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Xi Liang, Hengwei Liu, and David Reiner

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Abstract Building on previous stakeholder consultations from 2006 to 2010, we conduct a financial analysis for a generic CCS power plant in China. In comparison with conventional thermal generation technologies, a coal-fired power plant with CCS requires either a 70% higher on-grid electricity tariff or carbon price support of approximately US$50/tonne CO_2 in the absence of any other incentive mechanisms or financing strategies. Given the difficulties of relying on any one single measure to finance a large-scale CCS power plant in China, we explore a combination of possible financing mechanisms. Potential measures available for increasing the return on the CCS investment include: enhanced oil recovery (EOR), a premium electricity tariff, and operational investment flexibility (e.g. solvent storage, upgradability). A simulation found that combining several financing options could not only provide private investors with a 12% to 18% return on equity (ROE), but also significantly reduce the required on-grid tariff to a level that is very close to the tariff level of existing coal-fired power plants and much lower than the tariffs for natural gas combined cycle and nuclear power plants. Therefore, we suggest that a combination of existing financing measures could trigger private investment in a large-scale CCS power plant in China.

Keywords Carbon capture and storage, Coal-fired power plant, Electricity, Finance, China

JEL Classification Q4, Q42, O3, O13, P48

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Strategies for Financing Large-scale Carbon Capture and Storage Power Plants in China

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1. Introduction

China is the world's largest consumer of coal, mining over 3 billion tons of coal a year and it has now become the largest importer of coal. China had more than 650 GW of coal-fired power installed capacity by the end of 2010 and has been building at least 50 GW of new coal-fired power plants per year since 2005 [CEC, 2011]. The rapid growth of thermal generation capacity is likely to continue until 2030 according to estimates by the International Energy Agency (IEA) [2007: 88-91]. In the past five years, China has become the largest producer of greenhouse gases in the world and, by far, the leading driver of growth in greenhouse gas emissions globally. As a result, addressing carbon dioxide (CO_2) emissions and reducing the emissions intensity of Chinese energy and electricity sector in particular has become increasingly important.

CO_2 capture and storage (CCS) is the process of separating CO_2 from stationary sources (mainly industrial and power plants), and transporting and injecting the CO_2 into a geological storage site. CCS is currently the only promising technology to decarbonise fossil fuel power and industrial plants at a large scale. The IEA's 2°C Scenario (2DS), which assessed the strategies for reducing global GHG emissions through 2050, concluded that based on cost estimates, CCS would constitute some 14% of the cumulative emissions reductions required and that while the developed world must lead the CCS effort in the next decade, CCS must rapidly spread to developing countries, where most of the growth in emissions is occurring [IEA, 2013]. The IEA scenario would involve 950 GW globally (some 8% of all generation capacity) including 349 GW in China, the largest of any region (IEA, 2013)

This level of CCS deployment amounts to a tremendous global challenge. At present, there are only four commercial-scale CO_2 storage projects in operation around the world and a number of smaller-scale integrated ones, but no commercial scale fully integrated projects, although a few are nearing completion. These projects will involve power generation, but also industrial sectors such as cement, iron and steel, chemical production, and gas processing. The challenges of technology integration and scale-up can only be met through the experience of building and operating commercial-scale CCS facilities in a variety of settings. Since 2008, in China, three CO_2 capture pilot projects have started operation and two projects are still under construction. However, these early efforts are of limited scale and generally also offer commercial benefit from CO_2

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utilisation. In contrast with the millions of tonnes of CO_2 emitted from a large coal-fired power plant, the largest capture unit in China is only producing 120,000 tonnes per year, and the first integrated CCS project only captures 100,000 tonnes per year.

A large number of studies have explored the cost structure for CCS [DOE, 2007; Rubin et al, 2007; McCoy and Rubin, 2008; Dahowski et al, 2009; Herzog, 2010; Hammond et al, 2011], but few studies have investigated financing issues explicitly. Kessels and Beck [2009] organised two CCS finance experts meetings in London in 2007 and two subsequent meetings in New York. They concluded that: (1) market based instruments alone would not be sufficient to support large-scale investment in CCS; (2) governments need to provide more robust policies to provide certainty for investors in deploying CCS; and (3) a price of US$80-100 per ton CO_2 would be required to support the deployment of CCS. Liang et al (2010) investigated the financial strategies for CO_2 capture ready (i.e. careful design and possibly a small investment up front to make subsequent CCS retrofitting cheaper and easier) in China rather than a large-scale deployment of CCS, suggesting the separation of the financing of capture faculties from that of the base plant in order to apply for CCS project financing. Almendra et al (2011) summarise potential financing strategies for demonstrating CCS in developing countries. To date, however, there are still no targeted mechanisms to encourage a large-scale CCS demonstration project in China (Jaccard and Tu, 2011).

In December 2010, the 6th Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol (CMP 6) at Cancun recognised CCS as an eligible project level activity within the Clean Development Mechanism (CDM) [UNFCCC, 2010]. The inclusion of CCS in CDM may accelerate the financing of early CCS opportunities with low marginal abatement in developing countries, such as ammonia, fertiliser, cement, hydrogen productions. However, because there is currently more than 1 Gigatonne (Gt) of CO_2 emissions from these early opportunities in developing countries every year, though it might not significantly depress the carbon market [Zakkour et al, 2011], CDM is unlikely to be the primary incentive to finance a large-scale commercial CCS power plant in developing countries. There is very limited literature explicitly investigating the financial strategies to implement a large-scale CCS project in China. Therefore, this study tries to bridge the gap and examines the two following key research questions:

1. What is the on-grid tariff or carbon price required to support full-scale CCS deployment at a large coal-fired power plant in China?
2. In the absence of national political and regulatory support, what are the potential incentive mechanisms and strategies required to bridge the financial gap and trigger investment large-scale CCS coal-fired power plant in China?

The next section introduces the current technical and economic status of CCS technologies. The methodology and assumptions are presented in section 3, followed in section 4 by a case study investigating the investment required for a CCS power plant in China. Building on the results of the project financing model, the fifth section provides an in-depth discussion of potential strategies and measures needed to bridge the gap in financing a CCS power plant. The final section summarises the findings and offers some conclusions.

2. Status of CCS Technologies

2.1 Capture of CO_2

CO_2 capture technologies have long been used by industry to remove CO_2 from gas streams. There are currently three primary methods for CO_2 capture: post-combustion, pre-combustion and oxy-fuel (IPCC, 2005; IEA 2008).

- **Post-combustion**

Post-combustion involves scrubbing the CO_2 out of flue gases from the combustion process, which contains 4% to 15% of CO_2 by volume depending upon the plant. Chemical absorption, typically through the use of amine-based solvents and subsequent regeneration is the preferred method for post-combustion capture because the energy required is not particularly sensitive to low concentrations. CO_2 capture has been applied in a wide range of industrial manufacturing processes, refining and gas processing. In the 1980s, CO_2 capture from gas-fired boiler flue gases was used commercially for enhanced oil recovery (EOR) projects in the US [Chapel, et al., 1999]. In China, the first post-combustion capture project in Beijing (with 3,000 tonne of CO_2 captured per year), and the second post-combustion capture project in Shanghai (with a capacity of 120,000 tonne of CO_2 per year), are already in operation [Hart and Liu, 2010].

The current challenges facing post-combustion capture include: (1) developing novel solvents that can recover the CO_2 with a minimal energy penalty and at an acceptable cost; (2) designing innovative processes that can deeply reduce the energy penalty and capital cost. However, post-combustion capture also has distinct advantages: it can be applied to existing power plants without fundamental change to the production systems. The empirical study described in Section 3 focuses on post-combustion capture because a great majority of proposed and existing coal-fired power plants would require this technology to capture CO_2.

- **Pre-combustion**

Pre-combustion capture technologies are used commercially in various industrial applications such as the production of hydrogen and ammonia from hydrocarbon feedstock. Where coal is the feedstock, it needs first to be gasified to produce syngas. If natural gas is the feedstock, it needs to be reformed to produce syngas. Syngas must be processed in a shift reactor to produce a mixture of hydrogen and CO_2. Then the CO_2 is removed using physical sorbents from a high-pressure gas mixture (2 to 7 MPa) that contains between 15% and 40% CO_2.

Pre-combustion is particularly relevant for Integrated Gasification Combined Cycle (IGCC), in which coal is gasified with oxygen to produce syngas that, after cleaning, is burned in a gas turbine to produce electricity. Pre-combustion CO_2 capture from IGCC power plant has yet to be demonstrated; however, elements of the pre-combustion capture technology have already been proven in other industrial processes [IPCC, 2005; IEA, 2008]. The GreenGen 250 MW IGCC demonstration project, which began operating in 2011, and CCS is expected to be added in the second phase of the project.

The advantages of pre-combustion capture (through gasification) are: (1) multiple fuels can be used and multiple products produced, from electricity to chemicals, (2) the process is technically elegant, with efficiency gains from the integration, and (3) it offers an lower marginal cost to strip CO_2 from the syngas rather than to capture it from flue gases in a pulverized coal power plant, (where CO_2 is at lower pressure and diluted with other exhaust gases). Carbon capture from fuel at high pressure provides an approximately 60-to-1-volume advantage over post-combustion capture. With the CO_2 concentration taken into account, pre-combustion boasts an approximately overall 240-to-1 advantage. Despite of increasingly mature technology and growing reliability in recent decades, pre-combustion capture has been hindered by its higher capital investment, poorer reliability and availability, and inflexibility of operation.

- **Oxy-combustion (or Oxy-fuel)**

This process separates oxygen from air with the use of an established air separation unit and then burns the fuel in a mixture of oxygen combined with recycled flue gas to control the combustion temperature. Oxy-fired pulverized coal combustion plants do not yet exist at a commercial scale, although several new such plant constructions have recently been announced in the United States and Europe. There is as yet also limited experience of the ways in which Oxy-fuel retrofits might impact on boiler materials or the operation of plant as a whole.

The efficiency of Oxy-fuel power plants and their associated CO_2 capture systems depends heavily on the energy required for oxygen production. Research is currently focused on developing ion-transport membranes operating at 800°C to 900°C to produce oxygen from compressed air. Future developments could improve high-temperature operation and reduce the energy costs of O_2 separation from air.

The advantages of oxy-combustion are: much easier separation of CO_2, no solvent required, smaller physical size, and the potential to retrofit existing plants (though the boilers may be required to be reconstructed). The disadvantages are the need for very low SOx levels in the gas leaving the burners, as well as the higher temperature materials demanded in most cases. The cost of capturing CO_2 through Oxy-fuel depends on the type of power plant used, its overall efficiency and the energy requirements of the capture process.

IEA (2008) estimated the additional investment costs for CO_2 capture ranges from US$ 600 to 1700/kW, which is approximately 50% to 100% of the plant cost without CO_2 capture. In summary, most of CO_2 capture technologies are commercially available today, but the associated costs need to be lowered and the technology needs to be demonstrated at commercial scale.

2.2 Transportation of CO_2

CO_2 is transported predominantly via high-pressure pipeline networks. Ships, trucks and trains have also been used for CO_2 transport in early demonstration projects and in regions with inadequate storage. So far, studies on CCS have been focusing on developing capture and sequestration technologies rather than on transportation, which reflects the current perception that CO_2 capture probably represents the largest technological hurdle to implementing large-scale CCS, and that CO_2 transportation by pipelines does not present a significant barrier. This perception is no doubt reinforced by the large number of existing CO_2 pipelines in the world. In the United States, for example, there are 6,274 km of existing CO_2 pipelines [Dooley, et al, 2009]. Notwithstanding this perception, there are important unanswered policy issues related specifically to CO_2 pipelines which may require more attention, including regulatory, access, public acceptance, planning challenges for different regions, and cost [Liu and Gallagher, 2010]. The cost of onshore CO_2 pipeline transportation in China is estimated to be much lower than in developed countries. For a 20,000 t/d case, for example, the levelised cost of CO_2 transportation in China is about two-thirds of that in developed countries.

2.3 Storage of CO_2

CO_2 is stored by being injected into a geological formation. The three options for geological CO_2 storage are saline formations, depleted oil and gas reservoirs, and deep unminable coal seams [IEA, 2013]. Of the three, it is expected that saline formations will provide the opportunity to store the largest quantity of CO_2, followed by oil and gas reservoirs. A number of projects involving the injection of CO_2 into oil reservoirs have been conducted, primarily in the USA and Canada for enhanced oil recovery, and much of that has used natural rather than anthropogenic CO_2. In China, initial assessments [Dahowski et al, 2009] suggest that, theoretically, China has sufficient capacity in its deep saline formations to sequester over 3,000 Gt CO_2—more than 450 times China's total CO_2 emissions in 2005. 90% of China's large stationary CO_2 emissions sources are located within 100 miles of at least one identified storage formation; 85% have at least one storage option within just 50 miles.

3. Methodology and Assumptions

In order to conduct a comprehensive investigation on the financing requirements, opportunities and challenges to develop a large-scale CCS project in China, we combine the following research methodologies:

- First, we analyse the required on-grid tariff (eq. 1) or the cost of carbon abatement (chosen because they are straightforward to interpret) to finance a large scale CCS power plant. We then investigate the financial gap for a 1GW generic USCPC (ultra-supercritical pulverised coal-fired power plants) with post-combustion capture built in 2010. A cost cash flow model (including estimated tax) is developed for studying both the plant with and without CCS. The scenarios of financial leverage and fuel cost assumptions are compared in the study.
- Second, we investigate the potential sources of finance. The results of four stakeholder consultation studies from 2006 to 2010 are reviewed (Reiner and Liang, 2009). In 2009, the stakeholder study interviewed 16 financial stakeholders on the detailed investment requirements of CCS projects. Among the respondents were 9 stakeholders from large energy groups with experience in CCS. In the

stakeholder consultation in 2009, Internal Rate of return (IRR) was used as a hurdle rate to reflect an individual's risk perception of demonstrating CCS. In general, private investors would demand a higher return to compensate for the uncertainties of investing and operating CCS projects. Therefore, a higher required return on equity is applied for the hypothetical models for financing CCS projects.

- Finally, we demonstrate some hypothetical mix of financing options for implementing a large-scale CCS project in the near future.

The required on-grid tariff (ROT) is given by:

$$\mathrm{ROT}\ \left(\frac{\mathrm{US\$}}{\mathrm{MWh}}\right) = \frac{\sum_{t=1}^{n} \frac{\mathrm{CF_t}}{(1+\mathrm{R})^t}}{\sum_{t=1}^{n} \frac{\mathrm{E_t}}{(1+\mathrm{R})^t}} \qquad \text{(eq. 1)}$$

Where, R is the required return on equity; n is the effective life of the CCS power plant; CF_t is the annual cost cash flow at year t; E_t is the electricity generation at year t.

The annual cost cash flow at year t (CF_t) is given by

$$CF_t\,(US\$) = F_t + I_t + O_t \qquad (eq.\ 2)$$

Where, F_t is the financing cash flow at year t, incl. loan receivement; loan repayment and interest; I_t is the Investing cash flow at year t, incl. investment for base power plant, investment for CCS plant. O_t is the operating cash flow at year t, incl. fuel cost, nonfuel O&M, the cost for transportation, storage and monitoring of CO_2, the income from selling carbon credit, and estimated tax;

The cost of carbon avoidance or the required carbon price (RCP) is given by:

$$RCP\ \left(\frac{US\$}{tCO_2e}\right) = \frac{ROT_{cap} - ROT_{ref}}{EF_{ref} - EF_{cap}} \qquad (eq.\ 3)$$

Where, $\mathrm{ROT_{cap}}$ is the required on − grid tariff for financing the CCS power plant;
$\mathrm{ROT_{ref}}$ is the required on − grid tariff for financing the base power plant (i.e. without CCS);
$\mathrm{EF_{cap}}$ is the carbon emissions factor of the CCS power plant;
$\mathrm{EF_{ref}}$ is the carbon emissions factor of the base power plant (i.e. without CCS);
Note: the income of selling carbon credit is assumed to be zero when calculating RCP.

A majority of Chinese coal-fired powered power plants in planning or construction are supercritical or ultra-supercritical. We therefore assume that the underlying base plant is a 1 GW ultra-supercritical power plant with 41.8% net supply efficiency before adding CO_2 capture. The plant performance calculation is based on the IEA GHG [2006] PH4/33 study. The cost data is taken from CCS power plants cost assumptions by Liang et al [2010] and the current market information, base on 2010 constant price level. The total cost of fixed capital for the base plant is US$634 million which is equal to US$626/kW or CNY4069/kW. The non-fuel O&M cost for the base plant is US$32.5m and the additional O&M cost for the CO_2 capture plant is US$19.2m The capital cost for capture facilities is assumed to be US$155 million, 25% higher than the original capital. Under the baseline scenario, the plant is assumed to run at an 80% load factor. Equivalent availability factor (EAF) could be a proxy of operating risk of a CO_2 capture power plant. Le Moullec and Kanniche [2011] from EDF R&D estimated that the addition of a capture plant would decrease the availability factor by 1.4% due to an increased operational risk of forced outage. The impact of adding CO_2 capture plant on the availability factor is not significant, and therefore we are not considering this issue in the financial model.

The cost of coal in the financial model is $4/GJ (eqv. US$117/tonne or CNY762 per tonne 7000 kCal coal). Because the current 12-month average coal price is significantly above the five-year average, another scenario analysis is performed assuming the coal price at $5/GJ. Because a domestic carbon market does not yet exist in China, most stakeholders interviewed don't currently take into account either a future cost of carbon emissions, or the potential benefits of finance through the CDM. Consequently the financial model baseline scenario assumes the market price of CO_2 emissions eventually disappears. The required on-grid tariffs assessed in the study takes into account tax, which is estimated with reference to cost cash flow, tax code [SAT, 2011], required on-grid tariff, and the required return. The cost of transportation is assumed to be US$6/tCOe and the cost of storage is assumed at US$9/tCO2e based on the amount of captured CO_2. The study for the NZEC project [Reiner and Liang, 2009] indicated that stakeholders' required return (hurdle rate) for a CCS project ranges from 5% to 20%, while private stakeholders would require a higher return than public stakeholders. The baseline scenario therefore assumes the real required rate of return for the base plant is 10%, but rises to 12% for an unleveraged CCS project, or 15% for a CCS project with leverage (i.e. 15% required return-on-equity with 75% debt financing at 6% fix interest). In addition, we simulated the required on-grid tariff at different required rates of return (or discount rates). The free cash flow of the project in each operating year is assumed to be fully distributed to equity investors. The baseline scenario of the generic USCPC with CCS is shown in Table 1 below.

Table 1 Economic and Engineering Performance Assumptions of a Generic Ultra-supercritical Power Plant with Carbon Capture and Storage in China

Parameter	Data	Note
Plant Type	USCPC	
Base Real Required Return without Financial Leverage (Discount Rate)	12%	(10% applied for base plant)
Capacity before retrofit	1000	MW
Net Supply Efficiency (LHV) without CCS	41.8%	42.7% at full load
Capacity with 90% capture	799.04	MW
Net Supply Efficiency (LHV) with CCS	34.1%	
Lifetime Degrading factor	1.00%	
Fixed Capital Base Plant	634	M US$ ($6m working cap.)
Fixed Capital for Capture	155	M US$ ($5m working cap.)
Load factor	80%	
Coal Price	4	US$/GJ
On-grid Electricity Tariff	vary	for tax estimation only
CO_2 Emissions Price	0	$/tonne$CO_{2e}$
Emissions factor base	758.7	gram CO_2/kWh
Emissions factor with capture	97.7	gram CO_2/kWh
CO_2 Captured	852.2	gram CO_2/kWh
CO_2 avoided	660.7	gram CO_2/kWh

Full Load Coal Feed Rate	8700	GJ/hr
Non-fuel O&M	32.6	m
Fixed O&M (Non-fuel)	51.8	m
Decommissioning Cost	Equal to Salvage Value	
Corporate Tax	25%	(other taxes follow State Administration of Taxation) rule)
Depreciation	20	Years (straight-line)
Transport, storage and monitoring cost	15	$/tonne

4. Required Investment to Deploy CCS in China

The required on-grid electricity tariff to finance a CCS power plant in China is US$85.7/MWh (assuming a 12% required return), which is US$35.7 or 71% higher than the required tariff for the base plant (US$50/MWh, 10% required return), as shown in Figure 1. The required tariff is also very sensitive to fuel cost—when the assumed coal price rises from $4/GJ to $5/GJ in the baseline scenario, the required on-grid tariff significantly surges to US$96.6/MWh, US$37.9 or 65% higher than the required breakeven tariff for the base plant (US$58.7/MWh). The cost of carbon avoidance is US$50.9/tonneCO2e at the baseline scenario (US$4/GJ for coal, 12% required return), and the cost would rise to US$54.2/tonneCO2e if the lifetime coal price is assumed to be US$5/GJ (Figure 2). The required carbon price or tariff support is very sensitive to the required rate of return assumption. As illustrated in Figure 2, each 1% increase in required return would result in approximately US$0.9 growth in carbon avoidance cost.

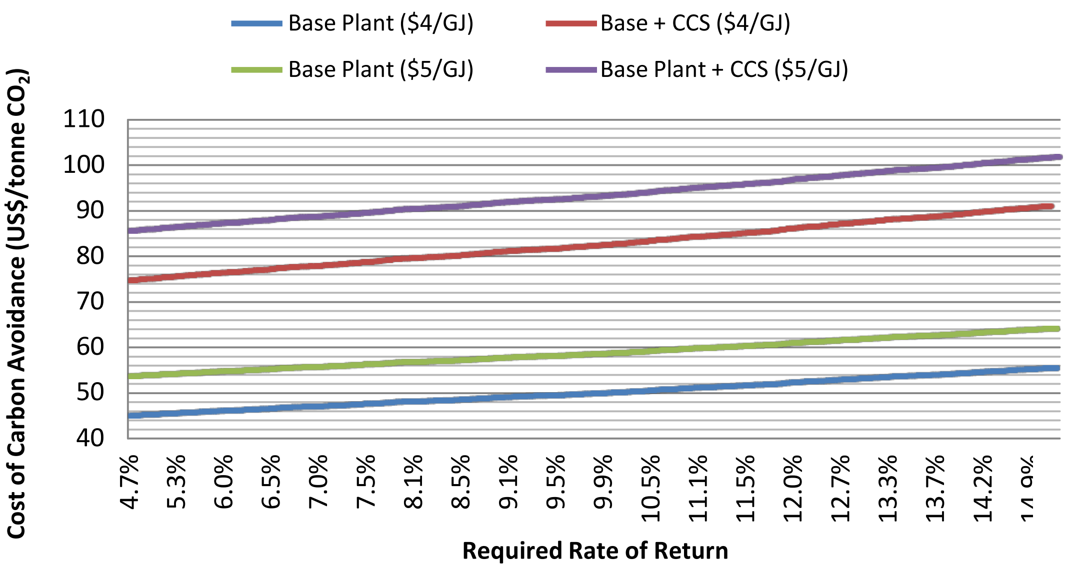

Figure 1. Required On-grid Tariff to Finance CCS at a USCPC Power Plant in China under Varied Required Returns Assumptions (Coal Price is $4/GJ and 5$/GJ, no carbon emissions cost and no financial leverage)

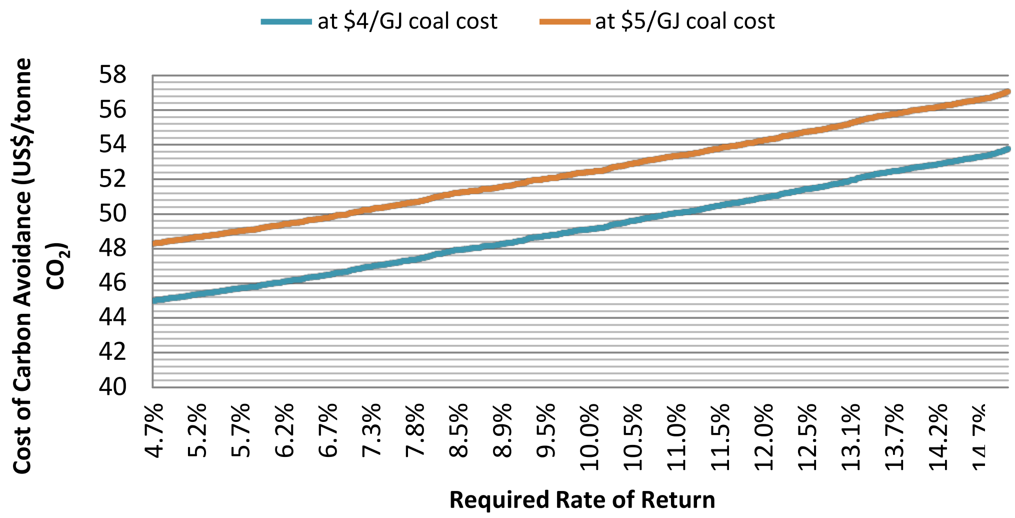

Figure 2. Estimated Cost of Carbon Avoidance (or required price of carbon) to finance CCS at a USCPC Power Plant in China under Varied Required Return Assumptions (Coal Price is $4/GJ and 5$/GJ, no carbon emissions cost and no financial leverage)

In the absence of any financial leverage, the extra cost of US$35.7/MWh (illustrated as the required on-grid tariff) for financing CCS is caused by a variety of factors (as illustrated in Figure 3). More than half of the extra cost (55%) is consumed by the capture process, while 36% is spent directly on CO_2 transportation, storage and monitoring. Specifically, in relation to the cost of capture, the most substantial proportion (24%) is spent on the extra fuel alone compared to capital (15%) and non-fuel O&M (13%). To compensate for the extra risk perceived by investors, a 2% higher required return is assumed for CCS compared to the base plant, and this results in a US$3.2 (or 9%) higher tariff requirement for CCS.

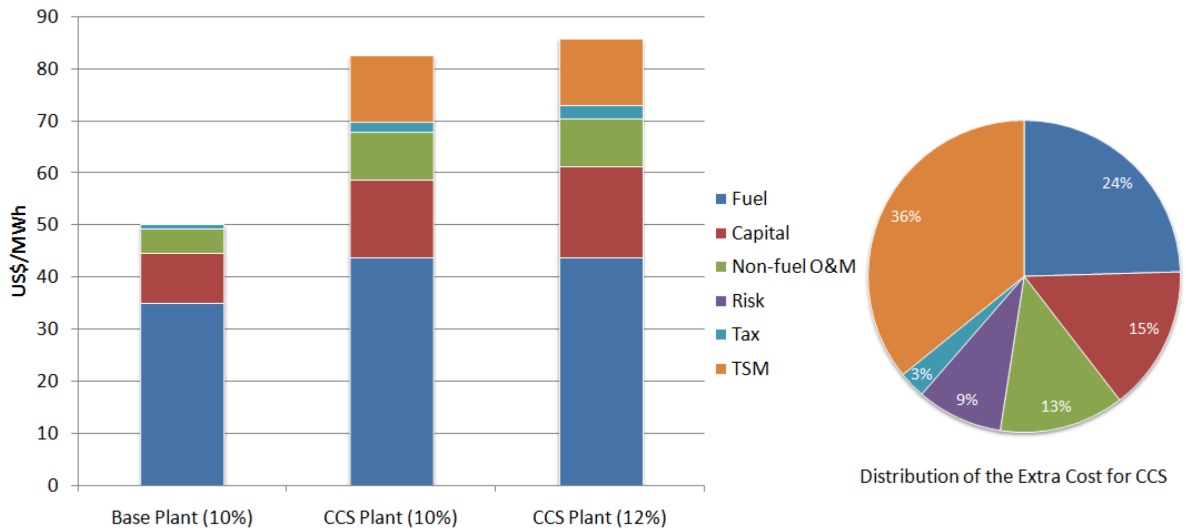

Figure 3. Structure of On-grid Tariffs for a CCS Power Plant in China (at 10% and 12% required rate of return and $4/GJ coal cost assumptions and no carbon market)

Financing conventional thermal power plants in China would normally include 70% to 80% debt finance. If a 75% debt finance scheme is realised for the CCS project, the overall required on-grid tariffs would be significantly reduced to US$77.5/MWh at 12% required return on equity (ROE) US$78.5/MWh at 15% required ROE, US$31.8/MWh higher than the base plant without CCS (US$46.7/MWh at 10% required ROE), as shown in Figure 4. This beneficial effect is due to the cost of debt financing (6% before tax) being much lower than the required return. In this scenario, the pressure to generate a higher return for equity investment in CCS would be significantly reduced, as most of the equity is replaced with debt capital, and only the remaining equity capital requires the additional 4% return provided by the incremental tariff. In these circumstances, investors might be able to tolerate a higher level of risk. The cost of transportation, storage and monitoring and fuel cost together contributes more than two thirds of the tariff premium. The cost of CO_2 avoidance per tonne would be reduced to US$46.3/tonneCO2e (at a 12% required ROE for CCS) or US$48.1/tonneCO2e (at a 15% required ROE for CCS). However, whether this assumed favourable scenario could be realised will largely depend on the risk appetite of lending institutions (e.g. commercial banks, development banks, shareholders).

Because Reiner and Liang [2009] found financial stakeholders in China have divergent perceptions towards an acceptable leverage ratio in financing a CCS project, we simulate the extra required on-grid tariffs using different financial leverage ratios. As illustrated in Figure 5, investing in CCS would add about US$36/MWh to the required on-grid tariff for the base plant in a 50% debt financing scenario (i.e. debt/equity = 1). If the assumed coal price rises from US$1/GJ to US$5/GJ, the required on-grid tariff would be increased by approximately US$11/GJ in parallel.

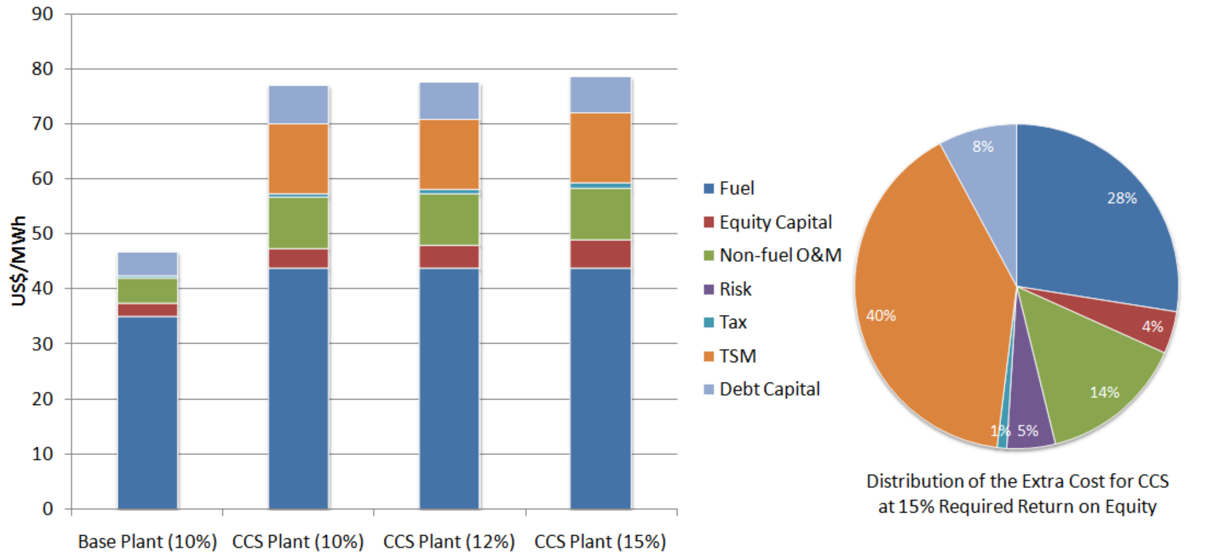

Figure 4. Structure of Required on-grid Tariffs for Financing a CCS Power Plant in China with 75% debt financing (with 6% fixed rate loan; 10%, 12% 15% required rate of return on equity and $4/GJ coal cost assumptions, and no carbon market)

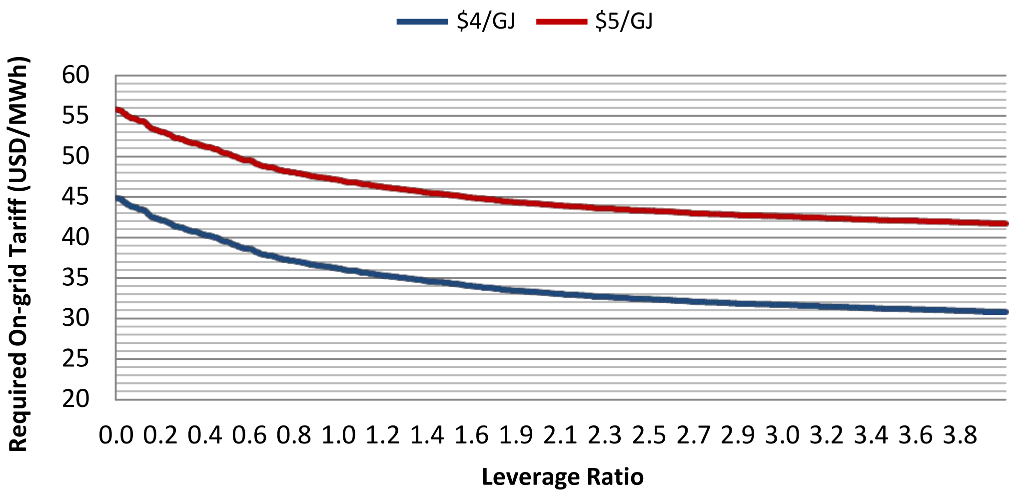

Figure 5. Additional Required On-grid Tarriffs for Financing CCS in a Generic USCPC in China versus Financial Leverage Ratios (Debt/Equity) at 15% required return on equity for CCS power plant and 10% required return on equity for the benchmark base power plant without CCS

5. Discussion

Developing a large-scale CCS power plant has a high marginal cost (71% higher without leverage) compared to a conventional power plant, but currently there is neither a premium tariff scheme nor a carbon support scheme to bridge the financial gap in China. Besides conventional equity investment from shareholders and loans from commercial banks, developing early large-scale commercial projects in China therefore may require a combination of financial strategies to improve the financial prospect, such as (1) CDM, (2) support by foreign governments, (3) support by Chinese national and/or regional governments, (4) grants and loans from domestic and/or multilateral development banks, (5) equity investment and loans from venture capital, and (6) special funds for supporting CCS industrial project developments.

Liang et al (2011) found that more than two thirds of the 113 stakeholders in their NZEC study believed that CCS is a necessary or very necessary technology to achieve a deep cut of carbon emissions in China, and that there were no significant regulatory and legal barriers to develop CCS projects in China. However, a study of financial stakeholders in that same NZEC survey found very different opinions on the required ROE and leverage ratios (Reiner and Liang 2012). In particular,

- 7 respondents from development banks and state-owned electric companies suggested a required rate of return lower than 10%, and some of them considered CCS to be a non-commercial (or social responsibility) investment.
- However, 9 respondents from commercial banks, oil companies and private power companies demanded much higher rates (i.e. 12% to 20%) to reflect the risk premium of demonstrating CCS in contrast with developing a conventional coal-fired power plant.
- Half of stakeholders considered that the debt-to-equity ratio in financing carbon capture facilities

should be low (i.e. less than 50% debt in total capital).

Building on the findings, potential mechanisms for co-financing a CCS project in China are outlined and discussed as below.

5.1 Private Financing Mechanisms

In this paper, private financing is defined as capital provided by commercial players, including equity investment provided by energy companies, venture capital, loans provided by energy companies, commercial banks. A higher investment return is obviously the most important investment driver in the private sector. Drivers for developing CCS projects may also link with corporate technology and environment strategies [Bowen, 2011], such as the early-mover advantages and social responsibility.

Energy Companies

To understand the drivers behind the five existing pilot projects in China, the 2009 NZEC stakeholder consultation interviewed key project developers from TPRI (thermal power research institute), China Shenhua Group and Yuanda Environment [Reiner and Liang, 2009]. They found the primary driver behind these projects is the corporate technology strategy (i.e. potential large-scale deployment of CCS). Most large Chinese energy companies have vertically integrated structures, which normally includes a R&D and engineering design institute. The interests of these institutes may influence the corporate strategy of the energy giants in China.

On the financial side, both post-combustion capture units (3,000t/a in Beijing and 120,000t/a in Shanghai) refine the captured CO_2 for the industrial grade and food grade CO_2 markets. Furthermore, the 10,000 t/a capture facilities developed by China Yuanda Environment (a subsidiary of China Power Investment Corp) at the Chongqing Shuanghuai Power Plant produces CO_2 for the industrial grade CO_2 market. However, the marginal cost of CO_2 capture is significantly higher than in other industrial processes such as hydrogen production in refinery plants, ammonia production plants, and natural CO_2 sources, so these post-combustion capture units hardly provide a sound ROE in the absence of other incentives. China Shenhua Group has constructed the first integrated CCS pilot project in China, which captures 100,000 tonnes of CO_2 per annum from the coal-to-liquid process and stores the CO_2 in a saline formation. Phase I of the GreenGen project only captures a small proportion of CO_2 for testing, so capture has little financial implication. All of the pilot projects are owned by large state-own enterprises (SOEs), and each SOE has more than US$10 billion in total assets. SOEs may not focus on maximising short-term economic return for shareholders, and therefore be more likely to undertake CCS pilot and demonstration projects (Dewenter and Malatesta 2001). Therefore, the impact of developing a CCS pilot project on their cash flows is negligible. However, none of these companies plan to scale up CO_2 capture to a million-tonne level in the short-term.

Commercial Banks

When energy company officials and commercial bankers were asked about the desired debt/equity mix for capture facilities in a power plant, they responded with an average split of 41% debt / 59% equity.

Furthermore, energy companies and commercial banks were reluctant to invest in large-scale CCS projects where less than 10% of the equity capital is provided by power companies. Commercial bank stakeholders didn't anticipate being major players in providing loans, and, on average, they suggested that 25% or less of the debt financing would be provided by them. Not surprisingly, they also stated they would require their claims be given higher priority in the event of default. Two commercial bankers suggested that financing for early CCS projects should be provided by development banks. Aside from commercial loans, a number of financial stakeholders perceived that vendor financing (e.g. supplier credits) might be possible, because large capture equipment manufacturers (OEMs) could be major beneficiaries of CCS demonstration projects.

Venture Capital and Smaller Investors

Venture capital (VC) could be another source of finance to support the equity investment in CCS [Burtis, 2010]. VC funds would normally provide US$1 to US$20 million for start-up companies in exchange for a substantial equity share. Although VC has supported CCS initiatives in US, Canada, EU and UK for various technologies, to date, VC has not been used to support CCS ventures in China [Burtis, 2010]. In a CCS project finance context, a typical commercial CCS power plant in China could require some US$ 800 million in capital investment (as shown in Table 1) and the high investment requirement may imply that any VC will be able to contribute a relatively small proportion of this. Perhaps more importantly, it is not sensible for a VC to invest in the base power plant without a clear exit strategy.

However, if the capital investment for the capture facilities is made by an entity separate from that for the base power plant, a VC could potentially only need to contribute some 20% of the total capital required ($155m shown in Table 1). As a result, there would be a lower capital-cost barrier to entry for developing CCS projects. Liang et al (2010) indicated the possibility of separating the financing of CO_2 capture assets from the base plant for financing capture ready. We could apply the concept for financing a CCS project: a CO_2 capture operating company would sign steam purchase and flue gas cleaning agreements with the power generation companies. The CO_2 capture company, if not also operating the transportation and storage businesses, could sell the captured CO_2 to oil companies for EOR or pay for transportation, storage and monitoring and sell the carbon credits through the emissions trading mechanism (e.g. CDM). Power generation companies may want to hold a minority share of the CO_2 capture operator in order to maintain the synergy of operating both base plant and capture plants. Splitting the CO_2 capture operating company from that for the base power plant would provide five distinct advantages: (1) less capital would be required in financing a CCS plants which may provide higher return for CCS investors; (2) the base plant could be financed using a conventional financing model; (3) power plant investors may find it easier to agree upon the business model for CCS, since some Chinese power plant operators have experience in selling steam as an alternative product of electricity generation but are less familiar with emissions reduction credits; (4) the CO_2 capture entity could leverage the return from technology learning and development (e.g. process optimisation, testing of solvents); (5) public financing could focus on supporting the incremental cost of carbon capture and storage.

5.2 Public Financing Mechanisms

Because private finance may not be able to fully support large demonstration of CCS projects, public support would play an important role in developing and financing early and large-scale CCS projects. The NZEC study outlines six potential sources of public finance for early CCS demonstration projects: the Chinese national government, Chinese local governments, foreign governments, domestic development banks, multilateral development banks, and special energy funds (incl. energy charities and foundation).

Chinese National Government

National Development and Reform Commission (NDRC), Ministry of Environment Protection (MOEP) and Ministry of Science and Technology (MOST) are the key national government ministries in regulating and financing CCS. Even though CCS has been recognised as an important technology to decarbonise the Chinese energy sector, NDRC (in charge of formulating national energy policy and authorising construction of large thermal power plants) has been slow to prioritise CCS because the significant energy penalty may hinder the energy conservation target (i.e. the GDP energy intensity target). Recently, however, NDRC issued guidance entitled "Promoting Carbon Capture, Utilisation and Storage Pilot and Demonstration", which focuses on six areas: (i) developing pilot and demonstration projects along the CCUS technology chain; (ii) developing integrated CCUS demonstration projects; (iii) exploring and establishing financial incentive mechanisms; (iv) strengthening strategy and planning for CCUS development; (v) promoting CCUS standards and regulation; and (vi) strengthening capacity building and international collaboration. Though still lacking in detail in terms of how this will be implemented, this offers the first clear signal of support for CCS, though with the emphasis placed specifically on utilization of CO_2, such as in EOR.

Reducing CO_2 emissions from coal-fired power plants are not yet a priority in MOEP, though it may play an important role in formulating emission performance standards and monitoring implementation of CCS. Long prior to the NDRC guidance, CCS was recognised as the key technology in the Chinese national medium and long-term programme outline for Science and Technology (2006~2020) formulated by the Ministry of Science and Technology [SCC, 2006]. Therefore, it may be possible to apply for scientific support grants for a large-scale early CCS demonstration project at a funding level of, say, less than US$25 million (e.g. establishing a national laboratory) but may be challenging to obtain substantial financial support (e.g. direct subsidy) through the NDRC at least until the 2013 guidance is more fully implemented.

Provincial and Municipal Governments

Local governments may play a more important role than the national government in financing CCS projects. Ten provinces and cities in China have been recognised by NDRC to pilot low carbon zones which include Guangdong and Shenzhen city [NDRC, 2010]. According to an anonymous official from the NDRC in Guangdong, it is now almost impossible to authorise any new unabated large coal power or chemical project. On the other hand, some developed areas have significant budgets for infrastructure investment and scientific development. For example, the Shenzhen municipal government, within its US$17 billion equivalent budget for 2010, allocated approximately US$1.54 billion for scientific development and US$3.17 billion for infrastructure investment [SZTJ, 2011].

A government interested in supporting CCS could claim that a large CCS demonstration plant would create significant job opportunities across the value chain and demonstrate the government's effort to implement a low carbon zone. We estimate that a local government (provincial or municipal) could provide up to US$50 million grant to support a large-scale CCS coal-fired power plant in the region. Even barring direct investment, a large-scale CCS project would likely be eligible for favourable tax schemes through local governments.

Foreign Governments

From a climate policy perspective, a number of countries have recognised the importance of developing CCS in China and prioritise CCS in bilateral and multi-lateral scientific and industrial project collaborations. There are a number of international CCS initiatives that may potentially provide support for a full-scale CCS project, drawing on earlier rounds of cooperation through the EU-UK-China NZEC project, Global Carbon Capture and Storage Institute, and the Australia-China joint study for a commercial scale CCS project. These initiatives may provide a limited but still significant source of funding for a large-scale CCS demonstration in China. The disadvantage is the possible long lead times due to the involvement of international actors. Interestingly, in the NZEC stakeholder consultation, financial stakeholders, on average, suggested 40% of initial equity investment should be subsided by foreign governments (Reiner and Liang 2012).

Chinese Development Banks

China Development Bank (CDB), the primary development bank in China, has not yet provided support for CCS. Interviews with senior CDB project appraisal officials in late 2010 found they were gravely concerned about the energy penalty of carbon capture and disagreed with the logic of burning much more coal to reduce carbon emissions. Therefore, at least in the short term, financial support from Chinese development banks seems unlikely unless the project benefits from strong political support.

Multilateral development banks

Multilateral development banks could be a major source of finance for developing early CCS projects in China. For example, the Asian Development Bank (ADB) has already provided a 26-year loan of US$135 million (6-year grace period, at LIBOR + 0.6%) to support 32% of the capital investment for GreenGen phase I (ADB, 2010). In addition, they provided a US$5 million grant for phase 1 and US$1.2 million in technical assistance support for phase 2 and 3 of the GreenGen IGCC project in Tianjin (Bhargava, 2010). However, the terms of the ADB loan requires GreenGen to obtain a 'reasonable electricity tariff' (i.e. a premium electricity tariff), maintain 1.2 times coverage ratio to repay the debt and gradually improve the debt to equity ratio. The terms of the loan imply that strong support by the national and/or local government(s) is an inevitable condition in order to obtain loans from multilateral banks. Raising long-term loans from foreign banks would impose a lower burden if, as many expect, the Chinese currency Yuan appreciates over the long term (Xu, 2009; Das, 2009).

A number of multilateral funding bodies exist which could support the development of carbon capture and storage projects, such as the Global CCS Institute (funded largely by the Australian government), the World Bank CCS Capacity Building Fund, the ADB CCS Fund and UNFCCC Strategic Climate Fund [Hart and Liu, 2010]. Most of these programmes would, however, only support a small fraction of the capital investment needed. More ambitious would be a multilateral scheme that would support the deployment of CCS [Liu and Liang, 2011].

Clean Development Mechanism (CDM)

The CDM is the Kyoto Protocol's flexible mechanism designed to allow projects in non-Annex I countries (i.e., most developing countries) that reduce greenhouse gas emissions to generate certified emissions reduction units (CERs). As described in the Introduction, CCS was formally recognised as a potential emission reduction measure in the CDM at COP16 in Cancun in 2010 (Decision 7/CMP.6) and the modalities and procedures for including CCS projects in the CDM were endorsed at COP17 in Durban in 2011 (FCCC/KP/CMP/2011/L.4). To successfully register any CDM project, a project must demonstrate 'additionality', i.e., that emissions reductions are additional to what would have occurred otherwise. Permanently storing CO_2 in a depleted oil field or saline formation provides no benefit other than reducing carbon emissions, thus it should be relatively straightforward to claim credit under the CDM. For EOR projects, because CO_2 injected into an oil field may re-emerge at the production well, incremental crude oil or gas extracted may produce more CO_2 emissions and there is an economic incentive for EOR independent of climate change concerns, it would be more difficult to demonstrate additionality.

5.3 Other CCS Financing Options

Enhanced Oil Recovery (EOR)

The captured CO_2 could be injected into nearly depleted oil fields to increase oil production. More than half of the crude oil consumed in China has to be imported and that figure is steadily increasing, so utilising CO_2 captured from coal-fired power plants to increase domestic production not only provides economic benefit but also addresses Chinese concerns over oil dependency since China has the advantage (from an EOR perspective) of having a number of older onshore oilfields suitable for EOR. In theory, when the crude oil price is above $100/bbl, the economic benefit of EOR may justify the cost of CO_2 capture from a coal-fired power plant and transportation. However, EOR cannot reliably be the only mechanism for financing a large-scale CCS power plant, because (1) the demand for CO_2 for EOR will vary over time but the lifetime of a coal-fired power plant is 30 years or longer and will supply CO_2 at a roughly constant rate; and (2) the marginal cost of capturing CO_2 could be much lower for processes such as ammonia, cement, or hydrogen production, so oil companies may not want to pay a premium price for higher cost CO_2 from coal-fired power plants. A long-term contract therefore would need to be signed between CO_2 producers (power plants) and consumers (oil companies) to secure the price and demand, which does not seem a sustainable solution for financing CCS except in very specific cases.

Premium Electricity Tariff

The Chinese on-grid electricity tariff is set according to the principle of 'cost plus reasonable profit'. The NDRC formulates the benchmark electricity price for each province, and the energy department of each province has flexibility in determining the tariff of every thermal power plant within its territory. For example, the current on-grid tariff for gas power plants in Guangdong is CNY530/MWh (eqv. US$82/MWh) and it is likely to rise significantly when a low cost Australian LNG contract expires in the near future. Many of these gas power plants are operating as base load. Because coal-fired CCS power plants can also significantly reduce the conventional pollutants, providing a gas or nuclear on-grid tariff to finance a CCS power plant is a possible approach. The cost of developing CCS power plants in Guangdong is likely to be higher than the national average, but may still be well below $100/MWh. In comparison, the on-grid tariff of nuclear power is approximately CNY450/MWh (eqv. US$73/MWh) and the actual price of purchasing nuclear is much higher for power grids if the lower flexibility of nuclear electricity is taken into account. Coal-fired power plants with CCS could be viewed as an alternative to gas and nuclear power plants and could apply for a premium electricity tariff in some developed areas in China (e.g. the Pearl River Delta and Hong Kong).

Plant Operational and Investment Flexibilities

Building a CCS power plant with pre-designed flexibilities may enhance the value of the investment, or in other words, reduce the on-grid tariff needed to finance the project. A CCS power plant can be designed to be flexible in relation to operations and investment. Concerning operations, in theory, the energy penalty for capturing CO_2 could be used as peak-load generation capacity. Chalmers et al [2009] suggest two options for increasing the value of a post-combustion capture power plant: CO_2 capture by-pass and solvent storage. From a purely economic perspective, when the short-run marginal cost (SRMC) of capturing CO_2 is higher than the carbon price or when the electricity tariff provides much greater benefit than capturing CO_2 (e.g. at peak times), a plant can by-pass CO_2 capture. Alternatively, when the electricity tariff increases to a certain level, CO_2-rich solvent could be temporarily stored and the energy intensive regeneration process could be deferred until the electricity price is sufficiently reduced. 'Rich' solvent storage would be the preferred means of flexibility from a climate policy perspective because CO_2 from the power plant would still be removed from the flue gas and would not be emitted to the atmosphere. However, the economics of operational flexibilities in CCS power plants requires further analysis of the capital investment required and impact of potential reform of Chinese electricity tariffs. In relation to investment flexibility, a power plant may increase its value by investing from the outset in upgradability, because the cost of CO_2 separation technology (e.g. the solvent) may be reduced significantly over the course of a plant's lifetime when the learning process takes place with the growth of global deployment capacity [Riahi et al, 2003]. Upgradability would allow a plant to reduce the cost of CO_2 capture by switching to a better and/or cheaper separation technology. Lucquiaud et al [2011] conducted an upgradability study on a generic CCS power plant and found the upgradability option could significantly increase the value of power plant investment and reduce the average lifetime levelised cost of electricity.

5.4 Financing Strategies

In summary, a portfolio of financing options could possibly be applied to develop large-scale CCS projects in China. To understand how these options might be combined in the near future, we estimate the required on-grid tariff under five different hypothetical scenarios (as illustrated in Table 2). Scenarios A to E assume the hypothetical project is funded with 50% equity and 50% debt under different combinations of financing support, although all scenarios involve funding from multiple sources.

Scenario A assumes a low level of support by the national government and local governments (only 5% of the total), 45% of the capital is provided by the operating company with 25% of capital from commercial loans and 25% from concessionary loans. An on-grid tariff of US$74.7/MWh would be required to justify the initial investment. Moderate public financial support (10% of original capital) demonstrated in scenario B could reduce the required on-grid tariff significantly but it is largely offset by higher required return if venture capital investment is introduced to support to investment. As illustrated in scenario C, a mix of grant support from national, local, foreign governments and development banks (30% of capital) could reduce the required on-grid tariff to US$65.1/MWh. The tax exemption has minor impact but can further reduce the required tariff by US$0.5/MWh. If CO_2 captured from the CCS project can be stored underground for enhanced oil recovery (EOR) and sell at US$20/t$CO_2$ captured, the required tariff would drop to US$58.8 level, much lower than the cost of baseload gas power plants, and near the tariff of coal-fired power plants without capture and the full levelised cost of nuclear power plants.

The required return on equity is assumed to be higher when the financial leverage ratio increases (i.e. debt to equity ratio) and vice versa. However, because the relatively lower cost in debt especially concessionary loan, the required on-grid tariff could be significantly reduced with a higher debt-to-equity ratio. For scenario with minor public support, a 100% equity financing will require US$80.3/MWh tariff level, a 75% debt ratio will lowers the required tariff to US$72.2/MWh. The impacts of financial leverage on scenario C (strong public support) and scenario E (EOR) are minor, (i.e. less than US$0.5/MWh). Perhaps, the most important of debt financing is less public grant support required for the project, while a large proportion of public support could be repaid through the project's life as a loan. This could reduce the public financing pressure while at the same time allow a higher equity return for the CCS operating company.

Table 2. Hypothetical scenarios for financing a large-scale CCS demonstration project in China through 50% equity and 50% debt financing

Options	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
	Minor public support	Venture capital & moderate public support	Strong public support	Strong public support & Tax Exempt	Strong public support & EOR
Equity					
Operating company (required return)	45% (18%)	30% (16%)	20% (14%)	20% (14%)	20% (14%)
National government	2.5% (grant)	2.5% (grant)	5% (grant)	5% (grant)	5% (grant)
Local governments	2.5% (grant)	2.5% (grant)	5% (grant)	5% (grant)	5% (grant)
Foreign governments	0	0	10% (grant)	10% (grant)	10% (grant)
Venture capital (required return)	0	10% (27.5%)	0	0	0
Chinese or Multilateral Development banks	0	2.5% (grant)	5% (grant)	5% (grant)	5% (grant)
CCS Special Funds	0	2.5% (grant)	5% (grant)	5% (grant)	5% (grant)
Debt					
Commercial loan (interest)	25% (8%)	0	0	0	0
Venture capital (interest)	0	25% (10%)	0	0	0
Concessionary Loans (interest)	25% (4%)	25% (4%)	50% (4%)	50% (4%)	50% (4%)
Value Enhancement Strategies					
EOR	n/a	n/a	n/a	n/a	\$20/tCO2e captured
Carbon Market (e.g. CDM) (per tonne CO2 avoided)	\$12	\$12	\$12	\$12	n/a
Corporate Tax Scheme	15%	15%	15%	Exempt (0%)	15%
Results					
Required On-grid Tariff (US\$/MWh)	**74.7**	**70.3**	**65.1**	**64.7**	**58.8**

Note:
1. Operational and investment flexibilities are not considered in the evaluation;
2. Revenue in tax estimation is based on the electricity price is at the levelised cost of electricity, therefore it could be underestimated;
3. The reference levelised cost of electricity is \$85.7/MWh assuming a 12% discount rate; and the reference on-grid tariff for coal-fired power plants without CCS is \$50/MWh using a 10% discount rate.

6. Conclusions

A substantial proportion of the world's new coal-fired power plants from now to 2030 will be built in China (as has been the case for the past 15 years), and CCS is the only solution to decarbonise these power plants at large-scale. However, as yet, there are few strong incentives or national policies to support the commercial demonstration and deployment of CCS in China. We review the status of CCS technologies and analyse possible financial models and strategies to develop large-scale integrated CO_2 capture and storage projects using only existing financial resources and incentive structures.

Without any debt financing or other support mechanisms, developing CCS in a generic USCPC power plant requires either an on-grid tariff of US$86/MWh or a carbon price of US$51/tonne$CO_{2,eq}$. If the required on-grid tariff could be reduced to below US$60/MWh, it would be economically viable to bring CCS into commercial operation. More than half of the extra cost of CCS comes from the capture process, while a third is spent on CO_2 transportation, storage and monitoring. Because capital costs are much lower in China compared with OECD countries, the cost of capture in China is very sensitive to fuel cost assumptions.

It will not be feasible to rely on any one single measure to finance a large-scale CCS project in China in the short term because CCS is not yet prioritised by the national government. Building on past stakeholder consultations, we examined a number of possible options for financing CCS in China. Aside from corporate equity investment and commercial loans, the Chinese national government, local governments, foreign governments, multilateral banks, venture capital, and CCS special funds could each provide different levels of support for demonstrating CCS projects. In addition, the economics of a CCS power plant could be enhanced through a range of mechanisms including EOR, domestic or international carbon markets, and a premium electricity tariff scheme. Based on several hypothetical financing scenarios, we found the required on-grid tariff could be lower than the current tariff levels of nuclear and natural gas power plants. EOR, though not a long-term option, can significantly improve the economics of a CCS power plant in China. On the other hand, if a global (or Chinese!) carbon market price reaches US$25/tCO2e, a CCS project with limited support mechanisms would reduce the on-grid tariff to US$58.8/MWh.

The economics of upgradability and operational flexibilities has not been investigated and may offer significant value enhancement opportunities. It is also worth investigating whether it is possible to separate the CO_2 capture investment and financing from that for base power plants which could ease the capital requirement for carbon capture and allow public financing to focus on additionality. Separating capture facilities from base plant may be easiest for post-combustion facilities since virtually all coal-fired generation, whether in China or elsewhere, is pulverised coal. For other configurations such as gasification (IGCC) or oxyfuel, it may be difficult to separate base plant and capture facilities, since the economics of IGCC may only be viable because higher base plant costs are offset by lower capture costs, relative to pulverised coal plants.

At some point, CCS may become a standard in coal-fired power plants whereby CCS is required in new build power plants, while some existing plants need to be retrofitted; Gibbins and Chalmers (2008), for example suggest this might happen globally around 2025. In China, over 50GW of new coal-fired generation has been built each year for the past decade [CEC, 2011], so a large number of existing coal-fired power plants will still have many years of remaining effective life in 2030.

The study identifies a number of policy recommendations for Chinese policy-makers.

- Although CCS is viewed as a medium- to long- term low carbon option for China, there are insufficient domestic incentives for CCS, since significant lead times are likely required to build capacity and develop workable business models. One possibility for developing a CCS demonstration programme for the first large-scale integrated CCS projects in China would be to consolidate various strands of financial support from foreign governments, multilateral institutions and domestic sources. On other hand, the Chinese government may consider providing at least moderate support for CCS, for example, by imposing a modest carbon floor price.
- The labour cost of building CCS power plants is much lower than in developed countries (GCCSI, 2011). Thus, even without a dedicated subsidy, the overall levelised cost of electricity of coal-fired power plants with CCS may still be competitive compared to unabated gas, nuclear and onshore wind power plants. In addition, provincial and municipal governments may provide financial support for developing a large-scale CCS project locally to generate other social benefits (e.g. R&D capacity, employment, supply chain).
- To reduce the upfront capital burden of financing a CCS project, policymakers should consider CO_2 capture investment as a separate entity independent of the base power plant. by the public sector.
- Other value enhancement strategies, such as enhanced oil recovery (EOR) and flexibility in plant design should be encouraged in demonstrating the first large-scale integrated CCS projects in China.

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References

ADB (Asian Development Bank), 2010. Loan Agreement (Tianjin Integrated Gasification Combined Cycle Power Plant Project). http://www.adb.org/projects/documents/loan-agreement-tianjin-integrated-gasification-combined-cycle-power-plant-project (last accessed on 10/July/13).

Almendra, F., West, L., Li, Z., Forbes, S., 2011. "CCS Demonstration in Developing Countries: Priorities for a Financing Mechanism for Carbon Dioxide Capture and Storage". WRI Working Paper. World Resources Institute, Washington DC. www.wri.org/publication/ccs-demonstration-in-developing-countries (last accessed on 10/July/13).

Bhargava, A., 2010. Promoting CCS Demonstration Project in Developing Country. ADB Approach and Initial Activities. http://cctech.or.kr/common/download.asp?idx_no=201 (last accessed on 10/July/13)

Bowen, F., 2011. Carbon capture and storage as a corporate technology strategy challenge. Energy 39(5), 2256-2264.

Burtis, P., 2010. Carbon capture and storage: a venture capital perspective. Amadeus Capital Partners and Imperial College London. http://www3.imperial.ac.uk/pls/portallive/docs/1/50161696.PDF (last accessed on 12/April/2011).

CEC (China Electricity Council), 2011. Analysis and Forecast of National Electricity Supply & Demand and Economic Situation: 2010-2011.

Chalmers, H., Leach, M., Lucquiaud, M., Gibbins, J., 2009. Valuing Flexible Operation of Power Plants with CO_2 Capture. Energy Procedia 1, 4289-4296.

Chapel, D.G., Mariz, C.L., Ernest, J., 1999. Recovery of CO_2 from Flue Gases: Commercial Trends. Originally presented at the Canadian Society of Chemical Engineers annual meeting, October 4-6, 1999, Saskatoon, Saskatchewan, Canada.

Dahowski, R.T., Li, X., Davidson, C.L., Wei, N., Dooley, J.J., Gentile, R.H., 2009. A preliminary cost curve assessment of carbon dioxide capture and storage potential in China. Energy Procedia 1, 2849-2856.

Das, D.K., 2009. The evolution of renminbi Yuan and the protracted debate on its undervaluation: An integrated view. Journal of Asian Economics 20, 570-579.

Dewenter, K. L. and Malatesta, P.H., 2001. An Empirical Analysis of Profitability, Leverage, and Labor Intensity, American Economic Review, 91(1), 320-334.

DOE (US Department of Energy) / NETL (National Energy Technology Laboratory), 2007. Cost and Performance Baseline for Fossil Energy Plants: volume I. DOE/NETL-2007/1281, Rev 1.

GCCSI (Global Carbon Capture and Storage Institute), 2011. Economics Assessment of Carbon Capture and Storage Technologies: 2011 Update.

http://www.globalccsinstitute.com/publications/economic-assessment-carbon-capture-and-storage-technologies-2011-update (last accessed on 10/July/2013)

Gibbins, J., Chalmers, H., 2008. Preparing for global rollout: A 'developed country first' demonstration programme for rapid CCS deployment. Energy Policy 36(2), 501-507.

Hammond, G.P., Ondo Akwe, S.S., Williams, S., 2011. Techno-economic appraisal of fossil-fuelled power generation systems with carbon dioxide capture and storage. Energy 36, 975-984.

Hart, C., Liu, H., 2010. Advancing Carbon Capture and Sequestration in China: A Global Learning Laboratory. China Environment Series Issue 11. Woodrow Wilson International Center for Scholars, 2010 (11), 99–121.

Herzog, H.J., 2010. Scaling up carbon dioxide capture and storage: From megatons to gigatons. Energy Economics, 33(4), 597-604.

IEA (International Energy Agency), 2007. World Energy Outlook 2007: China and India Insights. http://www.worldenergyoutlook.org/media/weowebsite/2008-1994/weo_2007.pdf (Last accessed online 10/July/2013).

IEA (International Energy Agency), 2008. CO_2 Capture and Storage: a Key Carbon Abatement Option. http://www.iea.org/publications/freepublications/publication/CCS_2008.pdf (accessed online 09/Jul/2013).

IEA (International Energy Agency), 2013. Technology Roadmap: Carbon Capture and Storage, 2013 edition. http://www.iea.org/publications/freepublications/publication/CCS_Roadmap.pdf (accessed online 09/Jul/2013).

IEA GHG (IEA Greenhouse Gas R&D Programme), 2006. Estimating future trends in the cost of CO_2 capture technologies. PH4/33, 2006/5. http://steps.ucdavis.edu/People/slyeh/syeh-resources/IEA%202006-6%20Cost%20trends.pdf (Last accessed online 10/July/2013).

IPCC (Intergovernmental Panel on Climate Change), 2005. Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press, Cambridge, UK.

Jaccard, M., Tu, J., 2011. Show some enthuisasm, but not too much: carbon capture and storage development prospects in China. Global Environmental Change 2, 402-412.

Kessels, J., Beck, B., 2009. Financing Carbon Capture and Storage Projects the Results of Two Expert Meetings. Energy Procedia 1, 4475-4479.

Le Moullec, Y., Kanniche, M., 2011. Optimization of MEA based post combustion CO_2 capture process: Flowsheeting and energetic integration. Energy Procedia 4, 1303-1309.

Liang, X., Reiner, D., Gibbins, J., Li, J., 2010. Getting ready for carbon capture and storage by issuing capture options. Environment and Planning A 42(6), 1286-1307.

Liang, X., Reiner, D., Li, J., 2011. Perceptions of opinion leaders towards CCS demonstration projects in China. Applied Energy 88(5), 1873-1885.

Liu, H., Liang, X., 2011. Strategy for promoting low-carbon technology transfer to developing countries: The case of CCS. Energy Policy 39(6), 3106-3116.

Liu, H., Gallagher., K.S., 2011. Preparing to ramp up large-scale CCS demonstrations: An engineering-economic assessment of CO2 pipeline transportation in China. International Journal of Greenhouse Gas Control 5(4), 798-804.

Lucquiaud, M., Liang, X., Errey, O., Chalmers, H., Gibbins, J., Abu Zara, M., 2011. Future-proofing coal plants with post-combustion capture against technology developments. 1st Post Combustion Capture Conference, Abu Dhabi, 17 May 2011.

McCoy, S., Rubin, E., 2008. An engineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage. International Journal of Greenhouse Gas Control 2(2), 219-229.

NDRC (National Development and Reform Commission), 2010. '国家发展改革委关于开展低碳省区和低碳 城市试点工作的通知' (A notice to develop pilot low carbon provinces and cities), 发改委气候司 (Climate Office of NDRC), No. 2010 [1578],

http://zfxxgk.ndrc.gov.cn/PublicItemView.aspx?ItemID=%7B029b3fe9-b2dd-4db2-aaad-a87c3c7b5785%7D (accessed online 10/July/2013).

Reiner, D., Liang, X. (2009), Stakeholders perceptions of demonstrating CCS in China. EU-UK-China Near Zero Emissions Coal Project Working Package 5.2 Report.

http://www.nzec.info/en/assets/Reports/CamNZECWP52finalrevisions97-03v28aug09Update.pdf (accessed online 10/July/2013).

Reiner, D., Liang, X. (2012), Stakeholder Views on Financing Carbon Capture and Storage Demonstration Projects in China. Environmental Science & Technology, 46(2), 643-651.

Riahi, K., Rubin, E., Schrattenholzer, L. 2003. Prospects for Carbon Capture and Sequestration Technologies Assuming Their Technological Learning. 6th International Conference on Greenhouse Gas Control Technologies (GHGT-6) 2, 1095-1100.

Rubin, E.S., Chen, C., Rao, A.B., 2007. Cost and performance of fossil fuel power plants with CO_2 capture and storage. Energy Policy 35(9), 4444-4454.

State Council of China (SCC), 2006. national medium and long-term programme outline for Science and Technology (2006~2020). (in Chinese)

SAT (State Administration of Taxation), 2011. 企业所得税税前扣税办法 (Deduction Methods for Corporate Tax)).

SZTJ (Shenzhen Statistics Bureau), 2011. 深圳市 2010 年国民经济和社会发展统计公报 (Economic and Social Development Statistics of Shenzhen City in 2010).

UNFCCC (United Nation Framework Convention for Climate Change), 2010. Carbon Dioxide capture and storage in geological formations as clean development mechanism project activities. Decision 7/CMP.6. http://unfccc.int/files/meetings/cop_16/application/pdf/cop16_cmp_ccs.pdf (accessed online 10/July/2013)

Xu, Y., 2009. Relevant international experience of real exchange rate adjustment for China. China Economic Review 20, 440-451.

Zakkour, P., Dixon, T., Cook, G., 2011. Financing early opportunity CCS projects in emerging economies through the carbon market: Mitigation potential and costs. Energy Procedia 4, 5692-5699.