Macroeconomic impacts of carbon capture and storage in China

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Carbon capture and storage (CCS) a key technology for reducing greenhouse gas emissions. However, a CCS facility consumes vast amounts of energy and capital. With this in mind we analyze macroeconomic consequences of a large scale introduction of carbon capture and storage (CCS) in China. To conduct the analysis we modify and extend the DRC-CGE, a macroeconomic model of the country. We find that in order to accommodate CCS on all its fossil fuel power plants by 2050 China will need to build about 20 percent more power stations than it otherwise would have done. X percent of investment resources will be spent on CCS. The macroeconomic welfare cost to the economy of 2050 is about xx/depends on financing (?). The consequences are (much) larger/smaller/about the same as a partial equilibrium analysis of CCS would have suggested.

1. Introduction

By general consensus carbon capture and storage (CCS) is a key technology for fighting climate change. According one recent study, CCS will contribute more than any other technology to reaching global carbon emission goals by 2050 (IEA, 2010a, the Blue Map scenario). An important argument for CCS is that it allows countries to rely on coal for power and heat supply. Coal is abundant and cheap in countries like the US, China, Russia and India, and a climate solution that allows coal consumption to continue is attractive for these countries. In China, for instance, all available evidence suggests that coal will be an important pillar of the economy for decades ahead. Several power plants begin operation every month, and most of them are expected to operate until 2050 or longer. This amounts to vast quantities of committed coal consumption, with associated CO_2 emissions running into billions of tons unless CCS is developed. For this and other reasons the IEA finds that reaching carbon emission goals without CCS would be 70 percent more expensive.

However, a CCS facility consumes large amounts of capital and energy. 30-40 percent more investment resources are required to build a plant with CCS compared to one without. A CCS facility on a power plant may consume 20-30 percent of its own energy production. These simple facts suggest that installing CCS on a large scale in a country based on coal fired power, is no small undertaking. It is likely to have macroeconomic consequences as the impacts of building CCS ripple through the markets for energy, capital and eventually also labour and goods markets.

In this paper we study macroeconomic impacts of implementing CCS on a large scale in China. China is chosen because it seems clear that if CCS is to be feasible globally it must be feasible in China. China consumes almost half the coal in the world (BP, 2011) and is the country with the most ambitious plans for building more coal fired power plants. The IEA Blue Map Scenario requires 600 CCS facilities to be built in China by 2050. Chinese policy makers have indicated some interest in the CCS technology and at least ten demonstration plants are set up or they are under way (e.g., Li Zheng et al., 2011). With one exception the plants are quite small, however.

Research has indicated a potential for CCS in several sectors in China. Cost-wise the potential could be the best in the petrochemical industry and possibly in coal-to-liquid projects (Li 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 analyzeCCS 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 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 extend the social accounting matrix in order to linkthe CCS technologies to the input-output matrix of the economy. (more highlights of what we have done Jianwu?)

A study of macroeconomic consequences of CCS in China is as far as we know a novel contribution to the literature. Morse, Rai and He (2009) speculate on macroeconomic impacts of CCS in China. They claim that "a widely overlooked fact about large-scale implementation of CCS in China is that it would almost assuredly result in significantly more coal use due to the parasitic load from CCS". Using simple projection methods they calculate that CCS at a scale prescribed by the Blue Map scenario would demand approximately 200-300 million tons per year of additional coal production. This, they claim, will require 340,000 additional workers and 19 billion RMB more investment in the coal industry. In addition, new transport routes will be built. The predictions of Morse, Rai and He are interesting as background for our analysis.

In addition to information provided by IEA (2010), 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 analysiscarbon abatement of 35 percent reduction compared to the baseline leads the model to forecast close to 500 GW of coal power with CCS in 2050. This suppliesone fifth of the required reduction. 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 percent of the required abatement.

While they do not emphasize macroeconomic impacts in their paper Liu, Shi and Jiang claim that they link their energy model to a CGE model in order to derive scenarios for energy demand. This allows them some grip on the scale and composition effects (Copeland and Taylor, ref) that follow from a carbon restriction. Allowing scale and composition effects are likely to lower the reliance on CCS for carbon reduction since energy demand is endogenous.

The financing mechanism of CCS is also 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. Domestic finance is however also a possibility, and in fact it is the only possibility considered by Chen (2011) and Liu, Shi and Jiang (2009). Liu, Shi and Jiang derive a shadow price on electricity in their mitigation scenario 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.

Our object of study is not primarily the energy market, but the wider economic repercussions that follow from the significant resource requirement associated with CCS. In this sense we are closer in spirit to the conjectures of Morse, Rai and He (2009) than to the energy market analyses of Chen (2011) and Liu, Shi and Jiang (2009). However, the energy market is also of interest and here we integrate the scale and composition effects into the analysis. Finally we open up for external finance of CCS and show that external finance has an impact not just on the macroeconomic cost for China, but also for the energy market.

The remainder of this paper is structured as follows: Section 2 gives background on CCS and presents our policy experiments. Section 3 presents the model we use and the baseline scenario. Section 4 presents… Section x 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 to 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 be difficult to find, etc.

Pre-combustion CCS requires a particular power plant technology, namely the Integrated Gasification Combined Cycle (IGCC). In an IGCC plant the coal is turned into a gas. The process breaks apart the chemical bonds of the coal and results in a gas consisting of$CO_2$and other elements. With further chemical modification it is possible to obtain highly concentrated CO_2. The highly concentratedCO_2can then be removed from the waste stream at a moderate variable cost.

IGCC is still an emerging technology. It is more effective than the conventional pulverized coaltechnology, 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, thebroad 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. Some argue that the costs would be lower in China than in Europe or the U.S. (reference). 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 research cooperation between China and the UK that is looking at 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 crucial 30 percent estimate is consistent with IEA (2008) (33 percent). For energy her assumption is that in 2030 an IGCC without capture has an efficiency of 45 percent, and a plant with capture has an efficiency of 38 percent. This works out as an energy penalty of 18 percent (8/45). Table x collects her and other estimates in the literature. In our model, we assume that the capital cost of CCS is 30% higher than that without CCS and that the cost of “operation and maintenance” is about

10% higher than traditional power plant. The energy penalty for CCS is set to 20%. Thelevelised cost of CCS is 30% higher than that without CSS. The remainder of overall mark-up comes from “transport and storage” costs.

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

		IGCC w/o	IGCC w/ CCS	Mark-up
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 (W/O TS)[2]	49. 4	67. 7	37%
Al-Juaied and Whitmore (2009)	levelized costs (W/O TS)	8	11. 5	44%
IEA (2010b)	Investment Cost	2200	3350	52%
	Fuel Cost	46%	35%	24%
	levelized costs	67	110. 5	65%

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

Whatever the details it seems 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 some political parties 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 hard commitments for carbon emissions.

In the external finance scenario CCS is financed from abroad. This scenario obviously leads to small macroeconomic costs for China since the intention of external finance is to neutralize cost impacts.

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 we generally assume cost-effective penetration, but in a sensitivity analysis we analyze the impacts of a designated policy to promote higher penetration.

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 toanalyze environmental policy and other policy reforms. In China the model is used in regionaldevelopment planning and macroeconomic planning for the State Council, including the 5-year plans.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) andenvironmental policy analysis (Aunan et al., 2007; Vennemo et al., 2009). The model is maintained atthe Development Research Center of the State Council in China. Table xsummarises main features ofthe model version used in this paper. For equations and a detailed description in English see Vennemo et al. (2008).With the aid of Table x we briefly review the main features of the model that influence on results.

Table 2 Main features of the DRC-CGE model

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

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 sectorsallows more precisemodeling of structural change in the economy. Structural change is a significant part of the macroeconomic impact of CCS and thereforequite important to capture in the analysis. Fisher-Vanden et al. (2004) have shown the significance of modelling structural change in some detail, or elsetoo much of the structural response to policy is subsumed in residual productivity growth changes.

Arguments for a large number of industries have tobe balanced against arguments in the opposite direction (e.g., large number of technology parameterswithout 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 aretransaction 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 imperfectly capture thecosts, with elasticities of transformation of about 3.0 between export and domestic production. On the import side so-called Armingtonfunctions are used with price elasticities of about 6.0. The parameters are chosen in order not toexaggerate the unspecified transaction costs.

Industries use the primary inputs capital, natural resources and land, agricultural workers, production workers andprofessionals (nested constant elasticity of substitution (CES) functions). Agricultural workers andproduction workers are interchangeable. Natural resources and land are reserved for hydropower production and agriculture. Professionals are reserved for manufacturing and service industries.

The model distinguishes betweennew capital, that is the current vintage of investment, and old capital, that is non-depreciatedinvestment of last year and before. Old capital is almost fully locked to production in the industrywhere it was invested. New capital can readily be substituted between industries and against otherproduction factors.

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 instanceprocess emissions from cement production.Industrial process emissions belong in this category.

DRC-CGE model has a flexible system of carbon mitigation policies. The simplest is a carbon taxthat also allows for exemptions for designated sectors or households. An alternative is to provide a cap on emissions at the national level. The model will then produce the shadow price of carbon, i.e. the carbon tax, as a model outcome. If a national cap is imposed, a single uniform tax will be calculated. Some more here on our external finance scenario.

The model is calibrated to the DRC Social Accounting Matrix with a 2007base year[1].

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 represent macro substitution possibilities of the economy. Two data problems then immediately emerge. One is that the Chinese IO-table and national accounts to not distinguish between different power generation technologies. Hence a procedure is needed for mapping cost and output data from different technologies to the national accounts data. The second data problem is that CCS is an unproven technology and cost estimates are uncertain. Our discussion of the evidence and choice of CCS technology parameters was explained above. Here we discuss how the electricity sector is modeled and how data are calibrated.

3.2.1 Modeling the power sector

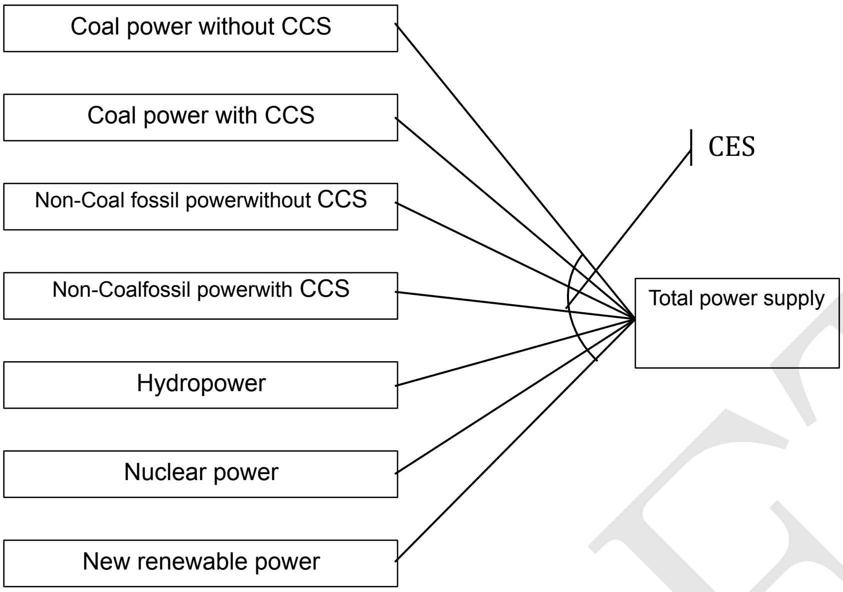
There are seven different power generation processes in model: coalpowerwith and without CCS, non-coal fossil powerwith and without CCS, hydro power, nuclear power andnew renewablepower.A nested CES structure is used for all power generation processes. But the CES composite is different for different generation processes, i.e, different inputs of intermediate goods and factors are used to generate power. In addition, the emission intensities of each process are different.

All powergeneration processes together make up total powersupply (see figure x). A CES structuremodelsthis composite, the total powercomposite. The substitution between

[1] The latest published Input-Output tables are 2007 tables.

different processes depends on relative production cost. The elasticity of substitution is as high as 20, reflecting the fact that power is an almost homogenous good.[2]

Figure1 Production technology in the power sector



In the model, fossil-fired powerwithout CCS, hydro and nuclear are used widely in the base year, while the powertechnologies with CCS become available in future periods. The base year price differentials that generate this pattern are given in table x.

Table the cost of each power generation technologies 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

Source： IEA (2010b) except the relative price of “Other electricity”. This price is based onhttp://www.newenergy.org.cn/html/0105/5171032525.html

3.3 The baseline scenario

A baseline scenario is required for comparison with scenarios with CCS. The design of the baseline may potentially influence quite substantively on estimated impacts. Our

[2] There are some differences in storage possibility and reliability. The CES model is also chosen for modeling convenience.

baseline builds on previous work (Li et al, 2011), but it extended here for the first time to 2050. A main macroeconomic feature of the baseline is that economic growth in China gradually slows down during the first half of the century. The reason is that China is catching up with other with the worldwide productivity frontier. Over time also, the potential is exhausted for spill-over from low productivity agriculture to high productivity manufacture (reflected below in the indicator for urbanization). It is also important that the aging society over time lowers the labourforce and saving rate. Finally the current growth rate of China depends on high and increasing investment rates, which are not sustainable over the course of a half century.

	2007	2010	2020	2030	2040	2050
GDP (2007 price)	2675	3460	7239	13612	20804	26494
GDP growth		9.0	7.5	6.3	4.2	2.5
Laborgrowth		0.4	0.2	-0.1	-0.7	-0.5
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

In our context the lower economic growth rate is interesting to the extent it influences the energy markets and the potential market for CCS. A lower growth rate is likely to reduce demand for fossil fuels by means of the so-called scale effect. 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_2intensity. How these elements play out, is portrayed in figure x.

Figure 2 GDP, energy and CO_2 in the baseline

Figure x 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.

Energy carriers also grow at different speeds: By 2050 powerconsumptionand natural gas grow to 500 percent of current levels, while consumption of coal and crude oil grow to 400. Jianwu, these are very high numbers. Is productivity growth too low? The figures reflect a productivity increase within power production and an increasing penetration of natural gas.

Background data shows that natural gas is not used for power production in the baseline scenario, hence the strong growth in natural gas is due to gas being used directly by households and firms, where it substitutes for coal. The process of exchanging coal for gas, which Europe underwent a couple of decades ago, has started in China too. It contributes to the relatively low growth in coal consumption. Coal's share in electricity production is stable at around 80 percent, consistent with the claim that the substitution between natural gas and coal occurs outside the power sector.

Among non-carbon power technologies hydro peaks at around 20 percent in 2020. From then on its potential is more or less exhausted. The share of nuclear increases somewhat from current levels, but levels out at between 5-10 percent of power from around 2020. The relatively low share of nuclear is due to cost.

Another interesting feature of the baseline is that CO_2emissions grow less than any of the energy carriers. This is because process emissions from cement and other sources are reduced in importance over the next decades. 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 to some extent, leading to low growth in process CO_2 emissions. Overall CO_2emissions in the baseline scenario are quite similar to those of the Business as Usual Scenario published by DRC and NDRC(2009).Exact reference, please.

4. Results

5. Conclusion

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