Macroeconomic impacts of carbon capture and storage in China

He Jianwu*, Li Shantong*, Haakon Vennemo# §

Carbon capture and storage (CCS) is a key technology for reducing greenhouse gas emissions. But a CCS facility consumes vast amounts of energy and capital. With this in mind we analyze macroeconomic consequences of a large scale introduction of CCS in China. We modify and extend the DRC-CGE, a macroeconomic CGE model of the country that is used for long-term planning and policy analyses.

We analyze an *internal finance* scenario of domestic funding, and an *external finance* scenario of international funding. In the external finance scenario CCS is installed on 70 percent of all power plants by 2050. This increases demand for coal in 2050 by one fifth and import of coal by one fourth. The strain on coal resources may be an important political concern for China. In the internal finance scenario coal resources are not strained since this scenario introduces a price on carbon that lifts prices of energy. Moreover, because the price on carbon cuts across the board the internal finance scenario is much more effective at reducing CO_2. On the other hand, in this scenario GDP goes down about four percent, which also raises political concern.

1. Introduction

By general consensus carbon capture and storage (CCS) is a key technology for fighting climate change. According to the IEA (e.g, IEA 2009) CCS should contribute more than any other technology to reaching global carbon emission goals by 2050. An important argument for CCS is that it allows countries to rely on coal for power and heat supply. Another is that it can be retrofitted on coal fired power plants. There is a huge number of new coal fired power plants in the world whose future emissions somehow must be reduced if greenhouse gas targets are to be met. These are reasons for the IEA and others to presume that CCS is a part of the answer to the threat of climate change.

However, a CCS facility requires large amounts of energy and capital. A CCS facility on a power plant may consume 20-30 percent of its own energy production. The CCS facility also adds 30-40 percent to the investment in the power plant. Installing CCS on a large scale is likely to have macroeconomic consequences as the impacts of investments and energy consumption ripple through markets.

---

*Development Research Center of State Council, PR China
#Oslo&Akershus University College, PO Box 4, St. Olavs Plass, 0130 Oslo, Norway. Haakon.Vennemo@vista-analyse.no. (Corresponding author)
§Thanks to Cao Jing and participants at the Workshop on Diffusion of Climate Technologies 2011, Norway for constructive comments to an earlier draft.

In this paper we study macroeconomic impacts of installing CCS on a large scale in China. China consumes almost half the coal in the world and is the country with the most coal fired power plants as well as the most ambitious plans for building more plants. The IEA hopes for 600 CCS facilities to be built in China by 2050. Chinese policy makers have indicated an interest in the CCS technology and at least ten demonstration plants are set up or they are under way (e.g., Li Z et al., 2011).

Research has suggested a potential for CCS in several industries in China. Cost-wise the potential could be the best in the petrochemical industry and possibly in coal-to-liquid projects (Li XC et al (2011), Hart and Liu (2010)), but the potential for large quantity CO_2-reductions is clearly the largest in power production. We wish to focus on the implications of large scale introduction of CCS, and analyze CCS in power production. Adding CCS in other sectors would probably not change the macroeconomic impacts materially.

In order for CCS to be feasible in China it is necessary to have sufficient storage capacity for carbon. Available research suggests that the storage capacity of China is sufficient (Li XC et al., 2011). However, we do not study the question here and instead just assume that storage capacity is available. If this assumption is not valid large scale CCS in China will be more difficult and costly than suggested by our results.

To study macroeconomic impacts of CCS in China we modify and extend a CGE model of China, the DRC-CGE. The model is frequently used by the State Council in preparation of macroeconomic policy. It has also been used for research purposes, in particular to discuss the impacts of climate and trade policy (Aunan et al, 2007; Vennemo et al, 2008, 2009). We modify the model by introducing technologies for CCS in fossil fuel based power production, and we extend the social accounting matrix in order to link the CCS technologies to the input-output matrix of the economy.

Despite its potential key role in determining the future of Chinese carbon emissions there has been little research on impacts of large scale CCS in China. Our paper is a novel contribution to the literature. Some recent papers have included CCS without putting it at the forefront of the analysis. An example is the Asian Modeling Exercise (e.g., Calvin et al., 2012), in which 23 economic models analyzed the same scenarios of global CO_2-pricing, and outcomes were compared. 20 of the models were global in nature, and although most of them included CCS as an option the details of CCS penetration were not in focus, and even less the macroeconomic impacts of CCS (see Clarke et al. (2012) for some discussion and comparison across models).

Papers by Chen (2011) and Liu, Shi and Jiang (2009) discuss the future role of CCS within the energy market of China. Chen uses the energy technology model MARKAL, and Liu, Shi and Jiang use a different energy technology model, MESSAGE-China. These models optimize the composition of energy supplies in order to minimize total system costs. In Chen's analysis 35 percent lower carbon emissions than in the baseline leads the model to forecast close to 500 GW of coal power with CCS in 2050. This supplies one fifth of the required abatement. Liu, Shi and Jiang (2009) assume almost 55 percent reduction in carbon emissions compared to the baseline, in other words considerably stricter than Chen. They do not give details of their CCS cost estimates. They find that CCS contributes about one tenth of the required abatement.

The financing mechanism of CCS is of potential importance for the analysis. In the international community, and in China, there is an expectation that the international community will finance a significant share of CCS, see below. Our paper is to an extent motivated by this possibility. Domestic finance is however also an option, and in fact it is the only option considered by Chen (2011) and Liu, Shi and Jiang (2009)[1]. Liu, Shi and Jiang derive a shadow price on electricity that is similar to a carbon tax. Given the carbon tax they analyze to what extent CCS emerges endogenously as a cost-effective response to the carbon restriction. Chen (2011) makes a similar assumption.

The consideration of external finance is another novel aspect of our paper. As an example of burden sharing it ties the paper to the large literature on burden sharing in greenhouse gas mitigation (e.g., Ringius, Torvanger and Underdal, 2002). External finance also provides a link to the literature on CDM and the potential of CDM to finance carbon abatement, particularly in China (e.g., World Bank, 2004).

In contrast to the recent energy system analyses our analysis does not just optimize the composition of energy supplies in order to minimize total system costs. In our analysis demand for energy is endogenous and it is the basic resources of the economy, labor and capital, that are exogenous at any point in time. Capital evolves in response to saving. As

[1] The global models of the Asia Modeling Exercise also discuss internal finance only.

emphasized by e.g., Copeland and Taylor (2004) there are in principle three ways that an economy could respond to an environmental regulation: By changing the scale of production, by changing the composition of industries, or by changing the techniques of production in each industry. While the previous national analyses draw the line somewhere between the technique and composition effect, a CGE based analysis such as our own is able to capture both scale, composition and technique effects.

The remainder of this paper is structured as follows: Section 2 gives background on CCS and presents our policy experiments. Section 3 outlines the model we use and the baseline scenario. Section 4 discusses the internal finance scenario. Section 5 discusses the external finance scenario. Section 6 briefly discusses a combined external&internal finance scenario. Section 7 concludes the paper.

2. Scenarios for CCS in China

Post-combustion and pre-combustion are the two main technologies for CCS, (e.g., IEA, 2008). Within each technology different designs are possible. There are also other technologies such as oxy-fuel and chemical looping, which do not concern us here.

Post-combustion works by treating the flue gas. To treat the flue gas and break out CO_2 one uses a chemical solvent absorbent such as monoethanolamine. The advantage of post-combustion is that one may retrofit it on traditional fossil fuel power plants. However, post-combustion is capital intensive compared to alternatives, and it is expensive in other ways: the energy penalty is large, the facility needs space that may it be difficult to find in the vicinity, etc.

Pre-combustion CCS requires a particular power plant technology, namely the Integrated Gasification Combined Cycle (IGCC). An IGCC plant turns coal into gas. More precisely it breaks apart the chemical bonds of the coal and obtains a gas consisting of CO_2 and other elements. With further chemical modification it is possible to distill highly concentrated CO_2. The highly concentrated CO_2 can then be removed from the waste stream at a moderate variable cost. CO_2 will not be completely removed, but the carbon emission from a plant with CCS is about 90 percent lower than from one without.

IGCC is still an emerging technology. It is more effective than the conventional pulverized coal technology, but it is also more capital intensive, and more complicated to operate. There are currently 20-30 IGCC plants world-wide.

The future of IGCC in China was recently analyzed by Liu, Shi and Jiang (2009). They argue that IGCCs begin to penetrate the Chinese market in 2020. From about year 2030 hardly any traditional coal is installed. By 2050 the share of IGCC is almost twice that of traditional coal, and also much larger than the share of so-called (ultra) supercritical coal, an advanced version of the traditional pulverized coal technology.

In this situation it is possible to model both post- and pre-combustion CCS in China. Post-combustion would be relevant for the significant group of traditional power plants. Pre-combustion would be relevant for the emerging IGCC plants. However, the broad brushed macroeconomic impacts are well established by examining one of them, and we choose to examine the emerging technology, pre-combustion CCS on IGCC plants. It follows that we examine the period 2020 to 2050, with an emphasis on the latter half of that period. Had we instead focused on post-combustion, the macroeconomic impacts would probably have been larger and/or penetration of would have been lower, since costs and energy consumption are larger for this technology.

Given a focus on pre-combustion CCS on IGCCs the next question is what the costs and resource requirements are and how these costs develop. Costs of CCS are uncertain. There is general consensus that costs will fall over time, but how much they will fall, and how fast, is not known. A representative attempt at putting numbers on this is Chen (2011). She reports the results of a large joint research project in China and the UK that is aiming for near zero emission coal technologies. She suggests that the capital cost of an IGCC plant with CCS is 30 percent higher than one without CCS. Assuming a capital cost of 1000 usd/kW in 2030 without CCS, the cost with CCS is worked out as 1300 usd/kW. The 30 percent estimate is consistent with IEA (2008) (33 percent). For energy Chen's assumption is that in 2030 an IGCC without capture has an efficiency of 45 percent, and a plant with capture has an efficiency of 37 percent. This works out as an energy penalty of 18 percent (8/45).

Table 1 collects her and other estimates in the literature. The estimates differ significantly, reflecting not just genuine uncertainty but also authors' assumptions about life-time, capacity factor, discount rate and other aspects of the calculation. Most authors calculate levelized costs of electricity production while some calculate capital cost and fuel cost separately. Some include transport and storage while others do not. The benchmark technology also differs. Table 1 refers to studies where IGCC without CCS is the benchmark.

In our model, we assume that the capital cost of CCS is 30 percent higher than that without CCS. The energy penalty for CCS is set to 20 percent. These assumptions are consistent with Chen (2011) and IEA (2008) and broadly consistent with IEA (2010). We assume the levelized cost of CCS without transport and storage is 30 percent higher than that without CCS, a figure consistent with Nicholson, Biegler and Brook (2011), and Golombek et al (2011). We assume the levelized cost of CCS with transport and storage is 65 percent higher than that without CCS. This is taken from IEA (2010).

The cost of transport and storage is very uncertain. It is heavily influenced by the distance between the power plants and the storage facilities, and the attributes of those facilities. For instance, a storage facility that conditions for enhanced oil recovery has quite different attributes from one that does not. In practice the cost of transport and storage will vary between power plants. If storage is off shore the cost of transport from inland plants will be high. If inland storage is used the opposite is true, etc. As long as little is known about the location of adequate storage facilities we can only make a guesstimate of the cost. We submit that the current cost of transport and storage is influenced by a lack of experience on the ground. We assume that it is reduced 50 per cent over the scenario period till 2050. This assumption is equivalent to assuming higher productivity growth in CCS than in other technologies, which we find reasonable.

Table 1 Cost estimates of IGCC power plant with and without CCS

		IGCC w/o	IGCC w/ CCS	% Mark-up w vs w/o CCS
Chen (2011)	Investment Cost	1000	1300	30%
	Fuel Cost[1]	45%	37%	18%
IEA (2008)	Investment Cost	1800	2400	33%
Nicholson, Biegler and Brook (2011)	Levelized costs	66	84	27%
Golombek et al (2011)	Levelized costs *without* TS [2]	49.4	67.7	37%
Al-Juaied and Whitmore (2009)	Levelized costs *without* TS	8	11.5	44%
IEA (2010)	Investment Cost	2200	3350	52%

	Fuel Cost	46%	35%	24%
	Levelized costs *with* TS	67	110.5	65%
This paper	Investment Cost (index)	100	130	30%
	Fuel Cost (index)	100	120	20%
	Levelized cost *without* TS (index)	100	130	30%
	Base year levelized cost *with* TS (index)	100	165	65%

Notes: 1. Energy efficiency; 2. TS refers to "transport and storage".

Whatever the details it is clear that the costs of a large scale introduction of CCS are significant. The question of who should pay for a large scale introduction of CCS is likely to come up. China maintains the position that in effect the international community should pay. In the international community NGOs and political parties in several countries have stated more or less the same. In fact, in the Copenhagen accord of 2009 the international community indicated a willingness to ramp up climate finance to 100 billion usd annually by 2020. If this funding materializes, some of it is likely to finance CCS in China, India and other countries reliant on coal.

With this in mind we construct two main policy scenarios. In the internal finance scenario CCS is financed by China itself. This is a reference intended for comparability with previous work – and because internal finance may become a reality e.g., if CCS becomes a strategic technology with export value and/or China in the future takes on ambitious commitments for carbon emissions. In the external finance scenario CCS is financed from abroad.

A final issue to consider is whether CCS is introduced to the extent that it is cost-effective, or whether there is a designated policy to promote CCS over and above cost-effectiveness. Such a designated policy may be motivated by positive external effects of CCS-deployment such as those associated with R&D. It may also be due to political preference. In this work our internal finance scenario amounts to cost-effective penetration. The internal finance scenario assumes a comprehensive domestic carbon tax or transferable quota, and CCS emerges in response. By contrast, the external finance scenario assumes the domestic carbon tax is zero and the international community finances CCS – the implication being that CCS is promoted over and above cost-effectiveness. This seems to us to be a principled benchmark while also reasonably feasible politically. In theory the international community could finance all measures that are cost-effective under a carbon tax, but in practice it is necessary to focus on particular technologies. CCS is probably the most obvious example. In a sensitivity analysis we investigate the properties of a solution where external finance of CCS is combined with a domestic tax on CO_2.

3. The model and baseline scenario

This section presents the model used in our research, and the baseline scenario 2010 – 2050.

3.1 Main features of the model

The DRC-CGE-model belongs to a family of CGE-models used extensively over the past two decades to analyze environmental policy and other policy reforms. In China the model is used in regional development planning and macroeconomic planning of the State Council, including the 5-year plans. The State Council is China's most important executive body, lead by the Premier, and often referred to as China's government. Internationally the model has been used for trade policy analysis (Zhai and Li, 2002; Vennemo et al., 2008), labour market reform (Hertel and Zhai, 2006), pension reform (Wang et al., 2004) and environmental policy analysis (Aunan et al., 2007; Vennemo et al., 2009). It has also recently been used in a joint DRC-World Bank study of China in 2030 (World Bank and DRC, 2012). The model is maintained at the Development Research Center of the State Council in China. Table 2 summarizes main features of the model version used in this paper. (There also exist multi-household and multi-region versions of the model). For equations and a detailed description in English see Vennemo et al. (2008). With the aid of Table 2 we briefly review the main features of the model.

Table 2 Main features of the DRC-CGE model

40 industries
34 consumption goods
7 electricity technologies
7 production factors
5 energy carriers
3 drivers of emissions
2 representative households

The model has 40 industries or sectors, including 1 agricultural sector, 4 mining sectors, 16 manufacturing sectors, 9 utility sectors, and 10 services sectors. The large number of sectors allows more precise modeling of structural change in the economy. Structural change in the economy is a significant part of the macroeconomic impact of CCS and therefore quite important to capture in the analysis. Arguments for a large number of industries have to be balanced against arguments in the opposite direction (e.g., large number of technology parameters without empirical backing), which explains why we have not disaggregated even more.

To avoid the well-known specialization problem of foreign trade the model assumes that there are transaction costs of transportation, logistics, marketing and bureaucracy associated with switching from domestic to foreign markets. The model uses Constant Elasticity of Transformation (CET) functions to capture the costs, with elasticities of transformation of about 3.0 between export and domestic production. On the import side so-called Armington functions are used with price elasticities of about 6.0. The parameters are chosen in order not to exaggerate the unspecified transaction costs.

Industries use the primary inputs capital, natural resources and land, unskilled workers, production workers and professionals (nested constant elasticity of substitution (CES) functions). Natural resources and land are only used in agriculture and non-carbon power production. Professionals are only used for manufacturing and service industries.

The model distinguishes between new capital, that is the current vintage of investment, and old capital, that is non-depreciated investment of previous years. Old capital is almost fully locked to production in the industry where it was invested. New capital can readily be substituted between industries and against other production factors.

New capital, i.e. net real investment, is determined by savings in a so-called neo-classical closure. Household savings rates are fixed. Corporate retained earnings are exogenous and the residual handed to owners. Government savings is the endogenous difference between tax and fee income, and expenditures. The current account surplus, another form of investment, is exogenous.

Carbon emissions in DRC-CGE-model have three drivers. Most are generated through intermediate consumption of fossil fuels. Emissions from industrial energy use belong in this category. Some are driven by final demand for fossil fuels. Household emissions e.g., from heating and transportation belong in this category. The remainder is generated by aggregate output—for instance process emissions from cement production and other industries.

DRC-CGE model has a flexible system of carbon mitigation policies. The simplest policy is a carbon tax that also allows exemptions for designated sectors or households. A carbon tax without exemptions was used in the current internal finance scenario.

An alternative is to impose a cap on emissions at the national level or some other level. The model will then produce the shadow price of carbon, i.e. the carbon tax, as a model outcome.

A second alternative is to impose a cap on some technology. For the external finance scenario we used this feature. We started off with the share of CCS that was produced for the internal finance scenario and converted into a cap on power production with CCS. The model then produced a shadow subsidy on power production with CCS that covered the cost of the technology. We also endogenized the transfer component of the current account in order to let the international community finance the subsidy. This increased transfer allowed the trade balance to deteriorate in equilibrium. The resources saved on the trade balance were then, by the workings of the macro-economy, channeled into building and operating CCS. In theory the resources spent on CCS should exactly match the resources saved on the trade balance, leaving the Chinese economy with a zero macroeconomic cost.

The model is calibrated to the DRC Social Accounting Matrix with a 2007 base year. The latest published Input-Output tables are 2007 tables.

3.2 CCS and energy modeling

In order to model the macroeconomic impacts of CCS it is essential to include in the model several power generation technologies. This is essential in order to include substitution possibilities of the economy. Two data problems then immediately emerge. One is that the Chinese IO-table and national accounts do not distinguish between different power generation technologies. Hence a procedure is needed to map cost and output data of different technologies to the national accounts data. The second data problem is that CCS is an unproven technology and cost estimates are uncertain. Our choice of CCS technology parameters was discussed above. Here we discuss how the electricity sector is modeled and how data are calibrated.

3.2.1 Modeling the power sector

There are five main power technologies operating in China in the base year: coal, natural gas, hydro, new renewables, and nuclear. However, there is one electricity sector in the input-output data base of the national accounts.

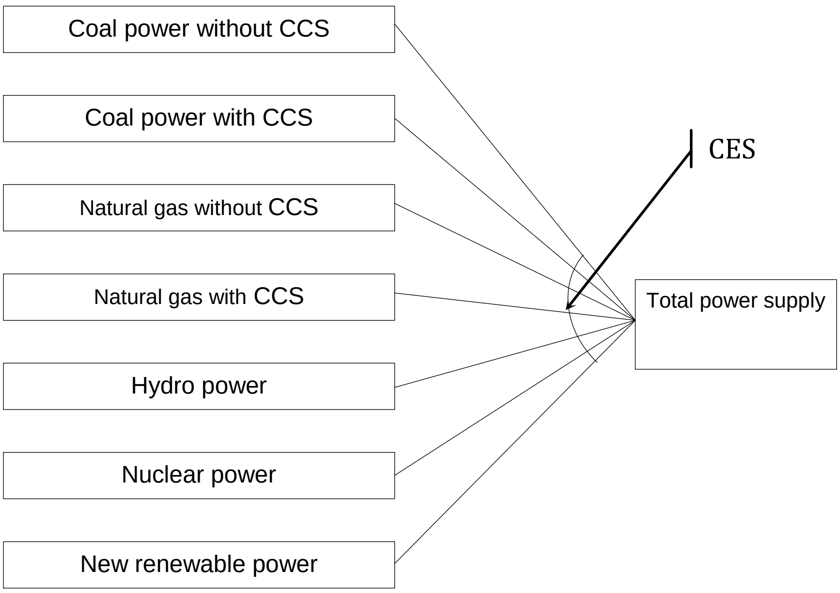
Because input-output data base must satisfy a numbers of key "row" and "column" equilibrium conditions in all its 42 sectors, we cannot simply enter the data base and alter a given set of flows without destroying one or more of these equilibrium conditions. When disaggregating the data it is necessary to compromise between the technological properties of each power technology and the row and column equilibrium conditions. It is desirable to make these compromises in the gentlest possible way. The procedure is invisible in presentation of results, but it is quite labor intensive and enhances the quality of results if done well.

The procedure we choose relies on the gross entropy method originally developed in information theory. The method minimizes a measure of the entropy distance between input-output parameters and their priors, subject to row and column constraints. See the Appendix for details of our procedure, which may interest other modelers in this field.

A nested CES structure is used to describe price and output responses for all seven power generation processes (the five current ones plus coal and natural gas with CCS). Land/natural resources are included in the production functions of the non-carbon technologies hydro, new renewable and nuclear. For hydro a logistic function is used to model the approach to the maximum hydro potential. As no official Chinese language estimate of the potential exists to our knowledge, an estimate is taken from World Energy Council (2007). For new renewables there is no exact resource limitation, but we use an upward sloping supply function to model locations of diminishing suitability. We use a supply function for nuclear as well. For nuclear it is not so much the physical suitability as the political suitability of different locations that matters. The strategy for developing nuclear in China requires that the economics are right, but that is just a necessary condition. In practice concerns over safety and long term storage are as important as the economics. In order to trade off the economic concerns with other concerns the supply function is useful. In effect we say that more nuclear is built when the economics improves, but not in indefinite amounts. A fairly elastic supply elasticity of 2.5 is used both in the case of new renewable and nuclear.

All power generation processes together make up total power supply (see Figure1). A CES structure models this composite, the total power composite. The substitution between different processes depends on relative production cost. The elasticity of substitution is 20 since power is an almost homogenous good.[2]

Figure 1 Production technology in the power sector



For technical reasons it is required that the CCS technologies have a non-zero base year share of production. This share is less than 0.1 percent.

The base year price differentials between the power generation technologies are given in Table 3.

Table 3 The cost of each power generation technology in base year (2007)

Power generation technologies	Relative price
Coal without CCS	1.0
Natural gas without CCS	1.3
Hydro	1.2
Nuclear	1.4
Other (wind, solar, etc.)	1.8
Coal with CCS	1.65

[2] There are some differences in storage possibility and reliability, as well as political preference that allow us to assume that electricity is not fully homogenous. The CES model is also chosen for modeling convenience since it allows all seven technologies to co-exist. Other modelers make a similar assumption, e.g., Mi et al., (2012).

Source：IEA (2010) except the relative price of "Other electricity". This price is based on New Energy Web (2010). At constant input prices the relative price of Coal with CCS is reduced to 1.475 by 2050.

3.3 The baseline scenario

A baseline scenario is required for comparison with scenarios with CCS. It is important to model the baseline carefully as it may influence estimated impacts. Our baseline builds on previous work (Li S, 2011 and World Bank and DRC, 2012), but it is extended here for the first time to 2050. In the baseline economic growth in China slows down during the first half of the century. One reason is that technology in China catches up with the most advanced countries in the world. Also, the potential is eventually exhausted for spill-over from low productivity agriculture to high productivity manufacture (reflected below in the indicator for urbanization). The aging society over time lowers the labor force and savings rate. This reduces growth in investment. The current growth rate of China depends on a high investment rate that is not sustainable over the course of a half century.

Table 4 Macroeconomic entities during the baseline

	2007	2010	2020	2030	2040	2050
GDP (2007 price)	2675	3441	7104	13099	19748	25313
GDP growth		8.8	7.5	6.3	4.2	2.5
Labor growth		0.4	0.2	-0.1	-0.7	-0.5
Investment rate		40.8	35.9	30.8	25.4	20.0
Population (Million)	1321	1354	1431	1462	1455	1417
Urbanization (%)	44.9	47.6	56.6	63.6	68.6	71.6

3.3.1 Energy markets and CO_2

The main feature of the baseline is that economic growth slows down. In our context the slow-down of growth is interesting to the extent that it influences the energy markets and the potential market for CCS. A reduction in the growth rate is likely to slow down the demand for fossil fuels by means of scaling the economy. It also influences demand for fossil fuels through the composition effect, the structural change from manufacturing to service in the economy during a growth path. Finally the productivity growth that to a large extent drives long term economic growth, will also drive the decline in the CO_2 intensity. How these elements play out, is portrayed in Figure 2.

Figure 2 GDP, energy and CO_2 in the baseline

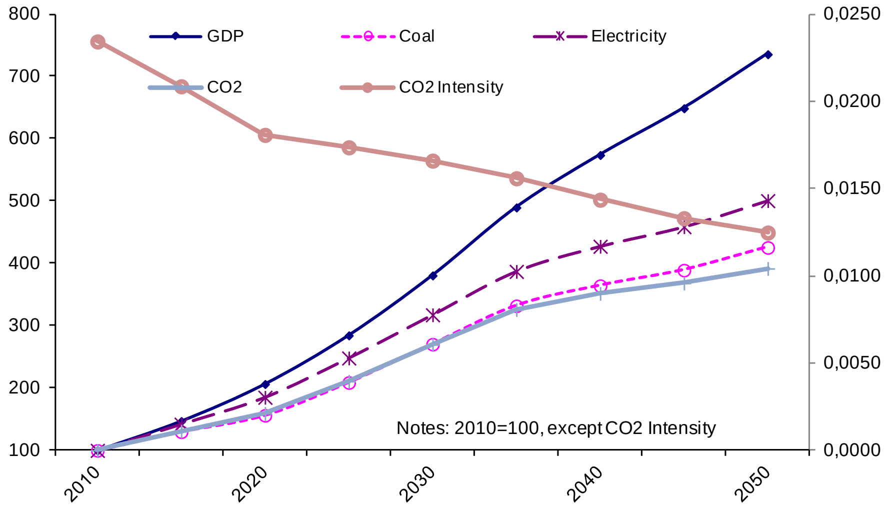


Figure 2 shows that in the baseline GDP grows much more strongly than any of the energy carriers. This reflects the strong impact of productivity on growth. The impact of productivity on growth is both direct and indirect: Directly it lifts production compared with the resource base including energy. Indirectly it stimulates structural change towards service sectors. Service sectors have significantly higher energy productivity than manufacturing, hence on aggregate GDP is lifted compared to energy inputs.

Indeed, one may legitimately ask the question why GDP is not lifted even more compared to the energy resource base. There are two reasons: One is that total factor productivity growth in the baseline is moderate by historical Chinese standards. It differs between industries (lowest in service industries) and over time (lowest in 2040-2050), but never is above 2.8 percent per year in any aggregate industry. It is not extraordinary productivity growth, but huge investments that generate China's extraordinary economic growth (which by the end of the simulation period is just ordinary). Another reason is that demand for transport energy services tends to increase at least on par with GDP. The growth in transport pulls energy and GDP closer together.

Energy carriers grow at different speeds: By 2050 power consumption grows to 500 percent of current levels, while consumption of coal grows to 400. The figures reflect a productivity increase within power production and an increasing penetration of natural gas.

Among non-carbon power technologies hydro peaks at around 20 percent in 2020 (Figure 3 below). From then on its potential is more or less exhausted. The share of nuclear increases somewhat, but levels out at between 5-10 percent of power from around 2020. The relatively low share of nuclear in the baseline is mostly due to the cost difference with coal. Recall from Table 3 above that nuclear has a 40 percent cost penalty compared to coal in the base year.

Another interesting feature of the baseline is that CO_2 emissions grow less than any of the energy carriers. This is because process emissions from cement and other sources gradually become less important. Currently, cement production in China is very high by international standards, reflecting the emphasis on investment and construction of the present economy. Many analysts consider the present emphasis on investment and construction unsustainable. The baseline reigns in investment over time (Table 4). We have compared our baseline estimate of CO_2 emissions with those of the global models of the Asia Modeling Exercise (Calvin et al., 2012). Our estimate is at the 75 percentile of the range of model-based estimates that they examine. The median of their baseline estimates is slightly lower than our estimate.

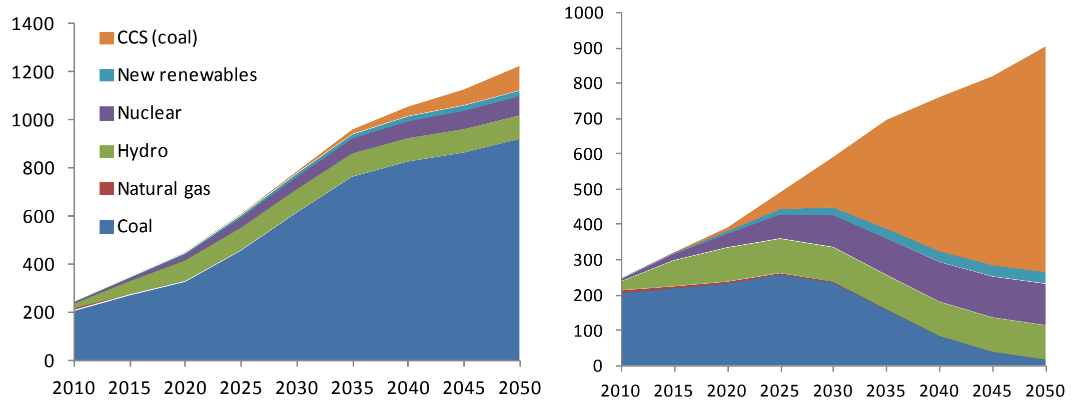
4. Internal finance scenario

Our main interest in this paper lies with the external finance scenario, but in order to set the stage it is useful to discuss the internal finance scenario first.

4.1 CCS penetration

In the internal finance scenario the price of CO_2 in China increases linearly from zero in the base year to 500 RMB/ton CO_2 in 2050. The 500 RMB tax level in 2050 is chosen for technical purposes as it brings about an almost complete switch from traditional coal based power to coal with CCS, see Figure 3. It is comparable to other recent exercises (Calvin et al., 2012).

Figure 3 Composition of power generation in the baseline (left) and internal finance scenario (right)



Price of CO_2 = zero Price of CO_2 in 2050 = 500

70 percent of all power production is generated by coal with CCS in the internal finance scenario, and only two percent is still without CCS. We note for reference with other papers that even a lower tax of 200 RMB/ton CO_2 according to our simulations generates 50 percent CCS in 2050.

We also note that according to the analysis CCS is not prevalent in China before 2025. The reason is that the IGCC plants required for pre-combustion CCS are not widely available before that time. Also, recall that the tax that incentivizes CCS is ramped up gradually.

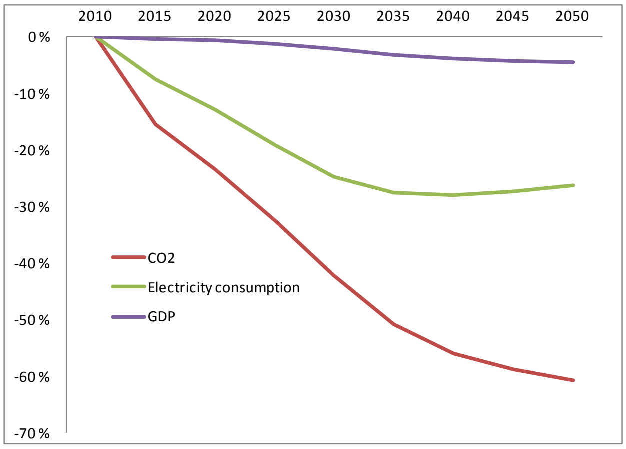
There is some scope for CCS in the baseline scenario. This is mainly an artifact of the CES-formulation for power generation. Higher demand for electricity in the baseline will stimulate all production technologies, but hydro and new renewable are constrained by resource availability, and nuclear is constrained for reasons of safety. Add to this the impact of the productivity increase specific to CCS and recall that the initial relative cost of CCS actually is lower than the cost of new renewables and not that far from the cost of nuclear, see Table 3 above. A further factor is the massive investment in the baseline, which turns out to reduce the economy-wide price of capital. Hence, the investment in a CCS plant becomes cheaper over time. These factors explain the scope for CCS in the baseline. Still there is no particular economic reason for China to invest in coal with CCS unless it has a carbon constraint or it sees a future in this technology.

4.2 Technique, composition and scale effects in the internal finance scenario

This section discusses how the economy responds to CCS in the internal finance scenario. Ignoring the technological details of CCS the internal finance scenario is similar to previous scenarios of the cost of a carbon constraint in China (e.g., Aunan et al (2007), Vennemo et al. (2009)). Previous analyses have shown that the Chinese economy is quite resilient to a carbon constraint. Basically this is because the economy over the long term is able to substitute out of carbon intensive activities, making use of the composition and technique effects in addition to the scale effect.

A similar picture emerges in our analysis of the internal finance scenario (Figure 4). We plot the reduction in carbon emissions, electricity consumption and GDP in the 500 RMB case.

Figure 4 Scale, composition and technique effects in internal finance scenario



By 2050 GDP is 4 percent lower than the baseline, electricity consumption is 26 percent lower, and CO_2-emissions are 60 percent lower than in the baseline. The difference between 4 percent and 26 percent shows the composition effect. After all, a reduction in scale of 4 percent should, other things equal, generate a reduction in electricity consumption of 4 percent. The remaining 22 percent signals a shift in the composition of the economy away from energy intensive industries towards labor intensive ones. It is also the case that industries substitute from electricity to other factors of production, and similarly on the household side. The incentive for all this substitution to happen is of course a substantial increase in the price of electricity. The price of electricity increases because the cost of producing electricity increases when carbon is given a price. The composition effect fizzles out from about 2030, which is when CCS becomes available and to some extent makes compositional change superfluous.

The difference between the 26 percent reduction in electricity consumption and the 60 percent reduction in CO_2-emissions is created by the technique effect. The technique effect is thus quite dominant, and CCS is the dominant new technique. CCS removes 90 percent of CO_2-emissions, meaning that if all electricity generators invested in CCS, the technique effect would achieve a 90 percent reduction in emissions from electricity. Observe from Figure 3 that this is almost the actual situation. In the internal finance scenario more than 98 percent of power production is either free of CO_2 or releases 10 percent of previous emissions (CCS). This means that the 40 percent of CO_2-emissions that is left in the economy (Figure 4), mostly comes from outside the electricity sector. Process emissions remain in the economy, and as well as emissions from the use of oil, coal, coke and natural gas for industrial purposes and in households.

We note for comparison with other research that a carbon price of 200 RMB in 2050 also is able to make substantial inroads into CO_2 emissions. Emissions decrease more than 40 percent. (Recall the CCS share of 50% in this scenario). Even a tax of a maximum of 100 RMB cuts CO_2-emissions 25 percent.

5. External finance scenario

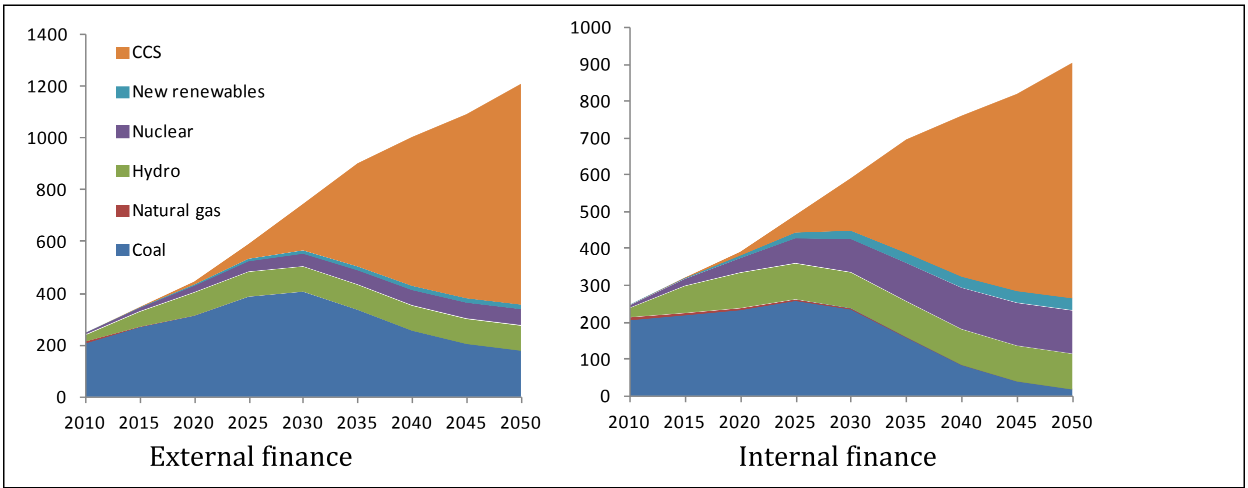
Recall the circumstances of the external finance scenario: China takes on no obligations for carbon reductions. The international community finances CCS at no cost to China. For concreteness we assume that the same share of CCS is financed as in the internal finance scenario. In other words, we analyze a program such that 70 percent of all power production in China takes place in CCS facilities. The program is similar to a gigantic CDM program except that we do not specify what the international community will do with the carbon savings it has funded.

The program is designed to leave China with zero macroeconomic cost, and achieves that purpose. There is no change in GDP, consumption, aggregate investment or economic welfare to report. From the change in the trade balance we may read off the cost of the program to the international community. This cost is equivalent to five percent of China's imports.

5.1 The electricity market

While there are insignificant impacts on macroeconomic entities the external finance scenario make a significant impact on the electricity and energy markets. Comparing the internal and external finance scenarios we notice that the external finance scenario includes more traditional coal fired power (Figure 5). Note that the right hand panel is repeated from Figure 3 for convenience.

Figure 5 Composition of power generation in the external finance (left) and internal finance scenario (right)



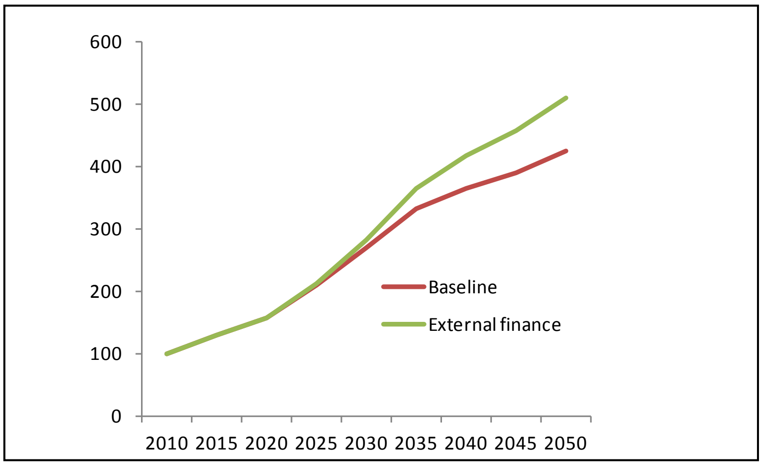
The reason is obvious when one thinks of it: A subsidy to CCS does not change the relative positions of hydro, nuclear and new renewables *vis à vis* traditional coal. Hence the market shares of hydro, nuclear and new renewables are not boosted and the market share of traditional coal is not weakened compared to these alternatives. This gives traditional coal a market share of 15 percent in 2050. Recall that it was as low as two percent in the internal finance scenario.

The lack of boost to all forms of low carbon electricity generation is of course the fundamental reason why a subsidy is less cost-effective than a price on CO_2. The difference between a subsidy and a price of CO_2 also shows up in total net electricity production: Above we saw that net electricity consumption decreased 26 percent in the internal finance scenario. By contrast, the external finance scenario is designed to leave the purchasers' price of electricity unchanged. This is the motivation for having the international community finance CCS – Chinese households and firms should not need to pay more for electricity. As a result electricity demand only changes from the baseline because of second order effects in the economy. These effects are small since the externally financed CCS in effect removes the price impulse from abating carbon.

5.2 The coal market

While the macro economy is largely unaffected by external finance of CCS we see large impacts on mining of coal (Figure 6).

Figure 6 Coal mining in the baseline and external finance scenarios. 2010 = 100.



Coal mining increases 20 percent in the external finance scenario. The main reason for this huge increase is that CCS facilities require energy for their operation. Since electricity production to the market is not changed the energy required by CCS translates into an increase in the demand for, and production of coal.

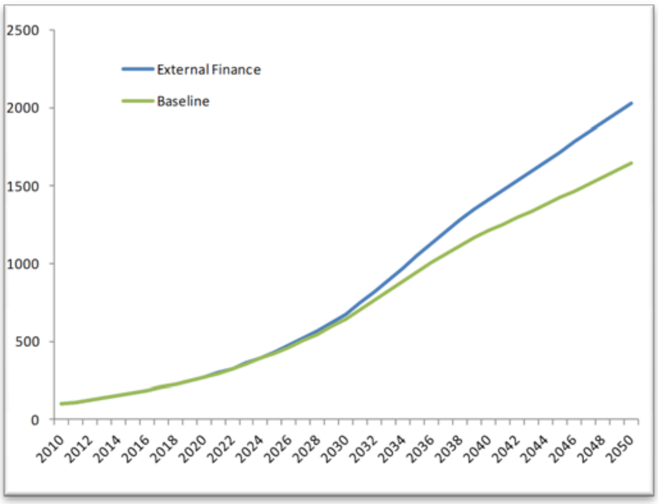
The own-demand for coal by CCS facilities accounts for about 16 of the 20 percent increase. Where does the rest come from? Like CCS, coal mining also requires energy for its operation. According to the input-output data about ten percent of the coal from a coal mine is used to operate the mine. This adds another 1.6 percent to the 16. The remaining 2.5 per cent or so is generated by additional transport demand, and by further, smaller changes in the economy.

It turns out that the additional demand for transport is also related to CCS. Transport demand in the external finance scenario increases about five percent, which must be considered a significant increase given that prices and incomes do not change much. The main reason for the increase in transport is the transport and storage component of the CCS technology. The transport sector increases to accommodate the need to send CO_2 to the storage facilities. It also requires transport to haul the additional coal to the power plants with CCS. All this additional transport requires coal. Directly and indirectly the additional demand for coal has its origin in the requirements of CCS.

In practice the increase in the demand for coal is likely to strain the logistic chain of the coal sector. Economic growth means that coal mining increases even in the baseline (Figure 6) and the requirements of CCS come on top of that. There are environmental costs as well: Increased coal mining means higher demand for water (this sector increases one per cent) and transport means higher demand for petroleum (also one percent increase).

However, politically the highest cost may be that coal imports increase. China is a net importer of coal in the baseline, continuing a trend that was initiated in recent years. The country has recently gone from being self-sufficient to being the world's largest importer of coal. Our external finance scenario projects that coal imports increase 25 percent by 2050 (Figure 7). Given the attention that China gives to energy security, this may raise political concern.

Figure 7 Coal import in the baseline and external finance scenarios. 2010 = 100.



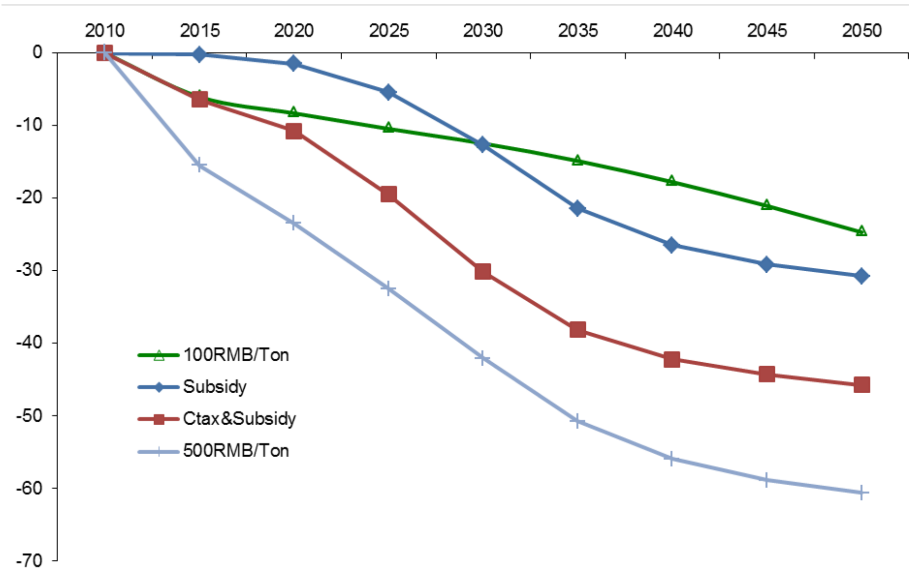
5.2 CO_2 emissions

From the perspective of the international community the purpose of funding CCS in China is of course to reduce CO_2 emissions in the country. However, the initiative does a surprisingly poor job in reducing emissions. Figure 8 plots emission reductions in the external finance scenario against the internal finance scenario that we have discussed above, and two other internal finance scenarios, namely 100 and 200 RMB/ton CO_2 in 2050. It is clear that, despite the huge share of CCS the external finance scenario seems to do no better than a tax of about 150 RMB in 2050.

The simulations indicate several reasons why the external finance scenario does a relatively poor job in reducing emissions. One is the fact that unlike a tax the external finance scenario does not stimulate to lower electricity consumption. Another is the fact that it does not stimulate hydro, new renewables and nuclear, leaving a bigger share of the pie to traditional coal. Since the pie itself is bigger, these two reasons work in tandem.

Looking outside of the electricity sector it is clear that the external finance scenario does not stimulate to lower consumption of petroleum and oil. And as discussed above the external finance scenario stimulates the consumption of coal. All these reasons contribute to the relatively modest impact on emissions of a large scale program to fund CCS from the international community.

Figure 8 Carbon emission reduction in the external and internal scenarios



6. Combining internal and external finance

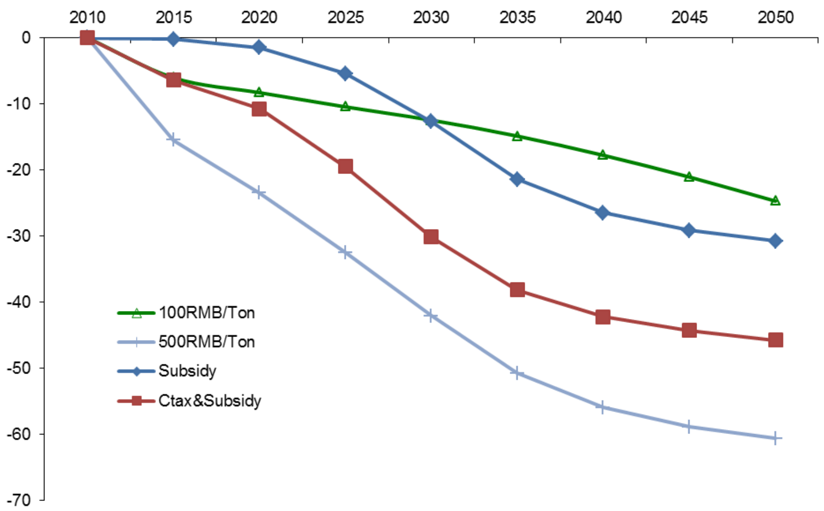
We argued previously that a carbon tax/price of zero may be a way of the Chinese government to signal that it has no intention of financing CCS on its own. However, the international community may require some Chinese will to regulate carbon emissions as a condition for funding CCS. To examine the consequences of this possibility we design a scenario in which a 100 RMB tax on CO_2 is combined with external finance of CCS.

Like above the international community finances CCS at 70 percent of all power plants. But the carbon tax also stimulates some CCS and the combined impact is to introduce

CCS on 80 percent of all power plants. The share of coal power without CCS goes to 5 percent, which is lower than external finance (15 percent) but higher than internal finance (2 percent). The share of non-carbon energy increases compared with external finance, but decreases compared with internal finance. Because of the 100 RMB tax component the price of energy increases some, and there is a modest 1 percent cost to GDP in 2050.

In terms of emission cuts this scenario borrows both from external finance scenario and from a tax of 100 RMB per ton CO_2 (Figure 8). The emission cut is higher than either the external finance scenario or a tax of 100 RMB manages on its own. But the cut is lower than the sum of those two scenarios and lower than the cut of the internal finance scenario.

Figure 9 Carbon reduction in the tax&subsidy scenario and other scenarios



7. Conclusion

The IEA and others have held forth CCS as a technologically challenging, but promising abatement technology for CO_2 since it allows economies to continue their reliance on coal. However, we have shown in this paper that introducing CCS on a large scale has challenges in addition to the technological aspects. In an emerging economy such as China the most realistic option may be for the international community to finance CCS. This option however implies a fairly strong increase in the demand for coal, with concurrent increases in transportation and water demand, as well as a strong increase in coal import. The increase in coal import may pose a particular worry for Chinese policy makers, who are concerned with energy security and search for policies that reduce energy import.

It also turns out that external finance of CCS on 70 per cent of all power production is no more effective than regulating carbon with a price of about 150 RMB/ton CO_2. This is because CCS on power plants is a measure that does not address emissions from industrial processes, and it does nothing to favor non-carbon energy sources *vis-à-vis* coal. The program is also quite expensive. It is equivalent to a deterioration of the trade balance of about five percent in 2050.

On the other hand external finance of CCS does succeed in neutralizing any GDP-cost of carbon abatement. The internal finance scenario, where CCS emerges endogenously in response to a tax or price of CO_2, does a much better job of reducing emissions since carbon from all sources becomes more expensive in all applications. But the internal finance scenario leaves China with a cost to GDP and economic welfare. A full scale introduction of CCS on 98 percent of all coal fired power, which according to our calculations arises in response to a year 2050 price of 500 RMB/ton CO_2, implies a GDP-cost of 4 percent. Also, internal finance implies significant structural change in the economy, although admittedly the structural change would mostly alter the path of changes that occur during a 40 year period.

The numerical details of the conclusion that we reach are dependent on the specification of the model. The specification of the cost mark-up of CCS is for instance important. But the main conclusions just given are valid as long as CCS requires significant resources in order to operate.

A reasonable conclusion from our analysis is that we have once again confirmed the supremacy of a price/tax on carbon over subsidy based technological solutions. However, politicians in the two largest carbon-emitting countries, including China, seem unwilling or unable to accept a price-based regulation. With burden-sharing also thrown in it strikes us as important to continue to analyze second-best options such as a large scale introduction CCS that is financed by the international community. One issue that has emerged from this research is that such a program may strain China's infrastructure for coal mining and coal delivery, and lead to significant import of coal.

References

Al-Juaied, Mohammed and Adam Whitmore (2009): Realistic Costs of Carbon Capture. Belfer Center Discussion Paper 2009-08, Harvard University.

Aunan, Kristin, Terje Berntsen, David O'Connor, Therese Hindman Persson, Haakon Vennemo and Fan Zhai (2007): Benefits and Costs to China of a Climate Policy. *Environment and Development Economics*, 12, 3, 471-497

BP (2011): *Statistical review of world energy*.

Calvin, Katherine, Leon Clarke, Volker Krey, Geoffrey Blanford, Kejun Jiang, Mikiko Kainuma, Elmar Kriegler, Gunnar Luderer and P.R. Shukla (2012): The role of Asia in mitigating climate change: Results from the Asia modeling exercise. *Energy Economics*, 34, S251-S260.

Chen, Wenying (2011): The potential role of CCS to mitigate carbon emissions in future China, *Energy Procedia*, 4, 6007-6014.

Clarke, Leon, Volker Krey, John Weyant and Vaibhav Chaturvedi (2012): Regional energy system variation in global models: Results from the Asian Modeling Exercise Scenarios. *Energy Economics*, 34, S293-305.

Copeland, B.R., Taylor, M.S. (2004): Trade, growth and the environment. *Journal of Economic Literature*, 42, 7–72.

Golan, Amos, George Judge, and Sherman Robinson (1994) Recovering Information from Incomplete or Partial Multisectoral Economic Data, *Review of Economics and Statistics* 76, 541-9.

Golombek, Rolf, Mads Greaker, Sverre A.C. Kittelsen, Ole Røgeberg og Finn Roar Aune (2011) Carbon capture and storage technologies in the European power market, *Energy Journal*, 32, 3, 209-238.

Hart, Craig and Hengwei Liu (2010): Advancing carbon capture and sequestration in China: A global learning laboratory, *China Environment Series*, 11.

Hertel, Thomas and Zhai, Fan (2006): Labor market distortions, rural–urban inequality and the opening of China's economy. *Economic Modeling*, 23, 1, 76–109.

IEA (2008): *CO_2 capture and storage: A key abatement option*. International Energy Authority, Paris.

IEA (2009): *Technology Roadmap Carbon Capture and Storage*. International Energy Authority, Paris.

IEA (2010): *Projected costs of generating electricity. 2010 edition*. International Energy Authority, Paris.

Li, XC; N. Wei; ZM Fang, Q Li, RT Dahowski and CL Davidson (2011): Early opportunities for carbon capture and storage in China, *Energy Procedia*, 4, 6029-6036.

Li Shantong (2011): *China in 2030* (in Chinese), Jingji Kexue Press.

Li Zheng, Zhang Dongjie, Ma Linwei, Logan West and Ni Weidou (2011): The necessity of and policy suggestions for implementing a limited number of large scale, fully integrated CCS demonstrations in China, *Energy Policy*, 39, 5347-5355.

Liu, Qiang; Minjun Shi and Kejun Jiang (2009): New power generation technology options under the greenhouse gases mitigation scenario in China, *Energy Policy*, 37, 2440-2449.

Mi, Raymond, Helal Ahammad, Nina Hitchins and Ewina Heyhoe (2012): Development and deployment of clean energy technologies in Asia: A multi-scenario analysis using GTEM. *Energy Economics*, 34, S399-S409.

NBS (2011): *China energy statistical yearbook*. China Statistics Press, Beijing.

New Energy Web (2010): It's time for adjusting on-grid price of renewable energy, http://www.newenergy.org.cn/html/0105/5171032525.html, accessed May 17, 2010. In Chinese.

Nicholson, Martin; Tom Biegler and Barry W. Brook (2011): How carbon pricing changes the relative competitiveness of low-carbon baseload generating technologies, *Energy*, 36, 305-313.

Ringius, Lasse, Asbjørn Torvanger and Arild Underdal (2002): Burden sharing and fairness principles in international climate policy. *International Environmental Agreements: Politics, Law and Economics*, 2, 1-22.

Robinson, Sherman and Moataz El-Said (2000): GAMS code for estimating a social accounting matrix (SAM) using cross entropy (CE) methods. IFPRI Working Paper, International Food Policy Research Institute, Washington, D.C. 20006, U.S.A., December 2000.

Robinson, Sherman, Andrea Cattaneo and Moataz El-Said, Updating and Estimating a Social Accounting Matrix Using Cross Entropy Methods. IFPRI Working Paper, International Food Policy Research Institute, Washington, D.C. 20006, U.S.A., August 2000.

Theil, H. 1967. *Economics and Information Theory*. Rand McNally.

Vennemo, Haakon, Kristin Aunan, Jianwu He, Tao Hu, Shantong Li and Kristin Rypdal (2008): Environmental implications of China's WTO accession. *Ecological Economics*, 64, 4, 893-911.

Vennemo, Haakon, Kristin Aunan, Jianwu He, Tao Hu and Shantong Li (2009): Benefits and costs to China of three different climate treaties. *Resource and Energy Economics*, 31, 139–160.

Wang, Y., Xu, D., Wang, Z., Zhai, F. (2004): Options and impact of China's pension reform: a computable general equilibrium analysis. *Journal of Comparative Economics*, 32,1, 105–127.

World Bank (2004): *Clean development mechanism in China. Taking a proactive and sustainable approach. 2nd edition*.

World Bank and DRC (2012): *China 2030. Building a modern, harmonious and creative high-income society. Conference Edition*.

World Energy Council (2007): *Survey of energy resources 2007.* World Energy Council.

Zhai, Fan and Li, Shantong (2002): The impact of WTO accession on income disparity in China. In Renard, M.-F. (Ed.), *China and Its Regions: Economic Growth and Reform in Chinese Provinces*, New Horizons in International Business. Edward Elgar, 121–146.

Appendix

Splitting Electricity Production by fuels

Electricity is most often generated at a power station by electromechanical generators, primarily driven by heat engines fueled by chemical combustion or nuclear fission but also by other means such as the kinetic energy of flowing water and wind. There are many other technologies that can be and are used to generate electricity such as solar photovoltaics and geothermal power.

However, in order to utilize China's IO data[3] for CCS analysis, it is necessary to split power generation by technologies (fuel source). Based on the availability of data, we introduce five categories for power generation: coal-fired electricity, non-coal fossil electricity, nuclear electricity, hydro-electricity and other electricity.

Because IO data base must satisfy a numbers of key equilibrium conditions in all 42 sectors, we cannot simply go into the data base and alter a given set of flows without destroying one or more of these equilibrium conditions. According to energy data and cost data for power generation from IEA, a Cross Entropy method will be used to share the single electricity production out among different technologies.

Methodology

The cross-entropy method is an approach which originates from information theory (Shannon, 1948) and then is brought to economics (Theil, 1967). In information theory, the cross entropy between two probability distributions measures the average number of bits needed to identify an event from a set of possibilities, if a coding scheme is used based on a given probability distribution, rather than the "true" distribution.

In 1990s, the cross-entropy method was applied to input-output table and social accounting matrix estimation. Golan, Judge, and Robinson (1994) use this to estimate the coefficients in an input-output table. Robinson et al. (2000) and Robinson and El-Said (2000) use the cross entropy to update and estimate social accounting matrix. In general, the cross entropy method is a method of solving underdetermined estimation problems, using all and only information available.

In this study, we follow the works of Golan et al. and Robinson et al. to estimate the input matrix for electricity production by technology.

Estimating of disaggregate electricity data

[3] As for China's IO table, there is only one aggregated sector for power generation.

Table A1 the schematic production matrix of electricity by fuel for one country

	Coal-fired electricity	Non-coal fossil electricity	Hydro-electricity	Nuclear electricity	Other electricity	Total
Intermediate input	$M_{45\times5}$					$R_{45\times1}$
factor						
Product tax/subsidy						
Total input/output	$C_{1\times5}$					

Table 1 shows the schematic production matrix of electricity by fuel for China. $M_{s\times el}$ is the input matrix for different power generations. Index *el* covers all types of electricity generation: coal-fired electricity, non-coal fossil electricity, hydro-electricity, nuclear electricity and other electricity. Index *s* refers all inputs: 42 intermediate input commodities[4], 2 factors and 1 net product tax (production tax minus production subsidy). By now, we just know the aggregate cost structure of electricity (R) with China's IO table and do not know M and C. C will be calibrated first. Then cross entropy method is used to estimate M.

The estimation of output for electricity by fuel

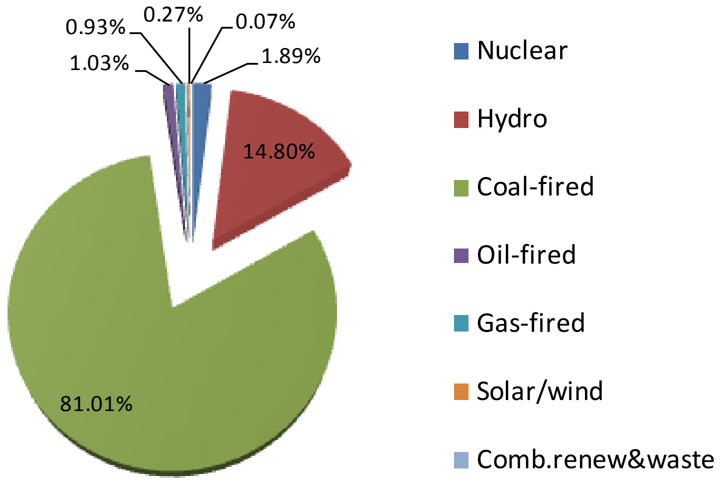
With IEA database/China's energy statistical yearbook, it's easy to find the electricity production in terms of physical volume, by country and fuel. Figure 1 shows the composition of electricity production by fuel type in 2007[5]. The following formula is used to calibrate the output of electricity in China from different fuels:

$$C_{el} = \frac{\delta_{el}E_{el}}{\sum_{el}\left(\delta_{el}E_{el}\right)}X^{ely} \qquad (1)$$

Where, E_{el} is the production of electricity by fuel in terms of physical unit (MWh) and comes from IEA database. δ_{el} is the cost disparity coefficient for different electricity category, see Table 3 in the main text. X^{ely} is the aggregated output of electricity in the IO table . C_{el} is output of electricity by fuel in terms of value (US$).

[4] Like we mention in the main text we have 40 industries producing these 42 commodities. Two service industries produce two commodities each.
[5] Because China's latest IO table is 2007 table, we also use 2007 energy data.

Figure A1 Composition of electricity production by fuel source (2007)

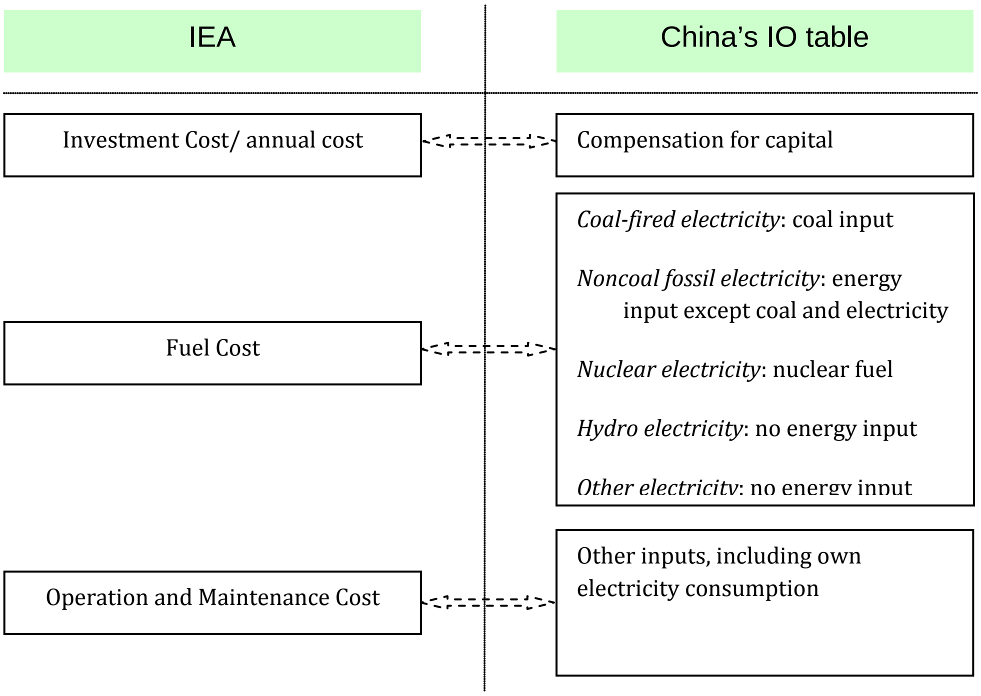


Source: NBS (2011).

The estimation of the production matrix

Because the cross entropy method begins with prior "information", we should find some additional information except C and R. It would be ideal to find the same cost structure data for each type of electricity generation. Unfortunately, we just find simple cost structure data for type of electricity generation. According to the data, the unit cost of electricity generation includes three parts: investment, operation and maintenance (O&M) and fuel costs. In order to utilize the cost data to estimate the production matrix of electricity by fuel, it is necessary to bridge the gulf between two classifications (IEA and China's IO table). We set up the correspondence between these two classifications (see Figure A2).

Figure A2 the correspondence between IEA cost and China's IO table



Now the cost share data from IEA can serve as the prior "information" in our estimation. The cross entropy method problem is to derive the estimated production matrix, which minimizes the Kullback-Leibler measure of the "cross entropy" distance between the prior cost information and the estimated cost information. The equilibrium conditions in SAM should also hold. The cross entropy problem is as follows:

$$\min \; entropy = \sum_{el}\sum_{ct}\left[\gamma_{el}\cdot\bar{\alpha}_{el,ct}\cdot\ln\left(\frac{\alpha_{el,ct}}{\bar{\alpha}_{el,ct}}\right)\right]$$

Subject to :

$$\sum_{s} M_{s,el} = C_{el} \qquad (2)$$

$$\sum_{el} M_{s,el} = R_{s} \qquad (3)$$

$$\sum_{f:s\to ct} \frac{M_{s,el}}{C_{el}} = \alpha_{el,ct} \qquad (4)$$

$$M_{s,el} \geq 0 \qquad (5)$$

The index *ct* covers three cost categories: investment, operation and maintenance (O&M), and fuel costs. $f: s \to ct$ is the image between the IEA categories (ct) and Input-output categories (s) defined in Figure A2. The output share for each electricity category in total electricity output ($\gamma_{el} = \frac{C_{el}}{\sum_{el} C_{el}}$) is incorporated into the cross entropy as weights. $\overline{\alpha}_{el,ct}$ is the "prior" cost share and is calculated based on IEA cost data.

As for constraint (2), the sum of all inputs must in the base year be equal to the output for each electricity category. In the constraint (3), for a given input (intermediate commodities or factors), the sum of input in all electricity categories must be equal to aggregate input in IO table. Equation (4) gives the definition of cost share in terms of investment, O&M and fuel, based on the estimated production matrix. The last constraint means that each cell in the production matrix is non-negative. To solve the problem, prior cost information and the aggregate cost structure of electricity in IO table are used to initialize $M_{s,el}$. With GAMS we solve the cross entropy problem.