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Coal cleaning: A viable strategy for reduced carbon emissions and improved environment in China?

Abstract:
China is a dominant energy consumer in a global context and current energy forecasts emphasise that China's future energy consumption also will rely heavily on coal. The coal use is the major source of the greenhouse gas CO2 and particles causing serious health damage. This paper looks into the question if coal washing might work as low cost strategy for both CO2 and particle emission reductions. Coal washing removes dirt and rock from raw coal, resulting in a coal product with higher thermal energy and less air pollutants. Coal cleaning capacity has so far not been developed in line with the market potential. In this paper an emerging market for cleaned coal is studied within a CGE model for China. The macro approach catches the repercussions of coal cleaning through increased energy efficiency, lower coal transportation costs and crowding out effect of investments in coal washing plants. Coal cleaning stimulates economic growth and reduces particle emissions, but total energy use, coal use and CO2 emissions increase through a rebound effect supported by the vast reserve of underemployed labourers. A carbon tax on fossil fuel combustion has a limited effect on total emissions. The reason is a coal leakage to tax exempted processing industries.

Keywords: Coal, China, carbon tax, CGE

JEL classification: [Klikk for å skrive inn tekst]

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1. Introduction

About 70 percent of current energy consumption in China is covered by coal, and future energy use is also expected to rely heavily on coal (Zhou, 1999, IEA, 1999). Unfortunately coal combustion is a vehicle of two major environmental problems through emissions of CO_2 and particulate matter to the atmosphere. The former pollutant is of great concern in the global greenhouse gas account, while the latter contributes significantly to domestic health problems in densely populated areas.

Coal cleaning has been launched as a strategy for improving both energy efficiency and environmental quality. In a conventional coal cleaning process, particulate matter is washed out, increasing the energy content of the final product while diminishing particle emissions. As a consequence more heat value is generated and less particulate matter emitted to the atmosphere per tonne carbon burnt. Those two benefits are obtained at a cost, and a question is whether the benefits are big enough to make coal cleaning worthwhile.

The Chinese government regards coal washing as an important element in the current strategy for energy supply and energy transportation systems, as emphasised in the Ninth Five Year Plan document on Clean coal technologies of China (SDPC 1997). However, the development of coal washing capacity has so far been sluggish. During 1993-1996 the capacity of new coal washing plants increased less than coal mining capacity (IEA, 1999). The implementation may still be hampered by the lack of proper incentives. Market reforms could make the coal sector break the cycle where producers claim that cleaned coal demand is too low while consumers complain about unreliable supply (World Bank, 1997). Coal cleaning has the potential to improve the environment, but the environmental benefits are in general external to the coal consumers. A policy for reducing air pollution should somehow improve the incentives to produce and use cleaned coal. A change in incentives could take place through a tax on carbon or particle emissions. Such emission taxes would fall more heavily on raw coal than cleaned coal and thus encourage a switch to washed coal.

A switch to cleaner coal would have significant effect on transportation demand. Raw coal contains a large amount of waste that now is transported all over China. It is estimated that 70 million tonnes dirt and rock are moved along with the high quality coal (Xu et al. 1997, cited in IEA, 1999). The majority of coalmines are located in the North and North-west of China, while coastal cities and provinces dominate the demand. Consequently, the raw coal load on the transportation system is huge. The coal transportation currently occupies about 45 percent of total railway capacity (IEA, 1999). Under the cleaning process about 25 percent of the coal weight is removed. Since thermal energy content is reduced less than weight in the coal washing process, there is a net reduction in transportation demand of about 20 percent per unit thermal energy.

The user of cleaned coal should be fully rewarded for lifting a burden from the national transportation system that currently runs under maximum load. As it is now, there is price control and an implicit subsidy of transportation services. The raw coal purchaser price contains a higher share of transportation costs per unit heat value than the clean coal price and thus incorporates a higher implicit subsidy per unit energy delivered. The raw coal user will keep this benefit, while those who switch to washed coal see a benefit foregone. The transportation element in the user price is significant, up to 70 percent of delivery prices (WB, 1997), and transportation cost distortions might be a factor that has significant impact on the market shares of raw coal and cleaned coal.

To increase the supply of cleaned coal, more capital and labour has to be allocated to coal washing. While labour is in surplus, the request for capital will impose an increased capital shortage on the economy. The capital shortage is more or less binding for industries, depending on their profitability and access to credit from the national banking system.

For several reasons then, it is hard to see how a partial approach can be conclusive when assessing the multiple benefits and costs of coal cleaning. To shed light on the complex effects of a coal cleaning policy, an economy-wide approach seems mandatory, but not yet at hand. This study aims at filling a gap in current knowledge on coal cleaning policy by taking the issue into a macroeconomic model framework.

To catch the variety of repercussions associated with deregulation of the coal cleaning sector and introducing a tax on emissions from coal combustion, this study uses a computable general equilibrium (CGE) model of the Chinese economy. The CNAGE model is developed by the National Bureau of Statistics of China in co-operation with Statistics Norway for environmental-economic analysis (NBS, 2001), in particular related to energy use and emissions to air.

The study presented below follows along the path of Zhang (1996, 1998) and Garbaccio et al. (1999), both focusing on energy demand and the effect of a tax on carbon emissions in China by means of a CGE model. While many basic model features are common for CNAGE and those two models, there are differences in dealing with the energy demand. In Zhang the sector mix of coal, oil, gas and electricity is determined by relative prices, whereas CNAGE has fixed sector energy mix at an upper level, but substitution between qualities within the coal input. Zhang also incorporates a market for capital goods, while our approach relies on exogenous allocation of capital among sectors. It adds to the differences that base years are different. Zhang has 1987 and Garbaccio et al. has 1992 as base years, whereas CNAGE builds upon the 1995 National Account. During the period 1987-1995 the economy was under steady reform. The change in incentives, technology and consumer behaviour taking place in this period is reflected in different sets of model parameters calibrated from base year data. An event of special relevance to this study is the liberalisation of coal markets in January 1994

(IEA, 1999). From then on, the majority of coal from state mines was no longer allocated according to plan prescription, and the dual price system was abandoned. In 1996 more than two thirds of the coal sales were left to the market. Hence, the energy data of 1995 that are used as input in CNAGE to a large extent incorporate the effects of the coal market liberalisation, whereas the previous models contain input data more distant from the current market situation.

Implementation of the Kyoto Protocol on reduction of greenhouse gases will bring new opportunities for China. As a developing country without greenhouse gas reduction requirements, China may benefit from the Clean Development Mechanism (CDM). The CDM might offer China additional investments in energy efficiency and clean technology in exchange of carbon emission rights. Coal cleaning projects could be a measure for converting China's vast reserves of CO_2 reductions into financial income and investments that stimulate growth according to domestic profitability and preferences. The study presented below approaches the question if coal cleaning can help extract China's potential resource in terms of carbon emission credits. While so doing, the economy-wide effects of the CDM project are focused. A special interest is related to the question if macro repercussions on emissions are significant compared with effects at plant level. If that turns out to be the case, the result indicate that debates on leakages and appropriate base-lines of energy projects under the flexible mechanisms of the Kyoto protocol gets complicated by still another dimension.

2. Modelling cleaned coal supply and demand

Below we present a set of equations that incorporates the essential role of coal in the empirical CGE model being used. The properties of the full-scale applied CGE model used for this study are outlined in section 3.

Consider an economy with three kinds of agents: producers, a representative consumer and the government. Production takes place in four sectors, which are coal mining, coal cleaning, production of a general good and the transportation sector. The general good can be consumed or invested. For simplicity we include other energy goods than coal in the general good. For the general goods sector, output $\left(X_0\right)$ is a function of labour $\left(L_0\right)$ and energy $\left(E_0\right)$:

$$X_0 = f\left(L_0, E_0\left(RC_0, CC_0, T_0\right)\right).$$

Energy use is represented as thermal heat. The sector demand for heat is met by raw coal $\left(RC_0\right)$ and cleaned coal $\left(CC_0\right)$. To obtain the required input of heat, the ordinary goods production sector needs transportation services $\left(T_0\right)$ for the coal to be delivered. Raw coal and clean coal have equal transportation costs per tonne delivered, but since cleaned coal generates more heat than raw coal per tonne, there is a trade off between the mix of coal qualities and transportation costs. Transportation supply (*T*) is a function of labour $\left(L_T\right)$, intermediates $\left(X_{OT}\right)$ and energy $\left(E_T\right)$:

$$T = g\left(L_T, E_T\left(RC_T, CC_T, T_T\right), X_{OT}\right).$$

Coal represented only 15 percent of total energy use in transportation in 1997. Transportation is capital intensive and competes for limited investments good produced in the general goods sector.

The coal -mines use labour $\left(L_M\right)$ and capital $\left(X_{OM}\right)$ as inputs to produce raw coal (*RC*):

$$RC = m\left(L_M, XO_M\right).$$

The coal-cleaning sector is using labour $\left(L_W\right)$ and capital $\left(X_{OW}\right)$ to remove impurities in raw coal:

$$CC = k\left(L_W, X_{OW}, RC_W\right).$$

Producers maximise profits at fixed prices.

A representative household maximises the utility:

$$U = h\left(E_H\left(RC_H, CC_H, T_H\right), X_{OH}\right).$$

Like in the Other goods sector, household thermal energy demand is an aggregate of raw coal $\left(RC_H\right)$, clean coal $\left(CC_H\right)$ and transportation $\left(T_H\right)$. Dispersed households are at the end of a wide network for coal distribution. The coal mix will have a stronger effect on their transportation costs than is the case in manufacturing.

The coal markets clear according to

$$RC = RC_W + RC_O + RC_T + RC_H$$

$$CC = CC_O + CC_T + CC_H \ .$$

This study highlights the necessity of thermal coal energy in both production and consumption. In processing industries and electricity production there is a fairly close technological link between thermal energy input and the final output. In this case it may be particularly useful to check consistency between model results and technological constraints when studying the expected switch from raw coal to cleaned coal. Households, on the other hand, may put more emphasis on other qualities of the coal than energy content, like how clean and easy it is to deal with. For instance, the lower particle and sulphur emissions and smaller volume in storage can be attractive properties of cleaned coal from households' point of view. There are some other sectors as well where benefits other than heat are significant to the user. Cleaned coal generates less sulphur emissions, which lower corrosion costs to enterprises with huge metal installations exposed or special sensitive equipment. These attributes of cleaned coal are taken into account by the substitution parameters of the sector coal aggregates in the model.

3. The computable CNAGE model

The main features of the stylised model presented above are implemented in the 35 sector computable CGE model CNAGE. The CNAGE model is quasi-dynamic and similar to models presented in Dervis et al. (1982) and Robinson (1989). Below we briefly describe the model whereas formal equations, variables and parameters are listed in the appendix.

Production takes place with labour, capital and energy as variable input factors in Cobb-Douglas functions with constant returns to scale. Sector use of intermediates is treated as a proportional shadow factor. Producers are price takers who maximise profits. Household demand is modelled as a linear expenditure system, based on maximisation of a Stone-Geary utility function. Basic (subsistence) consumption is proportional to population size.

We assume all markets to clear, except the market for labour. Demand of labour is endogenous, whereas the real wage is exogenous. There is a huge labour surplus in China. In urban areas the unemployment is estimated to about 8 percent, whereas 30 percent of the rural work force is underemployed (Economist, 2001). Economic growth over the next two decades is not expected to reduce the vacant reserve significantly. The government target growth of 7 percent per year is set to absorb additional labour supply through population growth and closedowns of state-owned enterprises. Hence, the model works as if labour is always available at the going real wage.

There is no capital market in the model. China has no private financial sector. Investment loans are channelled through state banks, and government priorities penetrate the economy through state bank operations. State banks are supposed to dominate lending practice over the time horizon of this study, although China after becoming a WTO member is obliged to open the door to foreign banks. However, China's requirements for foreign bank operators (like high branch operating capital requirements) may discourage foreign competition for individual saving deposits (Economist, 2002a). Further, the technically insolvent Chinese banking system may prevent rapid inflow of bank investments although equity has been for sale in public offerings (Economist 2002b). As a consequence, a majority of future private saving might continue being controlled and allocated by the government through the state banks. Correspondingly CNAGE allocates investments to sectors in fixed shares, initially according to sector base year share of total capital stock, but changed over time to reflect an expected structural change in demand and supply.

Saving is the driving force in the model. Foreign saving is exogenous, thus domestic saving is the essential variable for determining the economic growth potential. Private households save a fixed share of total income less taxes. Public saving is a residual of public revenues less exogenous public expenditure. Total savings determines nominal investments in real capital. Public expenditure grows by 5 percent per year, by assumption higher than population growth rate (1 percent) but lower than forecasted GDP growth (6.1 percent). Foreign trade is modelled along the Armington assumption.

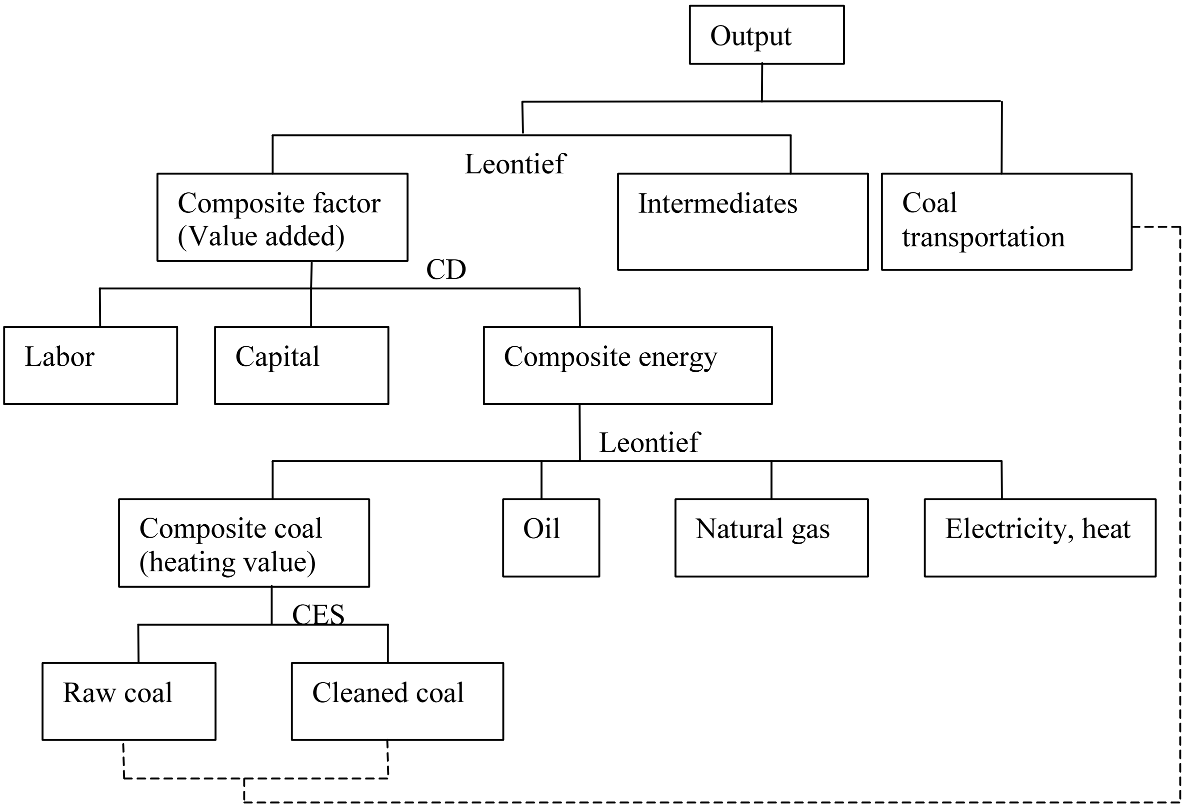
In production sectors the variable energy input is a Leontief aggregate of 18 energy goods, among them coal generated heat (composite coal).

The optimal coal mix of the composite coal depends on the relative prices of thermal energy from raw and cleaned coal. The costs of using raw and cleaned coal to generate heat include the cost of coal transportation, and coal transportation demand is a linear function of total coal use. The production tree in figure 1 gives an overview of the nested input structure.

Starting at the bottom, clean coal and raw coal together deliver coal heat value generated by a CES function. The CES-aggregate of washed coal and raw coal reflect the base year situation that cleaned coal use at sector level is positive in spite of the considerable price differential that is not fully compensated by the higher energy content and lower transportation cost of washed coal. This is so because there are inconveniences (extra maintenance, pollution, dirt) associated with raw coal use compared with washed coal. At the base year price level, some coal users still find it preferable to use cleaned coal, but the price differential prevents a substitution on a large scale. A fall in the cleaned coal price will tend to increase the number of users that find clean coal attractive enough to switch. The substitution elasticity by sectors are in the range of 0.5 to 4, assuming fairly high flexibility in most sectors (see the appendix).

Total coal heat value (composite coal) enters the Leontief aggregate of altogether 18 energy goods (represented as coal, oil, gas and electricity in the figure). This fixed technology aggregate creates total energy that enters the sector Cobb-Douglas production function as a variable input factor together with labour and capital. Other intermediates than energy and coal transportation are used in fixed proportion to output. Coal transportation demand is a linear function of the raw and cleaned coal consumption.

Figure 1. The input structure of production sectors



A reduction in the price of cleaned coal leads to higher share of cleaned coal in the composite coal. At the same time, composite coal can be bought at a lower cost per unit thermal energy. The coal heat remains a fixed share of energy use in production, but the cost reduction of coal transmits to the unit cost of energy. Cheaper energy is in turn substituted for labour, and there is a downward shift in the marginal productivity of currently fixed (allocated) capital.

This way of picturing the energy demand imposes some more or less binding limitations compared with the real setting. The flexibility in choice between coal qualities reflects a real option to users with widely different technologies, but boilers currently in use are not equally able to extract the full heat value of washed coal. However, over time, inefficient boilers will be replaced and increase the scope for maximum efficiency of washed coal. A more critical question is if fixed shares of energy goods in the energy aggregate is reasonable. As mentioned above, several forecasts support the prediction that coal will continue to be a dominant source of energy also during the next couple of decades. This is more the case in production than in consumption by households. In households new infrastructure (natural gas, heat, electricity) made available by the government and higher income will shift demand towards cleaner and more efficient energy carriers. In light industries, a conversion to electricity has already taken place. In other production sectors the price differential between coal and other energy carriers is generally too high to allow for substituting cleaner fuels for coal. This inertia in industrial energy structure might prevail, partly owing to the persistence of state owned enterprises (SOEs). While factory close downs or reform of the SOEs is an efficiency target, the restructuring of SOEs is also conditional upon policies for employment, income distribution and social stability. The implication for energy use is that coal in heavy industries is expected to remain for quite a while, and the assumption of coal as a fixed share of sector energy use may seem fairly relevant for the next decades. The coal quality and the coal use technology will therefore be crucial to the environmental role of coal.

In CNAGE, transportation use is basically an element of the Leontief aggregate of intermediates. In this coal cleaning study, the demand for coal transportation is split from the aggregate of intermediates and made a linear function of coal volume demand. The cost of transportation per tonne coal is the same for raw coal and washed coal. However, the unit transportation cost differs among sectors due to variations in distance to the mines and scale of purchases. The transportation costs in coal mining and coal cleaning are set equal to zero by assumption. In Electricity and heat production the cost of transportation is assumed to be fairly low, at 20 RMB per tonne. Power plants are generally located close to railways, enjoying the advantage of large-scale direct deliveries. In the Coking sector the transportation cost is set to 40 RMB per tonne. All other sectors including households are assumed to pay a transportation cost of 80 RMB per tonne coal. These assumptions lead to an average coal transportation cost of about 50 RMB. The NBS price surveys indicate 65 RMB as an average.

The model is based on the Input-Output tables of the National Accounts 1995 (NBS, 1997). The input structure of coal cleaning is identified by means of the National Accounts 1992 (NBS,1996), 1995 and the Energy Account 1995 (NBS, 2000). The coal cleaning adds RMB 117 to the raw coal price of 107 RMB per tonne. This price difference corresponds to the coal cleaning costs of US $ 13-14 per tonne quoted by IEA CCC (2002).

4. Reference scenario

The Chinese economy has been growing at an average annual rate of 9.8 percent during 1987-1997, and is expected to grow at a high, although somewhat reduced, rate in the future as well. In the reference scenario or business as usual (BAU) scenario of this coal cleaning study, GDP grows at an annual average rate of 6.1 percent up to year 2020. Real wages are exogenous and assumed to increase according to a historic trend until 2010, i.e. 1.4 percent per year in agriculture and 5.3 percent per year in other sectors. After 2010 the real wage growth rate outside agriculture falls to 3 percent.

Household saving rate is assumed to decrease from 28.5 percent in 1995 to 19.5 percent in 2020. The high current saving rate of Chinese households is assumed to reflect a careful attitude towards risk of unemployment and income loss. In a scenario with steady growth, the confidence is assumed to spread and encourage increased consumption. In household demand, we assume energy to take an increasing share, and expenditure shares of housing, cars, gasoline, LPG and passenger transportation are increased about 10 percent annually over the forecasted period. The expenditure shares of natural gas, commerce, restaurants, education and finance are supposed to rise 5 percent per year. The budget share of food falls 2 per cent per year. Finally the shares of all goods are adjusted proportionally to balance the expenditure system. Government consumption is exogenous and grows 5 percent per year, while the GDP growth rate is at 6.1 percent. We assume that current institutional reforms in the public sector may improve the efficiency and increase the level of public services although the share of government consumption in GDP is falling.

Production sectors receive exogenous shares of total nominal investments. Initially the allocation follows the base year sector shares, but over time these shares are adjusted to match a foreseen development in demand structure. We assume sector shares of total nominal investment in Food manufacturing, Transportation equipment, Construction, Freight transportation and communication, Commerce, Restaurants, Education and Finance to increase 5 percent per year. In Agriculture and Petroleum refineries the shares rise by 2 percent annually. Then the shares of total nominal investment in all sectors are adjusted proportionally downwards to balance the expenditure system.

The factor neutral technical change proceeds at different rates among sectors. Factor neutral technical change in Agriculture is 2 percent in the base year and increases gradually to 2.5 percent per year at the end of the simulation period. We assume that the technical progress in Agriculture proceeds more rapidly in the future, as improvements in infrastructure, education and higher income levels will ease penetration of more efficient technology. In all other non-energy sectors and the coal cleaning sector the factor neutral technical change is 3 percent per year initially and falls gradually to 0.5 percent per year at the end of the simulation period. In other energy sectors the rates of factor neutral technical change are negative due to constraints on resources and production capacity (Zhou, 1999). The annual rate of decline is set to 2 percent in Coal mining, and 1 percent in Petroleum refineries and Coking and coal gas production. Oil and Gas production faces a decline of 3 percent per year in productivity whereas the efficiency in the electricity sector falls 2 percent per year as the cost of distribution is rising when less densely populated areas are included in the power system.

Labour productivity rises by 1 percent per year in all sectors except in repair, restaurants, and passenger transport where it is increasing by 2 percent. In agriculture, labour productivity will initially rise by 3 percent per year.

5. The emerging cleaned coal market

Below we present the results that indicate how a deregulated market for cleaned coal might work. We do so by comparing the results of a model run up to year 2020 in the deregulation scenario with the development in the reference case.

The deregulation scenario involves a change at the supply side that generates economy-wide repercussions. The coal cleaning industry is now able to reinvest its profit and the resulting sector rate of capital accumulation turns out to surpass the sector capital growth in the BAU scenario where investments were allocated to the coal cleaning sector. The additional production capital generates a positive shift in productivity that results in a lower price and increased supply of cleaned coal.

The additional investments come at zero costs to the coal cleaning sector, as would be the case if the government allocated funds directly, or if capital was provided as part of a Clean Development Mechanism project under the Kyoto Protocol. However, higher investments in coal cleaning could incur a cost to the economy as a whole if the return on capital is higher in some other economic activity than in coal cleaning.

At the demand side, the base year situation with positive shares of cleaned coal in practically all sectors confirms that there is willingness among users to pay for cleaned coal even though the price of cleaned coal is roughly twice that of raw coal. When the price of cleaned coal falls, users consider the composite benefit from higher heat value, lower transportation costs and reduced maintenance costs. Better air quality and improved cleanliness in the working environment may also be taken into account. All relevant attributes are implicitly considered by the CES-function. The initial reduction in cleaned coal price due to higher productivity tends to increase the number of users that find cleaned coal attractive enough to switch. Cleaned coal demand is increasing correspondingly, until the price of cleaned coal increases sufficiently in relation to the raw coal price to re-establish equilibrium. But this is not the whole story. Besides these direct effects there are general equilibrium effects that work through the markets for raw coal and transportation.

The heat value gains following a switch to cleaned coal lead to reduced demand for raw coal, and the mine-mouth price of coal is lowered. Thus the energy saving obtained by increasing the share of cleaned coal generates a feedback to all coal users as reduced coal prices in general.

Similarly, the aggregate effect of many small users' decisions to increase their shares of cleaned coal is that total demand for transportation is reduced and so is the market price of transportation. Users currently assess the coal prices including transportation costs, and the transportation cost reduction generates a positive feedback to the coal demand in general, as coal use is very transportation demanding.

The supply side investment and productivity growth kick-starts the process where coal users harvest general equilibrium benefits of a switch from raw coal to cleaned coal. The point of dealing explicitly with the heat value gains and the transportation cost differential in this study is to make clear how large these general equilibrium effects turns out to be and how they affect coal users by changing relative prices of the two coal varieties and even lower the general cost of coal energy use.

Coal intensive industries will in particular benefit from the overall energy cost reduction of coal use. However, the reduction in user cost of coal will penetrate also to users of other energy goods, as about 70 percent of primary energy consumption in China is met by coal. Thus even energy use in a wider context becomes cheaper as a result of the improved thermal efficiency of coal made possible through coal washing. This cost reduction encourages more energy use in all sectors that have coal as a direct or indirect component in their input energy mix.

The aggregate impact of introducing flexibility in the choice between raw coal and cleaned coal is illustrated in tables 1 and 2. Table 3 presents the change in sector input structure, while table 4 shows the impact on sector coal use and emissions to air of CO_2 and PM_{10}.

It turns out in our study that total coal use is rising by as much as 10.3 percent and overall energy consumption is increasing about 2.5 per cent. The improved thermal efficiency of a cleaner coal mix in combination with cost reduction in coal transportation turns out to clearly strengthen the position of coal in the energy system of China.

Consumption of washed coal in 2020 turns out to be 62.5 percent higher under the deregulation scenario than in the reference scenario. The capacity growth in the coal cleaning-sector is made possible by a 27 percent increase in sector capital stock and 65 percent additional hire of labour. Consumption of raw coal is reduced by 3.4 per cent and cleaned coal has reached a market share of about 31 percent in volume terms in 2020.

The Electricity and heat sector benefits considerably from better access to cleaned coal and a more efficient coal mix. Thermal power production in China is almost exclusively based on coal and coal represents 20 percent of total electricity production costs (NBS, 1997). Washed coal input in the Electricity and heat sector in the deregulation case is almost 8 times higher than in the reference level in 2020. This increase is mainly driven by the more efficient combustion obtained by use of washed coal and the coal market repercussions. The electricity sector also benefits from reduced transportation costs due to a lower amount of coal use per unit coal energy consumed. However, the coal unit transportation cost of power plants is as low as 20 RMB per tonne coal compared to 50 RMB as the average for all sectors in the model. Hence the transportation benefit contributes less to the change in incentives relative to the improved energy efficiency in this sector than in other activities. It is the case, however, that coal transportation expenditure represents a high share of sector costs, so that even transportation savings count much to profits. Electricity and heat production increases by 0.8 percent. Most stationary energy use will take advantage of the cheaper coal energy directly or indirectly via the prices on electricity and heat.

The primary metal industry is a coal intensive production sector that reduces raw coal use by 16.6 percent and increases clean coal use more than three hundred percent (table 4). It is important to be aware of that primary metal production also uses coal indirectly as coke feedstock. The coking process is a preparation method that preserves most of the carbon and emissions for later use in combustion or industrial processes, mainly in primary metal production and chemical industries. In this way, more efficient coal combustion through cleaned coal use indirectly benefits the heavy, energy intensive industries.

In the Business as usual-scenario the coking industry is absorbing about 94 percent of total cleaned coal supply in 2020. When cleaned coal supply is increasing, coke production increases its use of cleaned coal by 34 percent, but other sectors increase their cleaned coal demand far more (2-4 times) and the coke sector's share of demand falls to 77 percent in the deregulation scenario.

It is a special feature of China that households consume as much as 21 percent of all coal. A factor that particularly might encourage the households to switch to washed coal is the high transportation cost of coal to small and dispersed consumers (80 RMB versus an average of 50 RMB). Our study shows that households respond to lower coal energy costs by increasing their coal energy use by 3.5 percent, as compared to the average increase for the whole economy of 10.3 percent. The households increase both raw coal (1.1 percent) and cleaned coal consumption (236 percent). Coal is assumed to keep a constant budget share in household expenditure growth due to the linear expenditure system of the model. Thus the model actually limits the increase in household demand of coal somewhat compared to a situation where substitution of cheaper coal energy for other goods and services were less restricted.

The sector effects depicted in tables 3 and 4 provide a key to understand some seemingly peculiar aggregate emissions results in table 1. While total raw coal combustion is reduced by 3.4 percent, the CO_2 emissions from raw coal combustion are reduced by as much as 5.5 percent. The reason is that a considerable share of the increased cleaned coal supply is absorbed by the coking industry (low emissions) for further delivery as feedstock to process industries where finally the coke contributes to process emissions. With process emissions included, total CO_2 emissions turn out to increase about half a percent (table 1).

With washed coal it is the other way around. The coking sector absorbs nearly half the increase in washed coal supply. Still the share of washed coal for coking is reduced from 94 percent to 77 percent. While total demand of washed coal less than doubles, CO_2 emissions from combustion of cleaned coal increase as much as 4.6 times.

This interaction between combustion and coke production for further processing is crucial for explaining the effect on particle emissions. In the case of PM_{10}, there is a substantial reduction of 2 percent in total emissions. The higher coal energy efficiency in particular stimulates heavy industries where large production units already have installed particle-cleaning equipment. Hence, the particle emission effect of higher coal use in process industries is to some extent mitigated, whereas the particle emissions of coal use in households and small enterprises reaches the air unabated. Thus there is a particle emissions reduction associated with an increase in heavy industries' share of coal use. As a consequence, the coal cleaning seems to be more efficient as a measure to reduce local air pollution than as an instrument for climate policy. However, particle pollution also has an impact on climate that is not taken into account in this study. Recent research indicates that soot from coal and bio-fuel may generate regional droughts and floods in East Asia and contribute to global warming (Chameides and Bergin 2002, Menon et al. 2002).

Considering the pressing urban air pollution problem in China, the option to reduce particle emissions at negative costs is interesting. The GDP actually increases 0.2 percent when clean coal production is let loose (table 2). While the overall economic effects are beneficial, however, they are not evenly distributed. Household income growth is held back as the economy is becoming more energy intensive. Additional demand for labour is only 0.1 percent and the real wage is constant. Gross profits are up with 0.4 percent while real investments increase by 0.1 percent.

There are possibly modelling shortcomings to be aware of when interpreting the results above.

The share parameters of the CES functions that aggregates coal inputs to coal energy are calibrated from base year data 1995. These share parameters bear relevance to the results in the sense that high clean coal share in the base year indicate a high sensitivity to a price reduction on cleaned coal. Electricity production has a high share of cleaned coal input in the base year, and the results show that this sector has the biggest relative increase in cleaned coal use (table 4). However, the base year shares of cleaned coal of various coal users possibly do not reflect the optimal coal mix as perceived by the coal users. If the cleaned coal use was effectively constrained by the output and allocation rules of cleaned coal, then the cleaned coal shares of the base year do not properly reflect the actual inclination to increase use of cleaned coal when it is becoming less costly.

There may be reasons to think that sectors have not been equally successful in obtaining their optimal coal mix. Some sectors may have had priority of supplies due to their substantial benefits in terms of reduced maintenance costs, or just by mere size and the convenience of large-scale deliveries. If this is the case, the cleaned coal share and the response to reductions in cleaned coal price in less dominating or privileged sectors can be underestimated in the model. However, it seems less likely that any sector in 1995, after major coal market reforms, have received cleaned coal considerably beyond what was optimal according to market prices. Hence, the base year data may tend to underestimate the switch to cleaned coal all in all.

Another feature that might not be well described by the model is the transportation market. Given the importance of transportation costs to the results of this study, the functioning of this market is of special concern. In 1995 there was still price regulation and capacity constraints in railway transportation. As infrastructure and markets develop, the cost of transportation might eventually be left to the users. With higher prices, the cost advantage of switching to cleaned coal would be even larger, but coal use in general would be reduced as user cost of coal would increase in general.

It is worth noticing that the Leontief technology in the model energy aggregate suppresses a substitution of coal for other energy goods due to the falling cost of coal energy. To introduce sector level substitution between other energy goods and coal would stimulate coal use even further and strengthen the result with respect to higher CO_2 emissions. The flexibility is likely to be higher in other sectors than processing industries. Households and smaller enterprises might reclaim some more coal from processing industries with particle filters. As a consequence, the positive effect on PM_{10} emissions might be smaller.

A particular uncertainty is of course associated with the elasticities of substitution in the CES function that determines the sector coal mix. The sensitivity of the results is indicated in the appendix. The conclusion turn out to be robust towards an overall 10 percent increase or reduction in the sector coal substitution elasticities.

The results indicate that several attractive properties of coal cleaning at micro level might turn out to have significant drawbacks at macro level. The attractive energy efficiency gains stimulates energy use to an extent that dominates over the initial energy saving. This rebound effect is significant and not modified through the labour market, as the increasing economic activity made possible by better use of energy does not make real wages go up. The improved energy efficiency allows for a significant expansion of production capacity, and the economy becomes more energy intensive. Our results illustrate the difficulties of determining the baseline in a Kyoto-related mechanism for reducing greenhouse gas emissions. If China signed contracts on coal washing or similar fuel switch micro-projects to trade carbon credits, the overall effect might differ significantly from plant level expectations. In the study presented above, there was no premium on carbon reductions. An inflow of foreign capital as payment for the carbon credits would clearly enhance the macro effect on emissions further by providing a slack in the general capital shortage of the economy. Higher investments would drive coal use and CO_2 emissions even more upwards. To prevent the bias towards higher energy intensity embedded in improved coal efficiency, specific measures would have to be taken, for instance via the mechanism for allocation of investments that currently tend to favour the energy intensive state owned enterprises.

Table 1. Coal use and emissions to air. Effect of deregulating cleaned coal supply. 2020

	Constrained cleaned coal supply	Deregulated cleaned coal supply	Deviation
	(10^9 RMB)	(10^9 RMB)	(percent)
Total energy	2411	2471	2.5
Coal use	441	487	10.3
Raw coal	350	338	-3.4
Cleaned coal	92	149	62.5
Total transportation cost by coal use	141	139	-1.3
	(10^4 tons)	(10^4 tons)	(percent)
Total CO_2 emissions[1)]	969076	973607	0.5
From raw coal	439400	415354	-5.5
From cleaned coal	5548	30966	458.2
Total PM_{10} emission[1)]	9563	9375	-2.0
From raw coal	7741	7337	-5.2
From cleaned coal	66	272	312.7

[1)] Including process emissions.

Table 2. Economic effects of flexible versus fixed coal mix. 2020

	Constrained cleaned coal supply	Deregulated cleaned coal supply	Deviation in percent
GDP (10^9 RMB)	26313	26358	0.2
GDP deflator	1.0045	1.0059	0.1
Consumer price index	1.0360	1.0381	0.2
Labour demand	5585	5590	0.1
Household consumption	11633	11650	0.2
Gross profit	8117	8154	0.4
Real investment	12286	12302	0.1
Government revenue	3893	3903	0.3

Table 3. Impact of deregulated cleaned coal production on sector activity and input use. Deviation from reference scenario. 2020. Percent.

Sector	Output	Capital	Labour	Energy
Agriculture	0.03	0.05	0.00	0.73
Coal mining	-3.40	0.06	-4.94	-3.96
Coal cleaning	62.18	27.01	64.80	67.13
Oil and gas	0.52	0.06	0.83	1.21
Electricity, steam and hot water	0.82	0.05	-0.24	1.49
Refineries	0.51	0.07	0.64	0.54
Coking	1.35	0.06	-2.51	2.96
Chemical	0.12	0.06	-0.39	0.80
Primary metal	0.33	0.06	-1.12	1.25
Transp. equipment.	0.21	0.08	0.19	1.13
Freight transportation.	0.03	0.07	-0.03	0.10
Passenger transportation.	0.10	0.06	0.13	0.12

Table 4. Impact of deregulated cleaned coal production on coal use and emissions to air. Deviation from reference scenario. 2020. Percent.

Sector	Total coal	RC	CC	CO_2	PM_{10}
Agriculture	1.6	-0.7	402.0	0.7	-0.1
Coal mining	-3.9	-4.0	240.5	-3.9	-4.0
Coal cleaning	67.2	66.8	128.9	86.1	66.9
Oil and gas	1.2	1.2	79.7	1.2	1.2
Electricity, steam and hot water	4.9	-4.7	776.9	0.8	-2.2
Refineries	14.6	-25.7	275.5	0.3	-14.1
Coking	10.3	-81.4	34.2	-24.9	-22.7
Chemical	5.7	-7.2	369.2	1.3	-3.7
Primary metal	11.6	-16.6	321.3	0.9	-8.7
Trans. Equip.	4.0	-3.5	388.0	0.9	-1.5
Freight trans.	5.7	-9.1	359.3	0.0	-3.6
Passenger trans.	12.4	-21.9	294.9	0.0	-4.5
Households	3.5	1.1	236.0	0.6	0.5

6. Emission taxes with cleaned coal options

So far in this study the only drive behind the switch to cleaned coal has been the potential energy efficiency increase embedded in the constrained coal-washing capacity. Further encouragement to such fuel switch might take place if coal use were subject to emission taxes on CO_2 or PM_{10}. In both cases a tax would fall more heavily upon raw coal than cleaned coal. Below we examine how CO_2 emission taxes could be expected to work under the deregulated and flexible coal mix scenario.

The emissions tax may be seen as a new and welcome source of income to the central government. Therefore the additional revenue generated by the emission tax is not recycled directly to consumers or enterprises as a reduction in other tax variables. All the revenue is adding to government savings and equally much to total investments. This is equivalent with letting the tax revenue be allocated to investments in production sectors in line with current and foreseen public priorities of economic development, as pictured in the reference scenario.

Previous studies that approach the effects of a carbon tax in China by means of CGE models include Zhang (1996, 1998), Garbaccio et al. (1999) and Fan and Zheng (1999). The study presented below complements those earlier works by including the option of coal cleaning. However, as mentioned in section 1, direct comparison with our results is difficult.

The aggregate effects of a low and a high CO_2-tax when there is flexibility in the choice of coal qualities are shown in tables 5 and 6, while tables 7 and 8 present effects at sector level. Scenario 1 represents the case with a CO_2-tax corresponding to US$ 5 per tonne carbon emission from fossil fuel combustion. In scenario 2 the tax is twice this level. In Chinese currency these tax levels correspond to about 11.3 RMB and 22.6 RMB per tonne CO_2. The coal price in 1995 was 107 RMB for raw coal and 224 RMB for washed coal. Thus, the low carbon tax adds around 18 percent to the raw coal price and 10 percent to the cleaned coal price (emission factors of coal combustion in China are generally 1.7 tonnes CO_2 per tonne raw coal and 2.1 tonnes CO_2 per tonne cleaned coal). The focus of this tax study is on fuel switch, hence the CO_2 emissions from industrial processes are not taxed, only emissions from fossil fuel combustion (also in processing industries). A tax on CO_2 emissions from industrial processes would fall heavily upon the state-owned enterprises and might accelerate the rate of closedowns, possibly beyond what is regarded as socially and politically acceptable. Imposing a CO_2-tax on process emissions in this study might add little substance to the understanding of the economic and environmental development path of these politically managed industries.

Table 5. Effects of a CO_2 tax on fossil fuel combustion on energy use and emissions to air. 2020

	Reference scenario	Deviation from reference scenario	
		Scenario 1[1)]	Scenario 2[2)]
	(10^9 RMB)	(percent)	(percent)
Total energy use	2471	-1.6	-3.2
Coal use	487	-2.6	-5.0
Raw coal	338	-3.0	-5.7
Cleaned coal	149	-1.7	3.4
Total coal transportation cost	139	-2.3	-4.4
	(10^4 tons)	(percent)	(percent)
Total CO_2 emission[3)]	973607	-1.8	-3.6
From raw coal combustion	415354	-3.1	-6.0
From cleaned coal combustion	30966	-5.0	-9.3
Total PM_{10} emission[3)]	9375	-2.6	-5.0
From raw coal combustion	7337	-2.6	-5.2
From cleaned coal combustion	272	-4.2	-8.0

[1)] US$ 5 per tonne carbon. [2)] US$ 10 per tonne carbon. [3)] Including process emissions.

Table 6. Economic effects of a CO_2 tax on fossil fuel combustion. 2020

	Reference scenario	Deviation from reference scenario	
		Scenario 1[1)]	Scenario 2[2)]
		(percent)	(percent)
GDP (10^9 RMB)	26358	0.0	0.0
GDP deflator	1.0059	-0.2	-0.4
Consumer price index	1.0381	-0.1	-0.1
Labour demand	5590	-0.0	-0.1
Household consumption	11650	-0.2	-0.4
Gross profit	8154	-0.4	-0.9
Real investment	12302	0.3	0.5
Government revenue	3903	1.2	2.3

[1)] US$ 5 per tonne carbon. [2)] US$ 10 per tonne carbon. .

Table 7. Impact of US $ 5 tax per tonne carbon emissions from fossil fuel combustion on sector production and input use. Deviation from reference scenario. 2020. Percent

Sector	Output	Capital	Labour	Energy
Agriculture	-0.01	0.20	0.00	-1.19
Coal mining	-2.95	0.22	-3.48	-5.83
Coal cleaning	-1.70	-1.41	-1.99	-1.61
Oil and gas	-0.92	0.22	-1.74	-2.58
Electricity, steam and hot water	-2.15	0.21	0.38	-4.01
Refineries	-0.89	0.23	-1.39	-0.94
Coking	-0.75	0.21	-1.04	-0.85
Chemical	-0.08	0.22	0.60	-1.39
Primary metal	0.03	0.22	0.59	-0.40
Trans. Equip.	0.04	0.24	0.21	-1.89
Freight trans.	-0.14	0.23	-0.35	-0.45
Passenger trans.	0.04	0.21	-0.18	0.11

Table 8. Impact of US$ 5 carbon tax on coal use and emissions to air. Deviation from reference scenario. . 2020. Percent

Sector	Total coal	RC	CC	CO_2	PM_{10}
Agriculture	-1.2	-1.2	-3.5	-1.2	-1.2
Coal mining	-5.8	-5.8	-13.1	-5.8	-5.8
Coal cleaning	-1.6	-1.6	-5.5	-3.1	-1.6
Oil and gas	-2.6	-2.6	-3.2	-2.6	-2.6
Electricity, steam and hot water	-4.1	-3.9	-6.2	-4.0	-3.9
Refineries	-1.3	-0.2	-2.7	-0.9	-0.7
Coking	-0.8	-1.7	-0.8	-0.9	-0.9
Chemical	-1.7	-0.9	-6.1	-1.5	-1.2
Primary metal	-0.7	0.1	-2.3	-0.4	-0.2
Transp. Equipment	-2.0	-1.8	-4.1	-1.9	-1.8
Freight transp.	-0.6	-0.2	-2.7	-0.5	-0.4
Passenger transp.	-0.3	0.8	-1.9	0.1	0.2
Households	-5.2	-5.2	-7.4	-1.9	-2.0

To get a clear picture of the effects, it is useful first to look at the changes at sector level. The emissions tax makes coal users pay more and coal industry earn less. Raw coal production is reduced by nearly 3 percent as a consequence of lower mine-mouth price (table 7). The increase in purchaser price of coal in particular affects electricity production, which is sensitive to the cost of coal energy. Energy use in the electricity sector is reduced by 4 percent, raw coal use by 3.9 percent and cleaned coal use by as much as 6.2 percent (table 8). It turns out that all sectors except coking reduce the input of cleaned coal more than use of raw coal. This counterintuitive effect can be explained by declining profit and investment reduction in the coal cleaning sector, and by leakage of cleaned coal to the tax exempted processing industries.

The tax makes output price of cleaned coal fall and demand shrink. This effect is more moderate, but otherwise similar to what happens in the raw coal market. Profit declines in both coal mining and coal cleaning, but the effects of lower profits differ between the two sectors. The investments in coal cleaning fully depend on sector profits and by lowering profits the carbon tax limits the possibility for rising productivity in coal cleaning. Coal mining is on the other hand able to increase investments because CO_2 tax revenues generate more saving and higher capital accumulation in the economy at large. This gives cleaned coal supply an extra negative shift and price increase compared with raw coal in the tax scenarios.

While most sectors reduce demand of washed coal more than raw coal, we se that the aggregate demand behaves according to expectation. Raw coal use is reduced by 3 percent, and cleaned coal use by 1.7 percent. The demand of cleaned coal is kept up by the coking sector and more basically by the processing industries. The coking sector absorbs as much as 78 percent of all cleaned coal and reduces cleaned coal consumption by only 0.8 percent. This moderate reduction in cleaned coal demand from the coking sector is the reason why aggregate cleaned coal consumption falls less than raw coal consumption. The cleaned coal price is kept up and increases the price differential that was result of the carbon tax per se. The processing industries, which use cleaned coal transformed to coke, are exempted from the tax and consequently they reduce the activity and demand for cleaned coal less than the average.

The marked reduction of washed coal use in thermal power production tends to lower prices on cleaned coal available to other users and enhance their demand. However, although this mechanism is at work, it is defeated by the shrinking demand and higher purchaser prices of cleaned coal following the carbon tax.

Total CO_2 emissions with process emissions included fall by only 1.8 percent as a result of the emission tax. The particle emissions reduction (2.6 percent) is larger than the CO_2 reduction due to the higher share of coal allocated to the tax exempted processing industries.

As for the economic effects, the impact on GDP is positive, but negligible (table 6). The additional growth in value added is generated by increased investments through higher tax revenues and higher government saving. The tax revenue increases by 1.2 percent, while investments increase 0.3 percent. The employment level is roughly conserved. The tax on carbon emissions makes the energy price increase and the following decline in energy use is compensated by increased use of labour (and the higher capital stock financed by the CO_2 tax revenue). However, the increase in electricity price hurts the labour intensive light industries. The following reduction in employment is not fully compensated, since the tax exemption favours the capital-intensive processing industries. Total employment tends to fall and household consumption declines about 0.2 percent. A profit reduction of 0.4 percent contributes to the reduction in household expenditure.

As for the distributional impact, the 0.4 percent reduction in profits is supposed to mainly affect the high-income groups. Household wage income is somewhat reduced. The direct distribution effect of the carbon tax on household fossil fuel combustion may be ambiguous. For liquids, gas and electricity the tax is likely to hurt high-income groups more. On the other hand, low- income groups may suffer the most from a higher price on coal. Evidence from household surveys indicates that an emission tax on coal could work regressively (Hansen et al., 2002).

7. Conclusion

Models never fully live up to our ambitions to adequately mirror a real and complex economy. For that reason our results naturally must be interpreted with care. However, our top-down analysis of coal cleaning might add some new perspectives upon the magnitude of general equilibrium effects associated with energy saving efforts in China.

The prospects of coal cleaning are frequently described as promising. Intuitively, the higher heat value, lower emissions and reduced transportation cost of washed coal should be realised. While so doing, it is useful to be aware that the outcome for the economy at macro level possibly might be increased energy use, higher energy intensity and rising CO_2 emissions as shown in this study. Even so, this result should not discourage the idea of coal cleaning, which might improve economic efficiency and increase GDP, which is clearly a priority for a developing country. However, this study may bring attention to the possibility that coal cleaning is a case for economic efficiency more than energy saving and climate policy.

The rebound effect dominates over the initial saving of energy in this study. The Chinese economy is investment constrained with a practically unlimited access to low cost labour. Any improvement in economic efficiency, including energy efficiency, creates a slack in the capital constraint and allows production to expand without being met by increasing costs. The still prevailing high energy intensity of the Chinese economy will contribute to push energy demand upwards. A fundamental driver behind the rebound effect is of course that energy saving makes energy use less expensive and thus stimulates further energy use.

Even if coal cleaning could not reduce carbon emissions, coal cleaning will certainly contribute significantly to local environmental improvement by reducing particle and sulphur emissions. This would represents a substantial welfare improvement given the serious and costly health damage from urban air pollution in China.

It turns out in our study that introducing a tax of US$ 5 per tonne carbon emissions from fossil fuel combustion is not particularly efficient in reducing carbon emissions even if washed coal were available in the market. Total energy use is reduced by 1.6 percent and carbon emissions 1.8 percent. The electricity sector is sensitive to the coal price and scales down as a result of the carbon tax. This modifies the price increase on coal for users like households, services and processing industries. A higher share of coal is channelled into coke production and further used as feedstock in primary metal production. Here the coal (coke) generates process emissions that are exempted from the carbon tax. This domestic carbon leakage tends to undermine the carbon tax on fossil fuel combustion as a measure to reduce emissions through enhanced use of cleaned coal. Of course, this effect might be countered through other measures, for instance directed towards the state owned enterprises. The point here is just that a partial consideration of the effect of a carbon tax on combustion has shortcomings. Repercussions via the coal market and coal prices should be taken into account.

It is noticeable that the coal and carbon leakage to the processing industries turns out to be positive for particle emissions due to already installed cleaning devices in those industries. Less soot particles would also help mitigate global warming and possibly reduce a threat of an even less stable regional climate in Asia. Soot emissions are highest from combustion in small and inefficient ovens like those in households. To come closer to the understanding of the climate effect of a carbon tax in China, the role of particles should also be taken into account.

Finally, consider coal cleaning as a CDM project. It has attractive properties when considered partially and locally, but, as it turns out in this study, the macro effect could be an increase of carbon emissions to air. It is an interesting question for further research if this tends to be the case for fossil energy efficiency projects under CDM in general. The leakage effects are much discussed for potential CDM projects related to land use and seen as an obstacle for verification of land use related carbon credits. However, our study may indicate that carbon leakage in energy related CDM projects also should be studied more thoroughly.

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Appendix

The CNAGE model

Equations

1. $X_i = hneut_i \cdot ad_i \cdot (techl_i \cdot L_i)^{\alpha} \cdot (techkf_i \cdot kf_i)^{\beta} \cdot (teche_i \cdot E_i)^{1-\alpha-\beta} \quad i \in I$

2. $W_i L_i = \alpha_i \left[P_i\left(1-tp_i\right) - \sum_j PC_j \cdot a_{ji}\left(1+ta_j\right)\right] X_i \qquad i \in I,\ j \in NEN$

3. $PE_i \cdot E_i = \left(1-\alpha-\beta\right)\left[P_i\left(1-tp_i\right) - \sum_j PC_j \cdot a_{ji}\left(1+ta_j\right)\right] X_i \quad i \in I,\ j \in NEN$

4. $EFIVE_{n,i} = E_i \cdot \dfrac{a_{n,i}}{ae_i} \qquad i \in I,\ \mathrm{n} \in NCOA$

5. $COAL_i = E_i \cdot \sum_c a_{c,i} \big/ ae_i \qquad i \in I,\ \mathrm{c} \in COA$

6. $PC_i \cdot XC_i = PD_i \cdot XD_i + pm_i \cdot M_i \qquad i \in IM$

7. $PC_i = PD_i \qquad i \in NIM$

8. $P_i \cdot X_i = PD_i \cdot XD_i + pee_i \cdot EE_i \qquad i \in EX$

9. $P_i = PD_i \qquad i \in NEX$

10. $PE_i = \left(\sum_n PC_n \cdot (1+TREMIS_{n,i}) \cdot a_n + PCOAL_i \cdot \sum_c a_c\right) \big/ ae_i \qquad \mathrm{n} \in NCOA,\ i \in I,\ \mathrm{c} \in \mathrm{COA}$

11. $PCI = \dfrac{\sum_i PC_i \cdot CD_i + \sum_j PC_j \cdot (1+TREMCD_j) \cdot CD_j}{\sum_k pc0_k \cdot CD_k} \qquad i \in NEN,\ j \in EN,\ k \in I$

12. $PK_i = \sum_j PC_j \cdot imat_{ji} \quad i,j \in I$

13. $PGD = \sum_i gshare_i \cdot PC_i \qquad i \in I$

14. $X_i = at_i \cdot \left[\gamma_i \cdot EE_i^{\rho_{ei}} + (1-\gamma_i) \cdot XD_i^{\rho_{ei}}\right]^{\frac{1}{\rho_{ei}}} \quad i \in EX$

15. $X_i = XD_i \qquad i \in NEX$

16. $$XC_i = ac_i \cdot \left[(1-\delta_i)\cdot M_i^{-\rho_{mi}} + \delta_i \cdot XD_i^{-\rho_{mi}}\right]^{\frac{-1}{\rho_{mi}}} \qquad i\in IM$$

17. $$XC_i = XD_i \qquad i\in NIM$$

18. $$\frac{M_i}{XD_i} = \left\langle \frac{PD_i}{pm_i}\cdot\frac{1-\delta_i}{\delta_i}\right\rangle^{\frac{1}{1+\rho_{mi}}} \qquad i\in IM$$

19. $$\frac{EE_i}{XD_i} = \left\langle \frac{pee_i}{PD_i}\cdot\frac{1-\gamma_i}{\gamma_i}\right\rangle^{\frac{1}{\rho_{ei}-1}} \qquad i\in EX$$

20. $$PRFT_i = X_i\left[P_i(1-tp_i) - \sum_{j\in(I-EN)} a_{ji}PC_j(1+ta_i)\right] - W_iL_i - PE_i\cdot(1+TREMIS_i)\cdot E_i \qquad i\in I$$

21. $$PRFTTOT = \sum_i PRFT_i \qquad i\in I$$

22. $$NETPRFT_i = PRFT_i - KF_i \cdot depre_i \qquad i\in I$$

23. $$Y = \sum_i W_i\cdot L_i + er\cdot trxk + PCI_{t-1}\cdot trd + trp\cdot(1-tq)\cdot PRFTTOT \qquad i\in I$$

24. $$YY = Y - td\cdot\sum_i W_i\cdot L_i - tdp\cdot trp\cdot(1-tq)\cdot PRFTTOT \qquad i\in I$$

25. $$\begin{aligned} GR = {} & \sum_{i\in I} tp_i\cdot P_i\cdot X_i + \sum_{i\in IM}\tfrac{tm_i}{1+tm_i}\cdot pm_i\cdot M_i + \sum_{i\in EX} te_i\cdot pee_i\cdot EE_i + td\cdot\sum_{i\in I}W_i\cdot L_i \\ & + (tdp\cdot trp(1-tq)+tq)\cdot PRFTTOT + \sum_{i,j} PC_j\cdot ta_j\cdot a_{ji}\cdot X_i - PCI\cdot trd \\ & + \sum_i TEMIS_i + \sum_e TEMCD_e, \qquad i,j\in I, e\in EN \end{aligned}$$

26. $$EXPEND = (1-s)\cdot YY$$

27. $$SUB = \left[\sum_i csub_i\cdot PC_i + \sum_j csub_j\cdot PC_j\cdot(1+TREMCD_j) + \sum_k csub_k\cdot PCDCO_k\right]\cdot(1+g)^t$$
$i\in NEN, j\in NCOA, k\in COA$

28. $$PC_i\cdot CD_i = PC_i\cdot csub_i\cdot(1+g)^t + q_i\cdot(EXPEND-SUB) \qquad i\in NEN\ \&\ i<>\text{"fr"}$$

29. $$CD_i = csub_i\cdot(1+g)^t + q_i\cdot(EXPEND-SUB)/PC_i + ctranh\cdot\sum_c ECDV_c \qquad i=\text{"fr"},\ c\in COA$$

30. $$PC_i\cdot(1+TREMCD_i)\cdot CD_i = PC_i\cdot(1+TREMCD_i)\cdot csub_i\cdot(1+g)^t + q_i\cdot(EXPEND-SUB)$$
$i\in NCOA(EN)$

31. $PCDCO \cdot CDCO = PCDCO \cdot \sum_c csub_c \cdot (1+g)^t + \sum_c q_i \cdot (EXPEND - SUB)$ c$\in COA$

32. $GD_i = gshare_i \cdot GDTOT$ $i \in I$

33. $GDTOT = gdtot0 \cdot (1+ggc)^t$

34. $GR = PGD \cdot GDTOT + SGOV$

35. $LS = ls_0 (1+g)^t$

36. $LD = \sum_i L_i$ $i \in I$

37. $U = LS - LD$

38. $W_i = relw_i \cdot windex0 \cdot PCI_{t-1} \cdot (1+v_i)^t$ $i \in I$

39. $INV = s \cdot YY + SGOV + (1-trp) \cdot (1-tq) \cdot PRFTTOT + er \cdot sfor + DEPREV - \sum_{i \in I} PC_i \cdot INVENT_i$

40. $INV = \sum_i PK_i \cdot DK_i$ $i \in I$

41. $DK_i = kshare_i \cdot DKTOT$ $i \in I$, $i \neq$ 'cmc'

42. $DK_i = {PRFT_i + KF_i \cdot depre_i - PC_i \cdot INVENT_i} / {PK_i}$ $i =$ 'cmc'

43. $KF_{i,t+1} = KF_{i,t} \cdot (1 - depre_i) + DK_{it}$ $i \in I$

44. $DEPREV = \sum_i KF_{i,t} \cdot depre_i$ $i \in I$

45. $INVENT_{i,t} = invent0_i \cdot (1 - 0.04 \cdot t)$ $i \in I$

46. $XC_i = \sum_j a_{ij} \cdot X_j + CD_i + GD_i + \sum_j imat_{ij} \cdot DK_j + INVENT_i$ $i \in NEN, j \in I$

47. $XC_i = \sum_j a_{ij} \cdot X_j + \sum_{j,c} ctran_j \cdot EENV_{c,j} + CD_i + GD_i + \sum_j imat_{ij} \cdot DK_j + INVENT_i$
$i =$ "fr", $c \in COA, j \in I$

48. $XC_i = \sum_j EFIVE_{i,j} + CD_i + GD_i + \sum_j imat_{ij} \cdot DK_j + INVENT_i$ $i \in EN, j \in I$

49. $SFORE = \sum_i pee_i \cdot EE_i - \sum_j pm_j \cdot M_j$ $i \in EX, j \in IM$

50. $EEN_{e,i} = eshen_{e,i} \cdot E_i$ $e \in EP,\ i \in I$

51. $ECD_e = eshcd_{e,i} \cdot CD_i \qquad e \in EP,\ i \in EN$

52. $EENSC_{s,e,i} = EEN_{e,i} \cdot eshsc_{s,e,i} \qquad s \in SC,\ e \in EP,\ i \in I$

53. $ECDSC_{s,e} = eshscd_{s,e} \cdot ECD_e \qquad s \in SC,\ e \in EP$

54. $EMIS_{p,s,e,i} = emf_{p,s,e,i} \cdot EENSC_{s,e,i} \qquad p \in PT,\ s \in SC,\ e \in EP,\ i \in I$

55. $EMCD_{p,s,e} = ECDSC_{s,e} \cdot emfcd_{p,s,e} \qquad p \in PT,\ s \in \mathrm{SC},\ e \in EP$

56. $TEMIS_i = \sum_{p,s,e} EMIS_{p,s,e,i} \cdot tem_p \qquad p \in PT,\ s \in SC,\ e \in EP,\ i \in I$

57. $TEMCD_e = \sum_{p,s,ep} EMCD_{p,s,ep} \cdot tem_p \qquad p \in PT,\ s \in SC,\ ep \in EP\$EN,\ e \in EN$

58. $TREMIS_i = \frac{TEMIS_i}{PE_i \cdot E_i} \qquad i \in I$

59. $TREMCD_e = \frac{TEMCD_e}{PC_e \cdot CD_e} \qquad e \in EN$

60. $HCO_{c,i} = scale_i \cdot \sum_e EENV_{e,i} \cdot epj_e \qquad i \in I,\ c \in COA\ \ e \in EP\$COA$

61. $PHCO_{c,i} \cdot HCO_{c,i} = PC_c \cdot (1 + TREMIS_{c,i}) \cdot EFIVE_{c,i} + PC_f \cdot ctran_i \cdot \sum_e EENV_{e,i}$

$i \in I,\ c \in COA, f = \text{"}fr\text{"},\ e \in EP\$COA$

62. $HCOH_c = scalh \cdot \sum_e ECDV_e \cdot epj_e \qquad c \in COA\ \ e \in EP\$COA$

63. $PHCOH_c \cdot HCOH_c = PC_c \cdot (1 + TREMIS_c) \cdot CD_c + PC_f \cdot ctranh \cdot \sum_e ECDV_e$

$c \in COA, f = \text{"}fr\text{"},\ e \in EP\$COA$

64. $COAL_i = arcc_i \cdot (cmshare_i \cdot HCO_{cm,i}^{-\rho_i} + (1 - cmshare_i) \cdot HCO_{cmc,i}^{-\rho_i})^{-\frac{1}{\rho_i}} \qquad \mathrm{i} \in I$

65. $CDCO = arch \cdot (cmhsh \cdot HCOH_{cm}^{-\rho} + (1 - cmhsh) \cdot HCOH_{cmc}^{-\rho})^{-\frac{1}{\rho}}$

66. $PCOAL_i \cdot COAL_i = \sum_c PHCO_{c,i} \cdot HCO_{c,i} \qquad c \in COA\ \ i \in I$

67. $PCDCO \cdot CDCO = \sum_{c} PHCOH_c \cdot HCOH_c \qquad c \in COA$

68. $\frac{HCO_{cmc,i}}{HCO_{cm,i}} = \left\langle \frac{PHCO_{cm,i}}{PHCO_{cmc,i}} \cdot \frac{1 - cmshare_i}{cmshare_i} \right\rangle^{\frac{1}{1+\rho_i}} \qquad i \in I$

69. $\frac{HCOH_{cmc}}{HCOH_{cm}} = \left\langle \frac{PHCOH_{cm}}{PHCOH_{cmc}} \cdot \frac{1 - cmhsh}{cmhsh} \right\rangle^{\frac{1}{1+\rho}}$

List of variables

Endogenous variables:

CD_i	=	Household consumption for commodity i
COALi	=	Composite coal use by sector i
CDCO	=	Coal use by households
CPI	=	Consumer price index
DEPREV	=	Total depreciation value
DK_i	=	Real investment of destination in sector i
DKTOT	=	Total real investment in other sectors than coal cleaning
E_i	=	Composite energy use by sector i
ECD_e	=	Use of energy carrier e by households
$ECDSC_{s,e}$	=	Use of energy carrier e from source s by households
Ee_i	=	Exports of commodity i
$EEN_{e,i}$	=	Use of energy carrier e by sector i
$EENSC_{s,e,i}$	=	Use of energy carrier e from source s by sector i
$EFIVE_{e,i}$	=	The use of energy goods e in sector i
$EMIS_{p,s,e,i}$	=	Emission caused by use of energy carrier e from source s by sector i
$EMCD_{p,s,e}$	=	Emission caused by use of energy carrier e from source s by households
EXPEND	=	Household expenditure on consumption
GD_i	=	Government consumption on commodity i
GDTOT	=	Total government consumption
GR	=	Total revenue of the government
$HCO_{c,i}$	=	Use of coal carrier c by sector i
$HCOH_c$	=	Use of coal carrier c by households
INV	=	Total nominal investment
INVENTi	=	The growth of inventories in sector i

Kf_i	=	Capital stock in sector i
Li	=	Labour in sector i
LD	=	Total labour demand
LS	=	Total labour supply
NETPRFT	=	The profit without depreciation of capital stock
PRFTi	=	Gross profit in sector i
PRFTTOT	=	Total profit in domestic production
Wi	=	Nominal wage rate in sector i
M_i	=	Imports of commodity i
P_i	=	Output price in sector i
PC_i	=	Composite price of domestic and imported commodities in sector i
$PCOAL_i$	=	Price of composite coal input in sector i
PCDCO	=	Price of composite coal by households
PD_i	=	Price of domestic produced and sold commodity i
PE_i	=	Price of composite energy input in sector i
PK_i	=	Price of capital in sector i
PGD	=	Price index of government consumption
$PHCO_{c,i}$	=	Price of coal carrier c used by sector i
$PHCOH_c$	=	Price of coal carrier c used by households
SFORE	=	The balance of foreign trade
SGOV	=	Government saving
SUB	=	Total basic consumption
$TEMIS_i$	=	Total emission tax on production
$TEMCD_e$	=	Total emission tax on household consumption
$TREMIS_i$	=	Emission tax rate on production
TREMCD	=	Emission tax rate on household consumption
U	=	Unemployment
X_i	=	Activity level in sector i
XC_i	=	Composite commodity of domestic and imported products
XD_i	=	National production for the domestic market
Y	=	Gross nominal household income
YY	=	Disposable income of households

Exogenous variables and parameters:

α_i	=	Cost share of labour
β_i	=	Cost share of capital
κ_i	=	Cost share of energy
γ_i	=	Share parameter in export equation
δ_i	=	Share parameter in creation of composite commodity
ρ_{ei}	=	Transformation elasticity in market allocation equation, exporting sectors
ρ_{mi}	=	Substitution elasticity in creation on composite commodity, importing sectors
a_{ij}	=	Input-Output coefficient
ac_i	=	Shift parameter in creation of composite commodity
ad_i	=	Shift parameter in Cobb-Douglas production function
ae_i	=	The use of composite energy per unit goods of sector i
$arcc_i$	=	Shift parameter in creation of composite coal use of sector i
arch	=	Shift parameter in creation of composite coal use of households
at_i	=	Shift parameter in market allocation equation, exporting sectors
cmhsh	=	Share parameter in creation of composite coal use of households
$cmshare_i$	=	Share parameter in creation of composite coal use of sector i
$csub_i$	=	Basic consumption of good i
$ctran_i$	=	Transportation fee per ton of coal use in sector i
ctranh	=	Transportation fee per ton of coal use in households
$depre_i$	=	Depreciation rate of capital in sector i
$emf_{p,s,e,i}$	=	The emission factor of use of energy carrier e from source s in sector i
$emfcd_{p,s,e}$	=	The emission factor of use of energy carrier e from source s by households
epj_e	=	Energy volume in joule per unit of energy carrier e
er	=	Exchange rate
$eshcd_{e,i}$	=	The share of energy carrier e in composite energy use of households
$eshen_{e,i}$	=	The share of energy carrier e in composite energy use of sector i
$eshsc_{s,e,i}$	=	The share of use of energy carrier e from source s in sector i
$eshscd_{s,e}$	=	The share of use of energy carrier e from source s by households
g	=	Growth rate of population
gdtot0	=	Total real government consumption in base year
ggc	=	The growth rate of government consumption
$gshare_i$	=	Government expenditure coefficient
$hneut_i$	=	The neutral technology parameter in production function

$imat_{ij}$ = Conversion matrix from destination to origin in investment

$invent0_i$ = Growth in inventories of good i in base year

$kshare_i$ = Share coefficient on total investment

ls_0 = Total labour supply in base year

$pc0_i$ = Composite price of domestic and imported commodities in sector i in base year

pee_i = World price on exports in domestic currency in the base year

pm_i = Price of competitive imports in domestic currency in the base year

q_i = Budget share of consumption

s = Marginal propensity to save

$scale_i$ = Shift parameter in creation of coal carrier use in sector i

scalh = Shift parameter in creation of coal carrier use in households

sfor = Foreign savings

t = Current period

ta_{ji} = Input tax rate on good j in sector i

td = Direct taxes on household income

tdp = Tax rate on profit owned by households

te_i = Tariff rate on exports

$teche_i$ = The technology parameter of composite energy input in production function

$techkf_i$ = The technology parameter of capital input in production function

$techl_i$ = The technology parameter of labour input in production function

tem_p = Tax rate on the emission of pollutant p per ton CO_2

tm_i = Tax rate on competitive goods imports

tp_i = Production tax rate

tq = Tax rate on gross profit

trd = Transfers from government to household

trp = The household share of profit

trxk = Transfers from abroad to households in US$

$relw_i$ = The relative wage rate in sectors i in base year

v_i = Real wage growth rate

windex0 = Wage rate index in base year

Parameter values

No.	Brief name of sectors	Import	Export	Labor	Capital	Energy	Coal aggregate
	Symbol	ρ_m	ρ_e	α	β	κ	ρec
01	Agriculture	0.6	0.9	0.835	0.133	0.032	-0.75
02	Coal mining	0.7	1.5	0.455	0.220	0.325	-0.5
03	Coal cleaning	0.7	1.5	0.288	0.095	0.617	1.0
04	Other coal cleaning	0.7	1.5	0.288	0.095	0.617	1.0
05	Oil and gas	0.7	1.5	0.252	0.521	0.227	-0.3
06	Metal mining	0.5	1.05	0.367	0.490	0.143	-0.75
07	Other mining	0.5	1.05	0.357	0.556	0.087	-0.75
08	Food	0.7	0.3	0.304	0.617	0.079	-0.75
09	Textiles	0.7	0.3	0.416	0.486	0.098	-0.75
10	Clothes	0.7	0.3	0.394	0.578	0.028	-0.75
11	Sawmills and furniture	0.7	0.3	0.373	0.578	0.049	-0.75
12	Paper	0.7	0.3	0.379	0.527	0.094	-0.75
13	Elec.,steam and hot water	0.5	1.05	0.088	0.381	0.531	-0.75
14	Refineries	0.5	1.05	0.031	0.114	0.855	-0.75
15	Coking	0.5	1.05	0.242	0.162	0.596	-0.75
16	Chemical	0.5	1.05	0.277	0.496	0.227	-0.75
17	Non-metallic mineral	0.5	1.05	0.362	0.448	0.190	-0.75
18	Primary metal	0.5	1.05	0.206	0.377	0.417	-0.75
19	Metal products	0.5	1.05	0.373	0.560	0.067	-0.75
20	Machinery	0.5	1.05	0.412	0.504	0.084	-0.75
21	Trans. Equip.	0.5	1.05	0.421	0.498	0.081	-0.75
22	Electric	0.5	1.05	0.324	0.639	0.037	-0.75
23	Electronic	0.5	1.05	0.202	0.780	0.018	-0.75
24	Instruments	0.5	1.05	0.637	0.294	0.069	-0.75
25	Repair	---	---	0.569	0.318	0.113	-0.75
26	Other manufacturing	0.7	0.3	0.277	0.410	0.313	-0.75
27	Construction	0.3	0.3	0.720	0.255	0.025	-0.3
28	Freight trans.	0.9	0.9	0.452	0.392	0.156	-0.75
29	Commerce	---	0.3	0.339	0.640	0.021	-0.75
30	Restaurants	0.6	0.3	0.620	0.344	0.036	-0.5
31	Passenger trans.	0.9	0.9	0.399	0.417	0.184	-0.75
32	Public utilities	0.6	0.3	0.276	0.653	0.071	-0.3
33	Cultural and research	0.6	0.3	0.756	0.218	0.026	-0.75
34	Finance	0.6	0.3	0.299	0.680	0.021	-0.3
35	Administration	0.6	0.3	0.781	0.168	0.051	-0.75
---	Households	---	---	---	---	---	-0.75

Deregulation of coal cleaning with alternative substitution elasticities (SE) in the coal aggregate

		Deviation from BAU		
	BAU	0.9 SE	SE[1)]	1.1 SE
GDP (10^9 RMB)	26 313,5	0,2	0,2	0,2
GDP deflator	1,0	0,1	0,1	0,1
PCI	1,0	0,2	0,2	0,2
Labor (L)	5 585,1	0,1	0,1	0,1
Household consumption (CD)	11 632,7	0,1	0,2	0,2
Gross profit (PRFT)	8 117,3	0,4	0,4	0,5
Real investment (DKTOT)	12 285,6	0,1	0,1	0,1
Government revenue (GOVREV)	3 892,9	0,2	0,3	0,3
Export (EE)	5 208,2	0,2	0,2	0,2
Import (M)	5 124,6	0,2	0,2	0,2
Total energy (10^9 RMB)	2 411,0	2,2	2,5	2,8
Coal use	441,3	9,1	10,3	11,5
Raw coal use	349,6	-3,0	-3,4	-3,8
Cleaned coal use	91,8	55,6	62,5	70,0
Total emission of CO_2 (10^6 tons)	969 075,7	0,4	0,5	0,5
Wherein: Caused by raw coal use	439 400,3	-4,5	-5,5	-6,7
Caused by cleaned coal use	5 547,9	373,8	458,2	555,4
Total emission of PM10 (10^4 tons)	9 562,6	-1,6	-2,0	-2,4
Wherein: Caused by raw coal use	7 740,5	-4,3	-5,2	-6,3
Caused by cleaned coal use	66,0	258,5	312,7	374,1
Total transportation cost by coal use (10^9 RMB)	140,8	-1,2	-1,3	-1,5

[1)] Substitution elasticity corresponding to ρec as listed among model parameter values in the appendix.

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