when the circumstances in downstream industries point to coal-specific taxes as the optimal regime. Thirdly, it is critical for policy makers to identify the group(s) which will become the losers in the reform process and come up with schemes to mitigate their losses, in order to reduce potential resistance from them.

The paper has limitations. Sustainable development of the coal sector involves at least two dimensions: environmental and intergenerational. The model depicted in the analysis does not explicitly address environmental issues, although it does incorporate negative externalities associated with coal firms. Further research attempt could be made to have environmental externalities directly modeled. The analysis in the paper is at large static, thus unable to address intergenerational externalities related to the sector, which are intertemporal in nature and require a more dynamic model. Last but not least, the paper does not touch upon the exact form in which coal-specific taxes take – price- or volume-based. Future research could be conducted to make comparison between them in order to shed light to benefits associated with price-based taxes, which are expected to come into effect in China soon.

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Appendix 1

- ***Expanded Algebraic expressions of q_{d*}, q_{f*}:***

$$q_d^* = \frac{(a-c)[2-5\gamma+4\gamma^2+\beta(-1+2\gamma)]}{4-8\gamma+7\gamma^2+2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)},\ q_f^* = \frac{(a-c)[2-\gamma+4\beta^2+\beta(-5+2\gamma)]}{4-8\gamma+7\gamma^2+2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)} \quad \text{(A1)}$$

- ***Expanded Algebraic expressions of π_{d*}:***

$$\pi_d^* = \frac{(a-c)^2(1-2\beta+2\beta^2)[2-5\gamma+4\gamma^2+\beta(-1+2\gamma)]^2}{[4-8\gamma+7\gamma^2-2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)]^2} > 0 \quad \text{(A2)}$$

- ***Expanded Algebraic expressions of $t(\beta, \gamma)$:***

$$t(\beta,\gamma) = \frac{\begin{array}{c}(a-c)[-12+52\gamma-103\gamma^2+98\gamma^3-41\gamma^4-\beta^4(5-12\gamma+20\gamma^2)+2\beta^3(13-40\gamma+62\gamma^2-28\gamma^3)\\ -\beta^2(47-170\gamma+294\gamma^2-220\gamma^3+68\gamma^4)+2\beta(18-71\gamma+129\gamma^2-108\gamma^3+38\gamma^4)]\end{array}}{\begin{array}{c}4[8-36\gamma+70\gamma^2-67\gamma^3+28\gamma^4+\beta^3(-7+26\gamma-36\gamma^2+24\gamma^3)+\\ \beta^2(22-89\gamma+152\gamma^2-132\gamma^3+48\gamma^4)+\beta(-20+84\gamma-149\gamma^2+130\gamma^3-48\gamma^4)]\end{array}} \quad \text{(A3)}$$

- ***Expanded Algebraic expressions of α under different taxation regimes***

$$\alpha_T(\beta,\gamma) = \frac{\begin{array}{c}12-52\gamma+103\gamma^2-98\gamma^3+41\gamma^4+\beta^4(5-12\gamma+20\gamma^2)+2\beta^3(-13+40\gamma-62\gamma^2+28\gamma^3)\\ +\beta^2(47-170\gamma+294\gamma^2-220\gamma^3+64\gamma^4)-2\beta(18-71\gamma+129\gamma^2-108\gamma^3+38\gamma^4)\end{array}}{4[2-5\gamma+4\gamma^2+\beta(-1+2\gamma)]^2} \quad \text{(A4)}$$

$$\alpha_F(\beta,\gamma) = \frac{\begin{array}{c}16-72\gamma+144\gamma^2-138\gamma^3+57\gamma^4+\beta^4(5-12\gamma+20\gamma^2)+2\beta^3(-13+40\gamma-62\gamma^2+28\gamma^3)\\ +2\beta^2(24-87\gamma+149\gamma^2-110\gamma^3+34\gamma^4)-2\beta(20-80\gamma+143\gamma^2-116\gamma^3+38\gamma^4)\end{array}}{2[2-5\gamma+4\gamma^2+\beta(-1+2\gamma)]^2} \quad \text{(A5)}$$

$$\alpha_N(\beta,\gamma) = \frac{\begin{array}{c}12-52\gamma+103\gamma^2-98\gamma^3+41\gamma^4+\beta^4(5-12\gamma+20\gamma^2)+2\beta^3(-13+40\gamma-62\gamma^2+28\gamma^3)\\ +\beta^2(47-170\gamma+294\gamma^2-220\gamma^3+68\gamma^4)-2\beta(18-71\gamma+129\gamma^2-108\gamma^3+38\gamma^4)\end{array}}{2[2-5\gamma+4\gamma^2+\beta(-1+2\gamma)]^2} \quad \text{(A6)}$$

- ***Expanded Algebraic expressions of $W_T(\beta, \gamma)$ under different taxation regimes***

$$W_T(\beta,\gamma) = \frac{\begin{array}{l}(a-c)^2[656-5856\gamma+24504\gamma^2-61096\gamma^3+103161\gamma^4-115620\gamma^5+85322\gamma^6-38052\gamma^7+7953\gamma^8\\ +\beta^8(5-12\gamma+20\gamma^2)^2+4\beta^7(-65+356\gamma-1052\gamma^2+1684\gamma^3-1576\gamma^4+560\gamma^5)\\ +2\beta^6(593-3622\gamma+11226\gamma^2-19916\gamma^3+21348\gamma^4-12160\gamma^5+2928\gamma^6)\\ +4\beta^5(-821+5521\gamma-18033\gamma^2+34368\gamma^3-40642\gamma^4+28680\gamma^5-11136\gamma^6+1904\gamma^7)\\ +\beta^4(6345-46604\gamma+161054\gamma^2-326284\gamma^3+415278\gamma^4-329064\gamma^5+154184\gamma^6-38432\gamma^7+4624\gamma^8)\\ -4\beta^3(2154-17089\gamma+62932\gamma^2-136770\gamma^3+189131\gamma^4-167012\gamma^5+89630\gamma^6-25428\gamma^7+2584\gamma^8)\\ +\beta^2(7416-62456\gamma+244358\gamma^2-570512\gamma^3+862758\gamma^4-858724\gamma^5+545668\gamma^6-200648\gamma^7+32344\gamma^8)\\ -4\beta(856-7484\gamma+30518\gamma^2-74809\gamma^3+119975\gamma^4-128457\gamma^5+89563\gamma^6-37176\gamma^7+7062\gamma^8)]\end{array}}{16[2-5\gamma+4\gamma^2+\beta(-1+2\gamma)]^2[4-8\gamma+7\gamma^2-2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)]^2} \quad \text{(A7)}$$

$$W_F = (a-c)^2 \times$$

$$\frac{\begin{array}{l}24-112\gamma+226\gamma^2-218\gamma^3+89\gamma^4+\beta^4(13-44\gamma+52\gamma^2)+2\beta^3(-33+128\gamma-190\gamma^2+92\gamma^3)\\ +\beta(-80+356\gamma-670\gamma^2+584\gamma^3-204\gamma^4)+2\beta^2(57-243\gamma+429\gamma^2-334\gamma^3+98\gamma^4)\end{array}}{4[4-8\gamma+7\gamma^2-2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)]^2} \tag{A8}$$

$$W_N(\beta,\gamma) = \frac{\begin{array}{l}(a-c)^2[(4-8\gamma+7\gamma^2)^2+\beta^4(5-12\gamma+20\gamma^2)+4\beta^3(-10+33\gamma-49\gamma^2+26\gamma^3)\\ +2\beta^2(44-168\gamma+293\gamma^2-242\gamma^3+82\gamma^4)-4\beta(16-64\gamma+118\gamma^2-107\gamma^3+43\gamma^4)]\end{array}}{2[4-8\gamma+7\gamma^2-2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)]^2} \tag{A9}$$

- ***Algebraic expressions of the coal firms' profit under different taxation regimes***

$$\pi_T(\beta,\gamma) =$$

$$\frac{\begin{array}{l}(a-c)^2[2-5\gamma+4\gamma^2+\beta(-1+2\gamma)]\\ \{\dfrac{[-4+28\gamma-61\gamma^2+62\gamma^3-23\gamma^4+\beta(5-12\gamma+20\gamma^2)+2\beta^3(-13+40\gamma-62\gamma^2+28\gamma^3)-2\beta(10-35\gamma+73\gamma^2-76\gamma^3+38\gamma^4)+\beta^2(43-154\gamma+278\gamma^2-220\gamma^3+68\gamma^4)]}{4[2-5\gamma+4\gamma^2+\beta(-1+2\gamma)]}\\ +2[4-8\gamma+7\gamma^2-2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)]\\ \{1-\dfrac{2-5\gamma+4\gamma^2+\beta(-1+2\gamma)}{4-8\gamma+7\gamma^2-2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)}\\ +\dfrac{[12-52\gamma+103\gamma^2-98\gamma^3+41\gamma^4+\beta^4(5-12\gamma+20\gamma^2)+2\beta^3(-13+40\gamma-62\gamma^2+28\gamma^3)+\beta^2(47-170\gamma+294\gamma^2-220\gamma^3+68\gamma^4)-2\beta(18-71\gamma+129\gamma^2-108\gamma^3+38\gamma^4)]^2}{16[2-5\gamma+4\gamma^2+\beta(-1+2\gamma)]^3[4-8\gamma+7\gamma^2-2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12^2)]}\}\}\end{array}}{2[4-8\gamma+7\gamma^2-2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)]^2} \tag{A10}$$

$$\pi_N(\beta,\gamma) =$$

$$\frac{\begin{array}{l}(a-c)^2[20-76\gamma+137\gamma^2-126\gamma^3+57\gamma^4+\beta^4(5-12\gamma+20\gamma^2)+2\beta^3(-27+92\gamma-134\gamma^2+76\gamma^3)\\ +\beta^2(129-502\gamma+878\gamma^2-748\gamma^3+260\gamma^4)+\beta(-92+370\gamma-686\gamma^2+640\gamma^3-268\gamma^4)]\end{array}}{4[4-8\gamma+7\gamma^2-2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)]^2} \tag{A11}$$

- ***Algebraic expression of government tax revenue under different taxation regimes***

$$G_T(\beta,\gamma) = t \times q_d^* =$$

$$\frac{\begin{array}{l}(a-c)^2[-12+52\gamma-103\gamma^2+98\gamma^3-41\gamma^4-\beta^4(5-12\gamma+20\gamma^2)+2\beta^3(13-40\gamma+62\gamma^2-28\gamma^3)\\ -\beta^2(47-170\gamma+294\gamma^2-220\gamma^3+68\gamma^4)+2\beta(18-71\gamma+129\gamma^2-108\gamma^3+38\gamma^4)]\end{array}}{4[4-8\gamma+7\gamma^2-2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)]^2} \tag{A12}$$

$$G_F(\beta,\gamma) = (a-c)^2 \times$$

$$\frac{\begin{array}{l}8-48\beta+62\beta^2-14\beta^3-3\beta^4-16\gamma+2\beta(78-93\beta+4\beta^2+10\beta^3)\gamma-2(-7+137\beta-157\beta^2+6\beta^3+6\beta^4)\gamma^2\\ +2(-3+136\beta-150\beta^2+12\beta^3)\gamma^3+(9-140\beta+132\beta^2)\gamma^4\end{array}}{4[4-8\gamma+7\gamma^2-2\beta(4-7\gamma+6\gamma^2)+\beta^2(7-12\gamma+12\gamma^2)]^2} \tag{A13}$$

Appendix 2

Hessian Matrices of π_d and π_f

$$H_d = \begin{vmatrix} \pi_{d11} & \pi_{d12} \\ \pi_{d21} & \pi_{d22} \end{vmatrix} = \begin{vmatrix} -\beta^2 - (1-\beta)^2 & -\beta(1-\gamma) - \gamma(1-\beta) \\ -\beta(1-\gamma) - \gamma(1-\beta) & 0 \end{vmatrix} > 0, \quad \pi_{d11} = -\beta^2 - (1-\beta)^2 < 0$$

$$H_f = \begin{vmatrix} \pi_{f11} & \pi_{f12} \\ \pi_{f21} & \pi_{f22} \end{vmatrix} = \begin{vmatrix} -\gamma^2 - (1-\gamma)^2 & -\beta(1-\gamma) - \gamma(1-\beta) \\ -\beta(1-\gamma) - \gamma(1-\beta) & 0 \end{vmatrix} > 0, \quad \pi_{f11} = -\gamma^2 - (1-\gamma)^2 < 0$$