

**Feasibility Study of CCS-Readiness in  
Guangdong Province, China (GDCCSR)**

**Final Report: Part 4**

**Techno-economic and  
Commercial Opportunities  
for CCS-Ready Plants in  
Guangdong Province,  
China**

**GDCCSR-ED Team**

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## **Disclaimer**

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The complete list of the project reports are as follows:

- Part 1 Analysis of CO<sub>2</sub> emission in Guangdong Province, China.
- Part 2 Assessment of CO<sub>2</sub> Storage Potential for Guangdong Province, China.
- Part 3 CO<sub>2</sub> Mitigation Potential and Cost Analysis of CCS in Power Sector in Guangdong Province, China.
- Part 4 Techno-economic and Commercial Opportunities for CCS-Ready Plants in Guangdong Province, China.
- Part 5 CCS Capacity Building and Public Awareness in Guangdong Province, China
- Part 6 CCUS Development Roadmap Study for Guangdong Province, China.

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## Background for the Report

CO<sub>2</sub> capture and storage (CCS) is an important technology to decarbonise the Chinese coal-dominated electricity sector. On average, approximately 1 GW of new coal-fired power capacity starts construction in China every week, but there is currently a lack of necessary incentives to support a large scale implementation of CCS in China, since these would have to be underpinned by a global climate change mitigation process with an appropriate level of ambition and shared responsibilities to drive widespread CCS. Li (2011) investigated 74 large coal-fired power plant sites<sup>1</sup> in China and discovered that less than one-fifth of these sites appear to have a high retrofitting potential. To avoid the long-term persistence of this unfavourable situation for subsequent CCS deployment, CO<sub>2</sub> capture ready (CCSR) is a design concept to ease the future retrofitting of fossil fuel plants<sup>2</sup> with CO<sub>2</sub> capture, transport and storage in their lifetime. Building new plants with a CCSR design and siting philosophy is crucial in terms of preventing carbon lock-in<sup>3</sup> of new plants.

Guangdong is a pioneer in the reform of the Chinese economy and one of the most developed provinces in China (OECD, 2010). The provincial government of Guangdong plans gradually to establish a green energy system. In late 2010 the government set a target to reduce carbon intensity and a pilot carbon emission trading scheme has started from 2012. However, by March 2010, 16GW of ultra supercritical pulverised coal power plants (USCPC) with a unit size of 1000MW were already in the construction stage, while an even greater amount of large coal-fired power plants are pending for approval. The implementation of CCSR concepts in these plants to ease subsequent retrofitting to CO<sub>2</sub> capture therefore becomes an urgent task in Guangdong. This study addresses the technical, economic, financial and stakeholder acceptability aspects of CCSR in Guangdong and investigates potential drivers and barriers to implement CCSR in Guangdong immediately.

This report forms the fourth part of the final report of the project “Feasibility Study of CCS-Readiness in Guangdong (GDCCSR)”. The project (April 2010 to Mar. 2013) is funded by the Strategic Programme Fund of the UK Foreign & Commonwealth Office joint with the Global CCS Institute.

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<sup>1</sup> The total installed capacity of each power plant site is equal to or larger than 1GW.

<sup>2</sup> Fossil fuel plants include coal-fired power plants, natural gas power plants, refinery plants and etc.

<sup>3</sup> Inability to retrofit a plant to CO<sub>2</sub> capture and reduce emissions in the lifetime.

## Executive Summary

Technical analyses undertaken for this study show that typical 1GW supercritical steam plant in China can be made carbon capture and storage ready (CCS ready, or CCSR) without compromising performance before CO<sub>2</sub> capture is added to the plant. Carbon capture-readiness would not penalise efficiency. Typical 1GW supercritical Chinese power plant steam cycles also present the ability to be retrofitted and subsequently upgraded with a range of solvents and meet the principles of good performance with capture, capacity to operate without capture and to be retrofitted with a range of future improved solvents.

Limited additional capital costs would be necessary to implement the capture-ready measures to ensure that the principles above are met. These low-cost measures would not significantly affect initial power capital costs. The main effect is to allow a wide range of possible capture equipment configurations to be realised at the time the plant is retrofitted with CCS, when technical requirements and economic performance of the technologies to be used will be known with sufficient accuracy to make the necessary decisions and optimisations.

The Real Options Analysis (ROA) model and simulation of a generic 1GW USCPC power plant in Guangdong shows that CCSR investment can provide US\$3 million to US\$16.9 million value to the power project. If the plant would otherwise be non-retrofittable, in absence of a CCSR design, the benefit of CCSR investment can reach \$81 million to US\$94 million. In addition, CCSR will also increase the retrofitting possibility by 5 to 8 percent; reduce the mean levelised cost of electricity by \$0.4/MWh and advance the optimal retrofitting timing by about 1 year.

In addition to assessing the economics of CCSR at individual plants, this report also investigates the concept of a 'CCS Ready Hub', which requires designing CCS ready systems at a regional planning level. The ability to transport CO<sub>2</sub> to secure storage sites with the capacity to match infrastructure investment capital recovery periods is a key requirement in addition to capture readiness at power plant and other major emission sites. The bulk of Guangdong's storage capacity is offshore and offshore storage also maximises the prospects of gaining public acceptance. But cost-effective pipeline transport and storage site development for offshore requires a degree of infrastructure sharing and hence common planning to achieve economies of scale. This leads to the concept of a 'CCS cluster', already pioneered in the UK and Netherlands (e.g. Central North Sea, Rotterdam Capture and Storage Demonstration Project), with a group of adjacent onshore emission sources linked to a group of offshore storage sites by a large, and hence cost-effective, common dense-phase CO<sub>2</sub> pipeline.

A case study to evaluate the economics of the 'CCS ready hub' in Shenzhen (Li, J., Liang, X., Cockerill, T., 2011) suggested that there would be approximately 5% reduction in the average CO<sub>2</sub> avoidance cost if designing CCSR occurred at a regional planning level rather than at the level of individual power plants. This implies a significant synergy through coordinating the

implementation of CCSR through the provincial or city governments. For initial projects, where first-mover learning and regulatory barriers must be overcome, sharing the development of a cluster with partners and government is likely to reduce effective risk-associated costs and accelerate deployment even more strongly.

Through communication with industry and government officials it was found that there were a number of potential drivers for CCSR, including:

- (a) the potential support from the provincial low-carbon energy and industry upgrade policy,
- (b) the role of CCSR in maintaining the security and diversity of electricity supply in Guangdong, leading to likely greater ease for permitting new power plants,
- (c) the power plant operators' reluctance to close plant earlier in its lifetime,
- (d) the possibility of partial retrofit and partial CO<sub>2</sub> capture,
- (e) potential financial support through the existing provincial or other local incentives to encourage innovation; and
- (f) attracting foreign Investment.

On other hand, the study also found a number of barriers, including:

- (a) lack of national policy support schemes,
- (b) rigid land control,
- (c) lack of information on CCSR design among power companies (although this reduced significantly over the course of the project),
- (d) uncertainties in achieving access to storage sites; and
- (e) lack of understanding and awareness of carbon markets or other possible financial support instruments such as increased electricity tariffs for CCS plants.

## **Report Structure**

This report consists of five sections. The first section of the report summarise the principles and definitions of CO<sub>2</sub> Capture Ready (CCS Ready, or CCSR). How are the CCSR principles implemented immediately in Guangdong? We conduct an online survey and two focus group discussions to understand the perceptions of stakeholders.

The second section presents a technical analysis of CO<sub>2</sub> capture ready design configuration for an ultra-supercritical coal-fired power plant (USCPC) in Guangdong.

Building on the existing studies on CCSR, for the third section, a real option analysis was conducted to investigate the economic value of CCSR and the possibility of retrofit in an individual project in Guangdong.

The transportation infrastructure and source-sink matching is essential for a large-scale implementation of CCS and so an essential component of a CCSR project. Therefore, the fourth section develops and analyses the concept of a capture ready hub and analyses its economics if

applied in Shenzhen city. Other than CCSR at individual projects, the CCSR hub concept suggests the implementation of CCSR at a regional planning level.

The fifth section discusses the perspective of plant developers on CCSR, following by an analysis of the perspective of the Guangdong provincial government on CCSR and some possible incentive mechanisms to finance the investment of CCSR immediately.

The last section concludes this study and discusses the implications for future work.

## 1. Summary of CCS Ready (CCSR) Principles

At the request of the Gleneagles G8 submit (G8, 2005), the IEA Greenhouse Gas Programme (IEA GHG) published a study (IEA GHG, 2007) which identified the following key elements for CCS Ready power plants:

*A CO<sub>2</sub> capture ready power plant is a plant which can include CO<sub>2</sub> capture when the necessary regulatory or economic drivers are in place. The aim of building plants that are capture ready is to reduce the risk of stranded assets and carbon lock-in.*

*Developers of capture ready plants should take responsibility for ensuring that all known factors in their control that would prevent installation and operation of CO<sub>2</sub> capture have been identified and eliminated. This might include:*

*A study of options for CO<sub>2</sub> captures retrofit and potential pre-investments*

*Inclusion of sufficient space and access for the additional facilities*

*Identification of reasonable routes to storage of CO<sub>2</sub>*

*Competent authorities involved in permitting power plants should be provided with sufficient information to be able to judge whether the developer has met these criteria.*

Since the IEA GHG definition, a number of studies have been conducted to further discuss the definition, the engineering requirements and the implementation of CCSR (ICHEME, 2007; Mott-McDonald, 2008; SCCS, 2008) In 2010, building on the study by IEA GHG, a joint IEA/CCSLF/GCCSI meeting and subsequent working party in which three members of the current project team (Gibbins, Li and Liang) participated prepared an internationally-agreed definition of Carbon Capture and Storage Ready (GCCSI, 2010) with an initial summary as follows and a full definition supplied in Appendix 1 :

*“A CCSR facility is a large-scale industrial or power source of CO<sub>2</sub> which could and is intended to be retrofitted with CCS technology when the necessary regulatory and economic drivers are in place. The aim of building new, or modifying existing, facilities to be CCSR is to reduce the risk of carbon emission lock in or of being unable to fully utilise them in the future without CCS (stranded assets). CCSR is not a CO<sub>2</sub> mitigation option, but a way to facilitate CO<sub>2</sub> mitigation in the future. CCSR ceases to be applicable in jurisdictions where the necessary drivers (for CCS) are already in place or once they come in place.”*

## **2. Technical Study on Steam Cycle Configuration for CCSR for Potential Ultra-supercritical Power Plant (USCPC) in Guangdong**

### **2.1 Introduction**

When considering building a plant as capture-ready for post-combustion capture, the design of the steam cycle is of critical importance for effective thermodynamic integration of the capture equipment with the power cycle. The thermodynamic integration may be less apparent and more complex than the need to leave space for capture-related equipment and tie-ins.

Regulatory and technology related uncertainties make effective thermodynamic integration throughout the whole operating life of fossil plants a challenging objective to achieve. The characteristics of the capture system are likely to be unknown at the time of commissioning whilst the plant must operate for an undetermined period without capture. These pre-requisites must be taken into account when designing steam turbines for CO<sub>2</sub> capture-ready plants. This work examines options for capture-ready steam turbines for (Huaneng Yuanan power plant design, taken here as a typical Chinese supercritical steam plant with a 1 GW capacity, as is proposed for Pinghai power plant. Pinghai power plant is located on the east side of Daya Bay approximately 100km South of Huizhou city in Guangdong.

In addition to the general requirements for making the plant carbon capture-ready as stated in the introduction above, amine-based post-combustion capture processes specifically require changes to the flue gas desulphurization (FGD) equipment design so that high levels of sulphur oxide removal can be achieved. Some developers may prefer to add a polishing unit after a previously installed FGD process during the CO<sub>2</sub> capture retrofit.

Making the steam cycle ‘capture friendly’ is also an important feature so as to be able to supply the required amount of steam for the capture system, at the pressure corresponding to the required saturation temperature for thermal regeneration of the solvent (allowing for pressure losses and temperature drops in the system).

Ideal principles to make plant carbon capture-ready are introduced below. Although, in practice, it is impossible to meet these principles simultaneously, power plant developers should aspire to trade-offs to achieve close matching, whilst maintaining satisfactory operability of the plant.

#### Ideal carbon capture-ready (CCSR) plant principles

1. The efficiency of a CCSR plant before capture is fitted should be the same as the efficiency of a state-of-the-art standard plant designed with no consideration of capture ready principles.
2. The efficiency of a retrofitted CCSR plant should be the same as a new plant built with CCS from the start – and with the same steam conditions – at the time when the retrofit occurs.
3. There should be no upfront additional costs for a CCSR plant compared with a standard state-of-the-art plant.
4. The retrofitted power plant should have the ability to operate without capture.

5. The CCSR plant should allow for future technology developments and when the capture technology is upgraded the retrofitted plant should have the same efficiency as a CCS plant – with the same steam conditions – built with perfect foreknowledge of what the upgrade technology would be.

It should be noted that the approach adopted here follows previous work in this area by Sekar (2005), Bohm et al. (2007) and Liang et al (2009). It implies that CCSR plants implement only minimal essential upfront capital cost options, with an acceptable loss in the maximum power output of the plant when it is fitted with CCS, and with little or no effect on plant performance prior to retrofit, since economics depends critically on unknown parameters, such as time to fit capture, future fuel, CO<sub>2</sub> prices, etc.

## 2.2. Methodology

The performance of the Huaneng Yuhuan power plant in the Zhejiang Province, China has been modelled in gPROMS (a process modelling software) based on a heat flow diagram provided by the project partners to provide relevant guidance for the design of carbon capture-ready steam plants in Guangdong with the same 1 GW capacity.

A diagram of the heat flow diagram is shown below in Figure 2.1. It is a supercritical steam cycle with a single flow HP cylinder, a double flow IP cylinder and two double flow LP cylinders. Steam exits the IP turbine around 6-6.5 bara, a value that is well suited for a retrofit with steam extraction directly from the IP/LP crossover pipe.

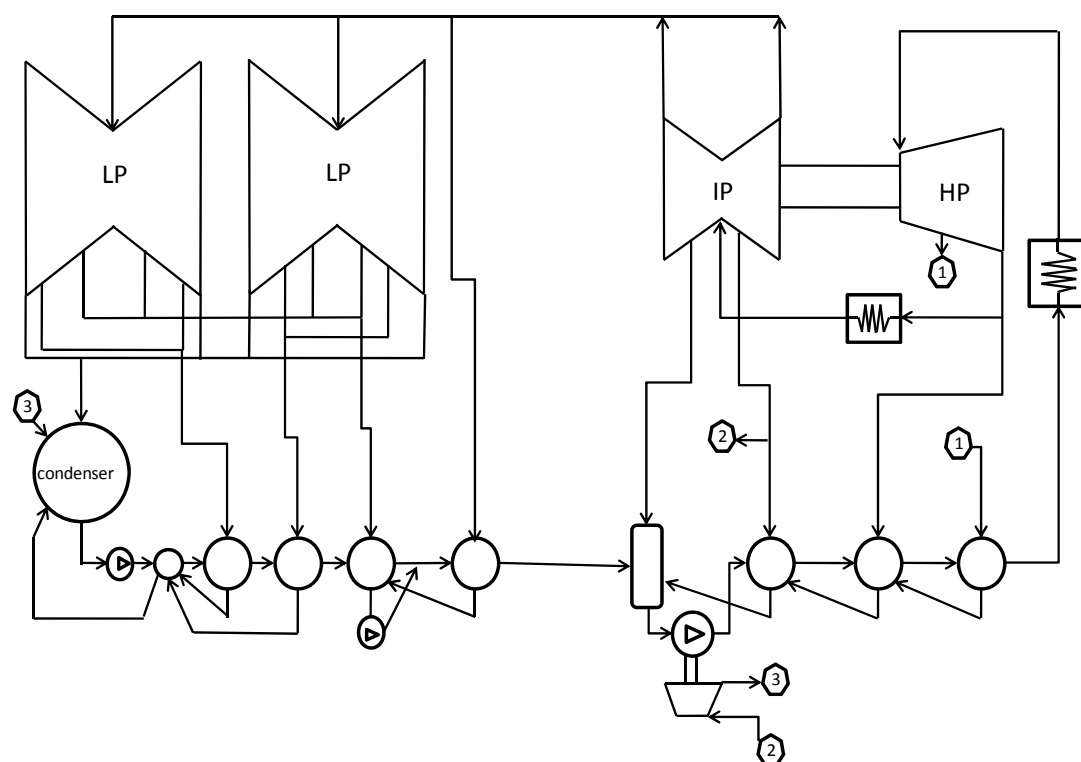


Figure 2.1 Heat flow diagram of the Huaneng Yuhuan power plant

The performance of the steam cycle without capture are calculated, and then compared to the performance of the cycle when capture is added. Other assumptions are reported in Table 2.1.

When the plant operates with capture, effective thermodynamic integration between the power plant and the capture and compression system is necessary to reduce the electricity output penalty of steam extraction. State-of-the-art integration is implemented to provide the thermal energy necessary for solvent regeneration in the capture plant and use low-grade heat available in the compression train for feed water heating:

Steam is extracted from the crossover pipe between the intermediate pressure (IP) and low pressure (LP) turbine to reject heat at a temperature as close as possible to the temperature of regeneration of the solvent.

The solvent reboiler condensate returns to the power cycle at a temperature as close as possible to the boiler condensate, as opposed to returning to the power cycle condenser.

Boiler condensate leaving the power cycle condenser is heated using low - grade heat from the compressor intercoolers and from the reflux condenser at the top of the desorber, as outlined in Figure 2.2.

**Table 2.1 Assumptions for modelling of the steam cycle**

<b>Steam cycle without capture</b>
<b>Base-load operation has been considered with the overload valve closed and no water-make up</b>
<b>Steam leakages through turbine glands and bearings have been neglected</b>
<b>Steam cycle with capture</b>
<b>Changes to LP turbine leaving losses have not been considered</b>
<b>Fuel specific emissions: 343.4 gCO<sub>2</sub> per kWh thermal LHV, based on median coal properties in Appendix 2</b>
<b>Boiler efficiency assumed to be 94%</b>
<b>Solvent energy of regeneration range from 2GJ/tCO<sub>2</sub> to 3.5GJ/tCO<sub>2</sub></b>
<b>Solvent temperature of regeneration of 100°C, 120°C and 140°C (with higher temperatures able to lead to reduced overall electricity output penalties due to reduced CO<sub>2</sub> compression power requirements)</b>

## **2.3 Carbon capture retrofit and capture-ready design**

When building a new plant carbon capture-ready it is important to take into account the uncertainty related to the selection of the capture technology. New solvents for post-combustion capture are still being developed. A key parameter is the temperature of regeneration of the solvent in the reboiler of the capture system, which determines the extraction pressure of steam

from the power cycle. When an existing unit is retrofitted, there is likely to be a mismatch between the steam extraction pressure required for solvent regeneration and the pressure of the crossover pipe between the IP and LP cylinder where low pressure can be extracted from. If the crossover pressure is too low, the capture system is likely to operate in a region where performance is sub-optimal and additional steam is required for the same amount of CO<sub>2</sub> captured and regenerated.

If the crossover pressure is too high, the LP turbine inlet needs to be throttled using the turbine inlet valve to maintain the crossover pressure and steam in the extraction line going to the reboiler also needs to be throttled. This creates a loss when pressure in the valve is reduced at the expense of an increase in entropy. Given that the outlet pressure of the LP turbine is set by the cooling temperature, and in this case limits the enthalpy drop, the LP turbine is effectively derated.

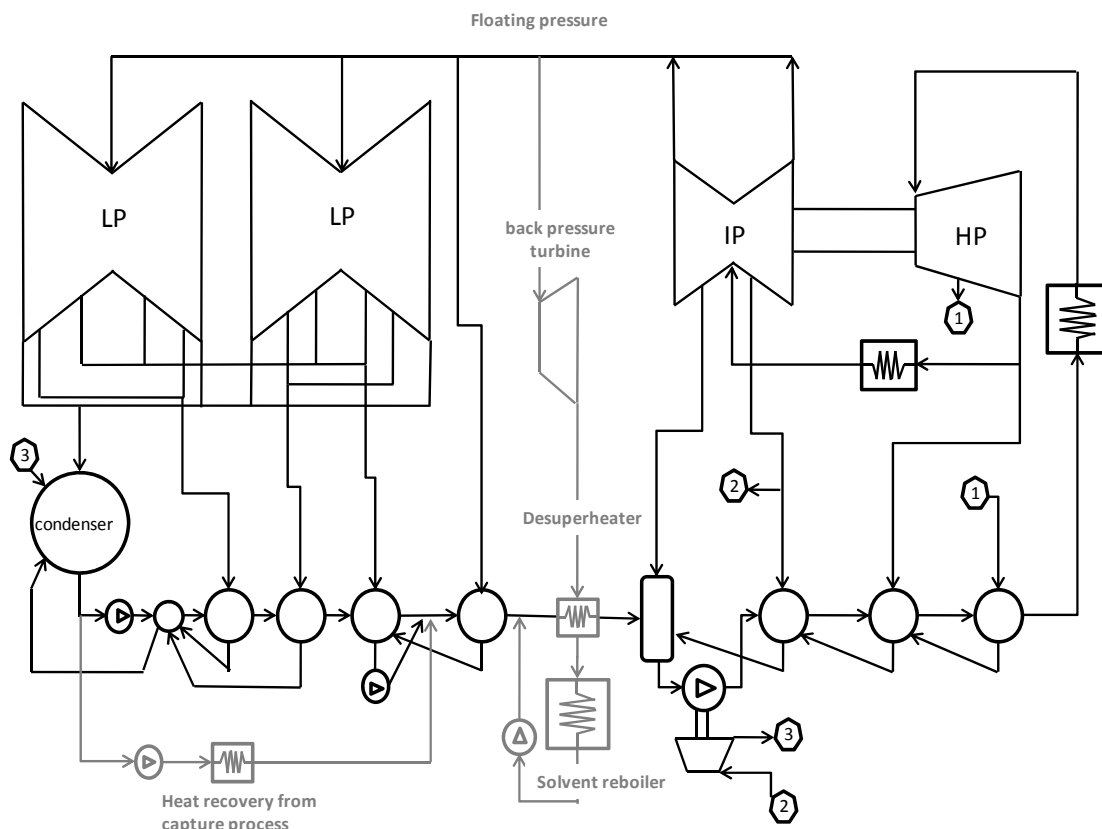
It is possible to avoid unnecessary thermodynamic losses by letting the IP turbine outlet pressure “float” when steam is extracted, also called “uncontrolled extraction”. The pressure is no longer controlled by the valve but rather determined by the amount of steam extracted and the low pressure cylinder steam swallowing capacity. This system can eliminate all losses in the LP turbine valve when the plant operates at base load, provided that the IP/LP crossover pressure does not drop below the extraction pressure required for the capture process. If this is the case, then throttling occurs at the LP turbine inlet, but performance is still improved since additional work is generated by the IP turbine.

The IP cylinder must be capable of accommodating both the reduced exit pressure and increased stage loadings with capture, increased blade bending moments and possibly also flow restrictions.

This may be done by suitably designing the last stages of the IP turbine from the outset so that the capture conditions can be sustained without any changes, thus avoiding the need to open up the cylinder and make any modifications. Alternatively, the IP turbine can be modified as part of the conversion to better match its new operating conditions. In both cases a slight loss in IP cylinder efficiency occurs with capture although this is likely to be within normal design variations.

Steam turbine design with high numbers of turbine stages, hence less work generated per stage, are more suited for floating pressure operation. Reduced IP turbine outlet pressure will also increase axial thrust on the bearings but it can be expected that this will be balanced out for double flow units like in this configuration.

The plant steam cycle uses Siemens technology with 50% reaction stage, i.e. high numbers of turbine stages, and also a double flow IP turbine. It is thus well suited for floating pressure operation (i.e. axial loads balanced, changing pressure/enthalpy drop distributed over many stages).



**Figure 2.2 Heat flow diagram of the Huaneng Yuhuan power plant with integration with the carbon capture unit**

For improved solvents with a low thermal energy of regeneration, and hence reduced steam flow, it is possible that the IP/LP crossover pressure, even when reduced from non-extraction values, will be higher than the steam pressure required in the reboiler. The addition of a back pressure turbine in the extraction line will avoid throttling losses and generate additional power. Although this turbine is not required for operation without capture it is recommended that arrangements are made as a carbon capture-ready feature. This notably involves provision for the addition of a mechanical device, such as a self-synchronising SSS clutch (SSS) at the free end of the generator and a turbine base-plate, to connect the back pressure turbine to the main shaft and avoid the need for a separate generator when the plant is retrofitted.

It is also worth noting that when operated without capture (e.g. to temporarily maximise power output at periods of high demand (Chalmers et al.)) the steam cycle returns to an operating regime similar to the conditions before retrofit to ensure that the plant operability is maintained.

## 2.4 Performance with capture

Steam turbine design for a subsequent capture retrofit should offer flexibility to allow for solvent upgrading (probably several times over the lifetime of the plant) as well achieving a low electricity output penalty at a selected design point (or averaged over a design range).

More flexible arrangements for steam extraction help avoid the risk of a retrofitted plant turning into a stranded asset after a period of technology change when less energy intensive solvents with potentially a different temperature of regeneration are likely to become available.

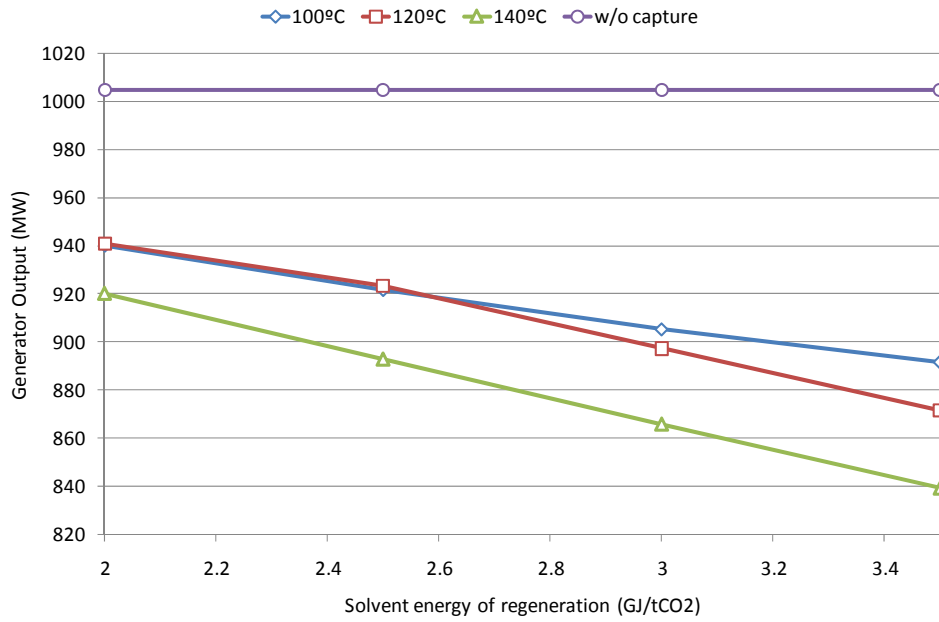
The fifth principle for the design of CCS ready (CCSR) plant previously proposed is now being considered. It is repeated below for clarity:

- A CCSR plant should allow for future technology developments, and when the capture technology is upgraded the retrofitted plant should have the same efficiency as a CCS plant with the same steam conditions built with perfect foreknowledge of what the upgrade technology would be.

Capture-ready steam turbines can be designed for a given steam extraction rate at the IP/LP crossover pipe to provide the right amount of heat for a specific solvent. Although it is impossible to design a capture - ready steam cycle with an ideal efficiency for a range of solvents, it is feasible to design steam cycles that can achieve performance close to the ideal for a given range of solvents. Future performance of solvents remains, by definition, unknown but reasonable options in the design of the steam cycle can handle a wide range of uncertainty

The capture-ready retrofit option proposed with a floating IP outlet pressure is capable of meeting this requirement for a range of solvents. A sensitivity analysis is presented below showing the performance of the steam cycle for solvent energy of regeneration varying from 2 GJ/tCO<sub>2</sub> to 3.5 GJ/tCO<sub>2</sub>, and temperature of regeneration of varying from 100°C to 140°C. Current state-of-the-art technologies for post-combustion capture rely on a range of solvents with energy of regeneration around 2.5-3 GJ/tCO<sub>2</sub>  $\pm$ 30%, and temperature around 100-120°C

The results are presented in Figure 2.3. It should be noted that this does not include power requirement for CO<sub>2</sub> compression and the ancillaries of the capture unit (additional flue gas blowers, solvent circulating pumps etc), which typically account for 80-120 kWh/tCO<sub>2</sub> depending on the solvent. For the coal chosen in this analysis this would correspond to an additional 60-90 MWe. It is difficult to predict compression requirements for unknown solvents since their thermodynamic properties have a significant effect on the performance of the solvent regeneration part of the capture system, which in return determines the inlet pressure of the compression train, and hence the power requirements.



**Figure 2.3 Generator output of retrofitted steam cycle for a capture rate of 90% for a range of solvent energy and solvent temperature of regeneration. Note that an additional 60-90MW penalty is occurred for compression to dense phase CO<sub>2</sub> at 110 bar and for capture ancillaries.**

It is also interesting to report the total electricity output penalty of adding capture so that performance can be evaluated independently of the properties of the coal chosen. The total electricity output penalty is defined as:

$$\text{Electricity Output Penalty} = \frac{\text{Efficiency penalty}}{\text{Fuel specific emissions}} \quad (\text{Eq 2-1})$$

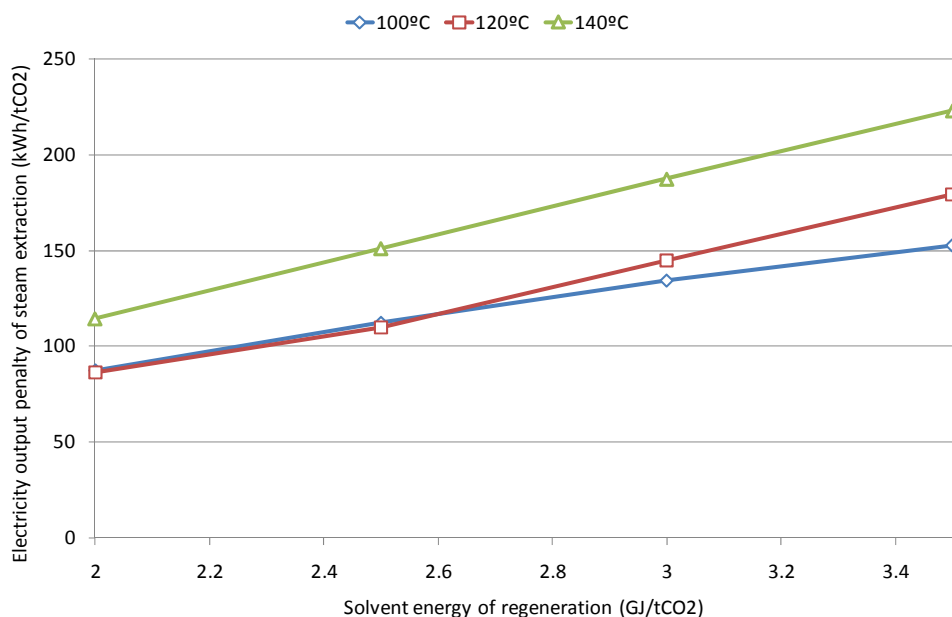
Electricity Output Penalty	(kWh <sub>e</sub> /tCO <sub>2</sub> )
Efficiency penalty	(kWh <sub>e</sub> /kWh <sub>th</sub> or % point LHV)
Fuel specific emissions	(tCO <sub>2</sub> /kWh <sub>th</sub> )

The electricity output penalty is the total net loss in plant output due to the capture and compressions processes, including the reduction in steam turbine power output due to steam extraction and the power requirement for compression and smaller amounts of power for the capture plant ancillary equipment but also including any offsets due to beneficial heat recovery for condensate heating and other purposes, divided by the absolute mass flow of compressed CO<sub>2</sub> exiting the plant boundaries, as indicated below:

$$\text{EOP} = \frac{1000 * (\text{Loss of generator output} + \text{Compression power} + \text{Ancillary power})}{\text{CO}_2 \text{ mass flow}} \quad (\text{Eq 2-2})$$

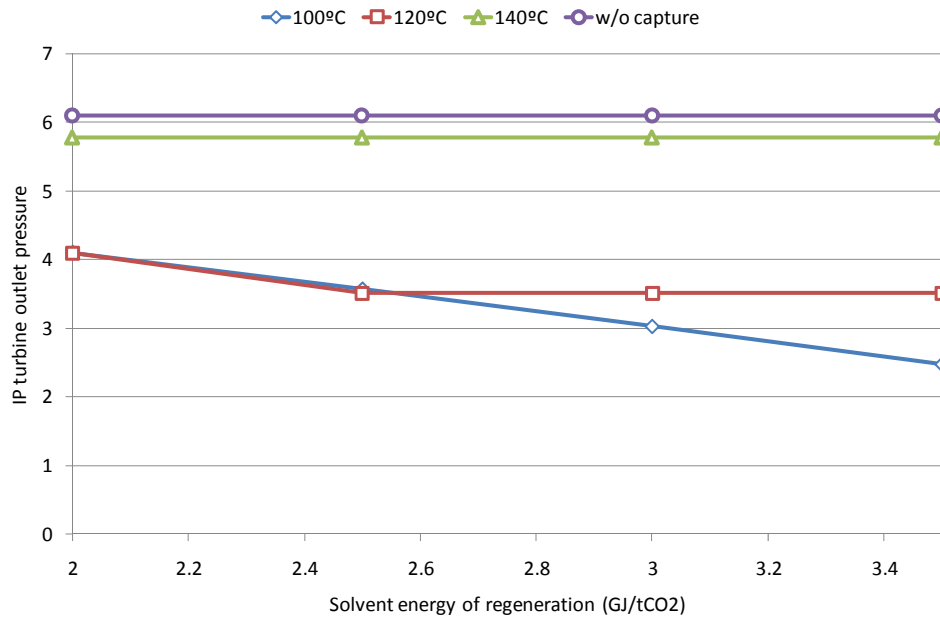
Electricity output penalty (EOP)	(kWh <sub>e</sub> /tCO <sub>2</sub> )
Loss of steam turbine generator output	(MW)
Compression power	(MW)
Ancillary power	(MW)
CO <sub>2</sub> mass flow	(tonne/hr)

Results are reported as the electricity output penalty of steam extraction in Figure 2.4.



**Figure 2.4 Electricity output penalty of steam extraction for a CO<sub>2</sub> capture rate of 90% and for a range of solvent energy and solvent temperature of regeneration. Note that an additional 80-100kWh/tCO<sub>2</sub> penalty is occurred for compression to dense phase CO<sub>2</sub> at 110 bar and for capture ancillaries**

The IP turbine outlet pressure is also shown in Figure 2.5 for the same range of solvents. The horizontal lines correspond to sub-optimal performance where the IP turbine outlet pressure has to be controlled by throttling the inlet of the low pressure turbine inlet with a valve in order to maintain solvent temperature of regeneration. It shows that high temperature of regeneration solvents regenerated at 140°C would require throttling of the LP turbine, whilst low temperature solvents regenerated at 100°C would not. The latter would be capable of performance very close to new-build plants built with perfect knowledge of the solvent from the outset. For solvents regenerated at 120°C performance would be very close to new-build plants, except for solvents requiring low levels of steam extraction.



**Figure 2.5 Intermediate turbine outlet pressure for a CO<sub>2</sub> capture rate of 90% and for a range of solvent energy and solvent temperature of regeneration. Note that the horizontal lines correspond to sub-optimal performance where the low pressure turbine inlet has to be throttled to maintain solvent temperature of regeneration**

## 2.4 Carbon Capture Ready measures

This analysis shows that typical 1GW ultra supercritical steam plant in China can be made carbon capture-ready without compromising performance before CO<sub>2</sub> capture is added to the plant. Carbon capture-readiness would not penalise efficiency. Typical 1GW supercritical Chinese power plant steam cycles present the ability to be retrofitted with a range of solvents and meet the principles of good performance with capture, capacity to operate without capture and to be retrofitted with a range of future improved solvents.

Limited additional capital costs (0.5% to 3%) would be necessary to implement the following capture-ready measures to ensure that the principles above are met. These low-cost measures would not significantly affect capital costs. The principle additional items to implement carbon capture-readiness to the steam cycle are:

- Access to steam extraction from the IP/LP crossover within the turbine hall
- A tee-piece with a flange for a suitably sized steam off-take to be connected at the IP/LP crossover and a spool piece for the valve (or a spool piece for both),
- Allocate space for a throttling valve in the extraction line downstream of the steam off-take tee,
- Reinforcement of the last IP turbine blades to tolerate pressure and temperature variations at the IP/LP crossover
- Reinforcement of turbine hall foundation for the future addition of a back pressure turbine, ideally at the free end of the alternator (see below)
- Provision for a clutch for connection of an additional back-pressure turbine to the main alternator shaft free end

### 3. The Economics of CCSR: A Case Study of a Generic Ultra-supercritical Power Plant (USCPC) in Guangdong

#### 3.1 Background

The section presents the methodology and results of an economic model for valuing CCSR in a generic ultra-supercritical pulverised coal (USCPC) power plant in Guangdong<sup>4</sup>. We take the perspective of a project investor to investigate the value of CCSR and the strategy for exercising the option of retrofitting CCS to the USCPC plant<sup>5</sup>.

#### 3.2 Methodology

A deterministic net present value may fail to capture the option value of retrofitting involved in the sequential decision-making (to retrofit or not) occurring at each year. Therefore, building on previous studies on the economics of CO<sub>2</sub> capture ready (Liang et al, 2009; Sekar, 2005), a real option approach (ROA)<sup>6</sup> is applied to value of the retrofitting option in a generic 1GW USCPC generation unit power plant built in Guangdong.

Uncertainty is the driver of the option value. We build a stochastic cost cash flow model and use option value at each time-step (i.e. year) as the criterion to justify the decision of retrofitting.

The ROA decision-making framework for retrofitting is a complex model with American style claims (i.e. options could be exercised anytime from now to an expiry date), therefore it requires a backward looking algorithm to find the optimal exercise boundary. We will use a least square regression method with Monte-Carlo simulation to estimate the continuation without upgrade and upgrade option exercised value at each option decision node (Long staff and Schwartz, 2001).

At year  $t-1$ , the total value of a project if the retrofitting option is anticipated to be exercised in year  $t$  is:

$$V_t^{retro} = \sum_{n=t}^L D(t,n) E_t[V_t^{retro}] K \quad (\text{Eq. 3-1})$$

where  $D(t,n)$  denotes the discount factor applied at time  $t$  to the cash flows impact of exercising an the retrofitting option at year  $n$ , the retrofitting year is  $t$ ,  $V_t^{retro}$  is the expected cash flow impact of retrofit at year  $n$  affected by the retrofit at year  $t$ , and  $K$  is the one-off investment for retrofit.

At  $t-1$ , the anticipated continuation value which is the optimal option value of the project if choosing not to exercise the retrofitting option at year  $t$ :

<sup>4</sup> We apply the electricity tariff, coal price, capital and labour cost of Guangdong for this study.

<sup>5</sup> The model would be able to apply for analysing a specific plant base on subsequent engineering studies.

<sup>6</sup> The real option approach assumes the business decisions are dynamic. It captures the value of flexibilities in making decisions in an investment's lifetime. For example, by investing in a coal-fired power plant, an investor has option to expand, close down, retrofit, change the operational load factor. The value of these options cannot be captured through traditional deterministic approach.

$$V_t^{cont} = \sum_{n=t}^T D(t, n) E_t[V_n^{cont}] \quad (\text{Eq. 3-2})$$

where  $V_t^{cont}$  is the optimal value at year  $t$  affected by the continuing running decision at year  $n$ .

At year  $t-1$ , if the anticipated value of retrofitting to capture is higher than the anticipated value of continuing running without exercising the retrofitting option, the retrofitting investment will take place at year  $t$ . Our study investigates the retrofitting option from year 5 (2012), the value of the project will be equal to the risk neutral value of retrofitting at year 5 and the option value to continue running at year 5.

$$V_{t-1} = ((1 - p_t^{retro})V_t^{cont} + p_t^{retro} V_t^{retro})D(t-1, t) \quad (\text{Eq. 3-3})$$

Where  $p_t^{retro}$  is the risk neutral probability of retrofitting at year  $t$  anticipated at year  $t-1$ .

A number of uncertainties could potentially affect the investment decision of retrofitting the underlying power plant. The main driver of retrofit is the cost of emitting CO<sub>2</sub> (i.e. carbon price). The retrofitting investment and electricity penalty need to be justified by the avoidance of CO<sub>2</sub> emissions and hence lower carbon emissions cost.

$$dC_t = \alpha dT + \sigma dz \quad (\text{Eq. 3-4})$$

Where  $\alpha$  is the expected growth rate;  $\sigma$  is the instantaneous standard deviation.

The study transformed the eq. 3-4 into a discrete time process to model the annual carbon prices. The real growth of carbon price is assumed to be 4% per annual (as shown in Table 3.1). The initial carbon price refers to CDM project contract price which is \$15/tCO<sub>2</sub>e (or CNY93) in 2012. This will imply a mean cost of CO<sub>2</sub> emissions at \$21/tCO<sub>2</sub> (or CNY 130) in 2020 and \$30/tCO<sub>2</sub>e (or CNY186) in 2030.

In China the on-grid electricity tariff of thermal power is significantly affected by the cost of coal. The correlation coefficient of the coal price and electricity tariff is set at 60%. The price of coal and the on-grid electricity tariff are assumed to follow a mean reverting process. The growth of both coal and electricity is projected to rise with inflation. Both prices tend to drift towards its long term mean assumptions which are \$4/GJ for coal (or CNY750/tonne metric coal) and \$0.065/kWh (or CNY0.42/kWh) for electricity. The study transformed the eq. 3-5 into a discrete time process to model the annual electricity prices.

$$dP_t = \theta(\mu - P_t)dt + \sigma \varepsilon_t \quad (\text{Eq. 3-5})$$

where  $\theta$  is the mean reversion rate,  $\mu$  is the long-run equilibrium rate,  $\sigma$  is the standard deviation,  $\varepsilon_t$  is the random component.

As Li (2010) indicated, less than 20% of large power plant sites have good retrofitting prospect,

therefore we analyse two scenarios: A. the plant is retrofittable without CCSR, but CCSR investment would reduce the cost and efficiency penalty in and after retrofitting; and B. the plant is unable to be retrofitted in absence of CCSR investment. In Scenario A, the value of CCSR would be equal to the difference of retrofittable options (i.e. option value with CCSR – option value without CCSR – investment for CCSR). In scenario B, the value of CCSR would be equal to the total value of retrofitting option less the investment of CCSR.

**Table 3.1 Assumptions for the Economic Analysis**

Parameters	Data	Notes
<b>Plant Type</b>	USCPC	
<b>Risk-Free Discount Rate</b>	5%	
<b>Capacity before retrofit</b>	1012.5	MW
<b>Net Supply Efficiency (LHV) before retrofit</b>	41.80%	42.7% at full load
<b>Efficiency Penalty without CCSR at retrofit (CCSR will not cause energy penalty)</b>	8.4%	(reduction with CCSR, please see Table 3.1)
<b>Capacity with 90% capture</b>	808.4	MW 8.4% efficiency penalty
<b>Lifetime Degrading factor</b>	1.00%	
<b>Fixed Capital Base Plant</b>	634	US\$ million (eqv. \$626/kW)
<b>Load factor before retrofit</b>	70%	
<b>Load factor after retrofit</b>	80%	
<b>Coal Price</b>	4	\$/GJ
<b>Std dev of coal price</b>	10%	
<b>On-grid Electricity Tariff</b>	0.065	US\$/kWh
<b>Std dev of On-grid Tariff</b>	5%	
<b>2008 Carbon Price</b>	15	\$/tonne
<b>Annual Real Growth of Carbon Price</b>	4%	
<b>Std dev of Emissions</b>	10%	
<b>Emissions factor base</b>	758.4	gram CO <sub>2</sub> /kWh
<b>Emissions factor w capture</b>	97.6	gram CO <sub>2</sub> /kWh
<b>CO<sub>2</sub> Captured</b>	852.3	gram CO <sub>2</sub> /kWh
<b>CO<sub>2</sub> avoided</b>	660.8	gram CO <sub>2</sub> /kWh
<b>Full Load Coal Feed</b>	8808.75	GJ/hr
<b>Fixed O&amp;M (Non-fuel)</b>	32.54	US\$ million
<b>Fixed O&amp;M after Upgrade (non-fuel)</b>	56.34	US\$ million
<b>Decommissioning Cost</b>	Equal to the salvage value	
<b>Tax</b>	25%	20 years depreciation
<b>Transportation, Storage &amp; Monitor Cost<sup>7</sup></b>	10	US\$/TonneCO <sub>2</sub> e captured

Note: All results are presented in US\$, and all assumptions in the model are base in Yuan with 6.5 Yuan/Dollar exchange rate.

The major technical and economic assumptions are shown in Table 3.1. The USCPC plant in this

<sup>7</sup> The transportation cost estimate for Guangdong by Li et al (2013) for this project is US\$ 10.2 to 16.3 / tonne CO<sub>2</sub> for a 8.8 million tonne annual capacity pipeline while the storage cost estimate is US\$6.5 / tonne.

study is assumed to start construction in early 2012 for three years and start operation in early 2015. CCS Ready design doesn't cause energy penalty. When a plant is retrofitted, the efficiency penalty (i.e. 8.4%) will be an important input to the economic study, which is obtained by the ASPEN model developed by Li (2010). The required capital investment for retrofit and the additional fixed O&M after retrofit refers to the cost of non-capture ready plant in IEA GHG (2007) shown in Table 3.2. The total transportation, storage and monitoring costs are assumed to be US\$10/tonne CO<sub>2</sub> captured. Increasing the load factor after retrofit is a possible method to recover the revenue loss caused by the electricity penalty in capturing CO<sub>2</sub> (Liang, 2010). In this study, we assume the load factor is increased from 70% to 80% after retrofit. All assumptions are in real terms and for 2010 constant prices.

**Table 3.2 Assumptions for Plant Retrofitting Performance and Investment (IEA GHG, 2007)**

(% of original plant before capture)	Non-CCSR	CCSR essential with throttled LP turbine	CCSR essential design with floating LPT	CCSR essential design with clutched LPT
<b>Additional pre-investment</b>		0.49%	0.74%	2.89%
<b>Additional investment for later capture retrofit</b>	23.58%	21.90%	21.85%	21.23%
<b>Non-fuel O&amp;M costs after retrofit</b>	73.15%	66.43%	63.73%	62.07%
<b>Efficiency penalty Reduction after capture retrofit</b>		11.64%	16.56%	19.71%

### 3.3 Simulation Results

Under the scenario A where the plant is retrofittable without CCSR investment, the value of essential CCSR with throttled low pressure turbine (LPT) is significant and equal to US\$8.45 million (Table 3.3, Figure 3.1). The probability of retrofitting to capture would be increased by 5% from 41% to 46%. The CCSR essential design with floating LPT design has the highest financial benefit, \$16.39 million, and it also significantly reduces the average cost of electricity by providing a cheaper retrofitting option through a plant's lifetime. The chance of retrofitting is increased from 41% to 48%. CCSR essential design with clutched LPT has marginally higher performance in retrofitting, but the much higher up-front cost meant that economic performance was worse than for alternative CCSR designs.

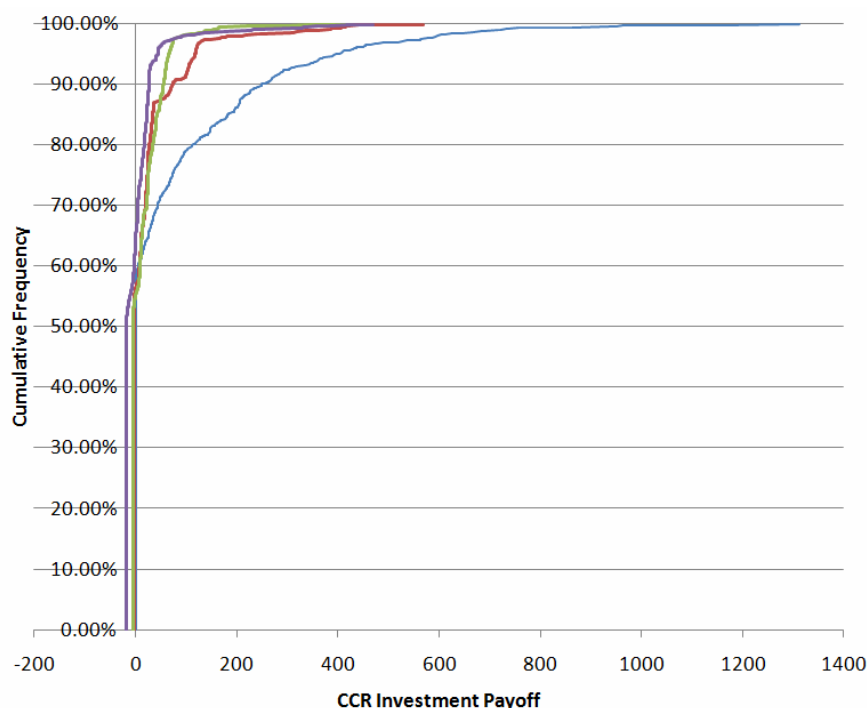
In Scenario B where the plant is not retrofittable in the absence of a CCSR design, the value of CCSR investment is \$ 86.54 million for throttled LPT, while perhaps more important CCSR would increase the chance of retrofitting from 0% to 46% during the plant's lifetime (Table 3.3, Figure 3.2). For the floating LPT CCSR design, the CCSR benefit would amount to \$94 million and the impact of CCSR on COE (Cost of Electricity<sup>8</sup>) reaches US\$1.4/MWh. The odds of retrofitting to CO<sub>2</sub> capture increases from zero to 48%.

<sup>8</sup> COE (Cost of Electricity) is the levelised cost of electricity, i.e. the required electricity tariff to achieve breakeven in a power plant's lifetime.

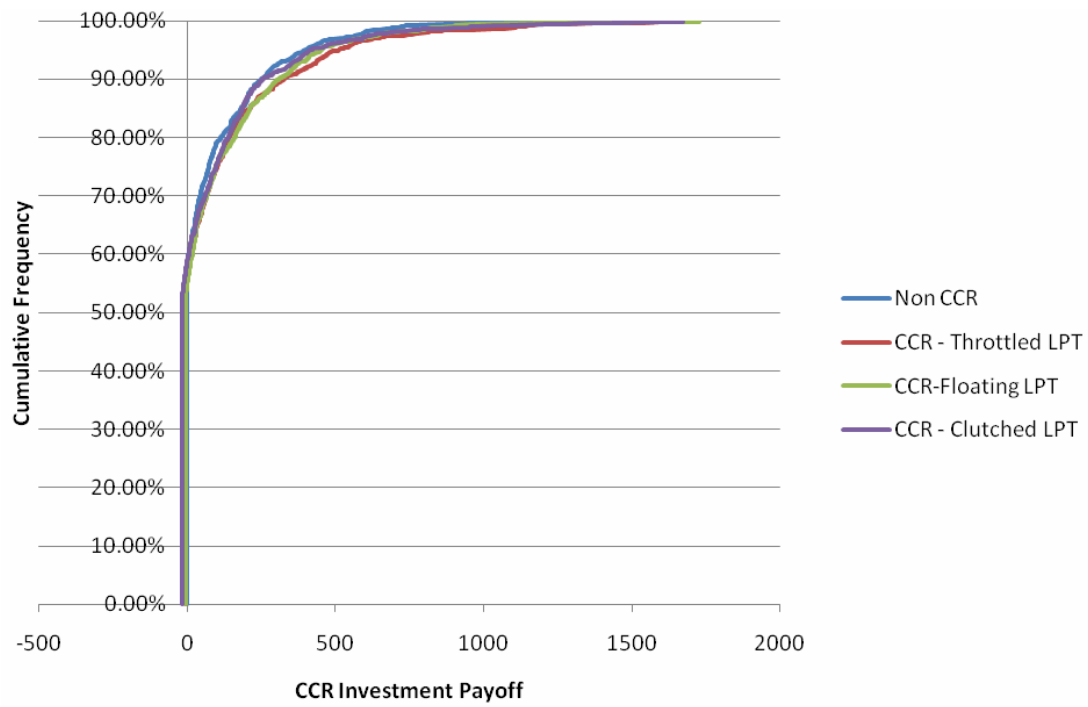
**Table 3.3 Option Value of CCSR, Retrofitting Possibilities and the Impact on the Levelised Cost of Electricity of Various CCSR Investments under Different Scenarios**

	Non CCSR	CCSR essential with throttled LPT	CCSR essential design with floating LPT	CCSR essential design with clutched LPT
<b>Impact on COE* (US\$/MWh)</b>	-1.09	-1.26	-1.40	-1.41
<b>Retrofitting Chance</b>	41%	46%	48%	49%
<b>Retrofitting Option Value (US\$: million)</b>	78.09	89.65	99.17	99.73
<b>CCSR Investment (US\$: million)</b>		3.11	4.69	18.32
<b>CCSR Benefit in Scenario A (US\$: million)</b>		8.45	16.39	3.32
<b>CCSR Benefit in Scenario B (US\$: million)</b>		86.54	94.48	81.41

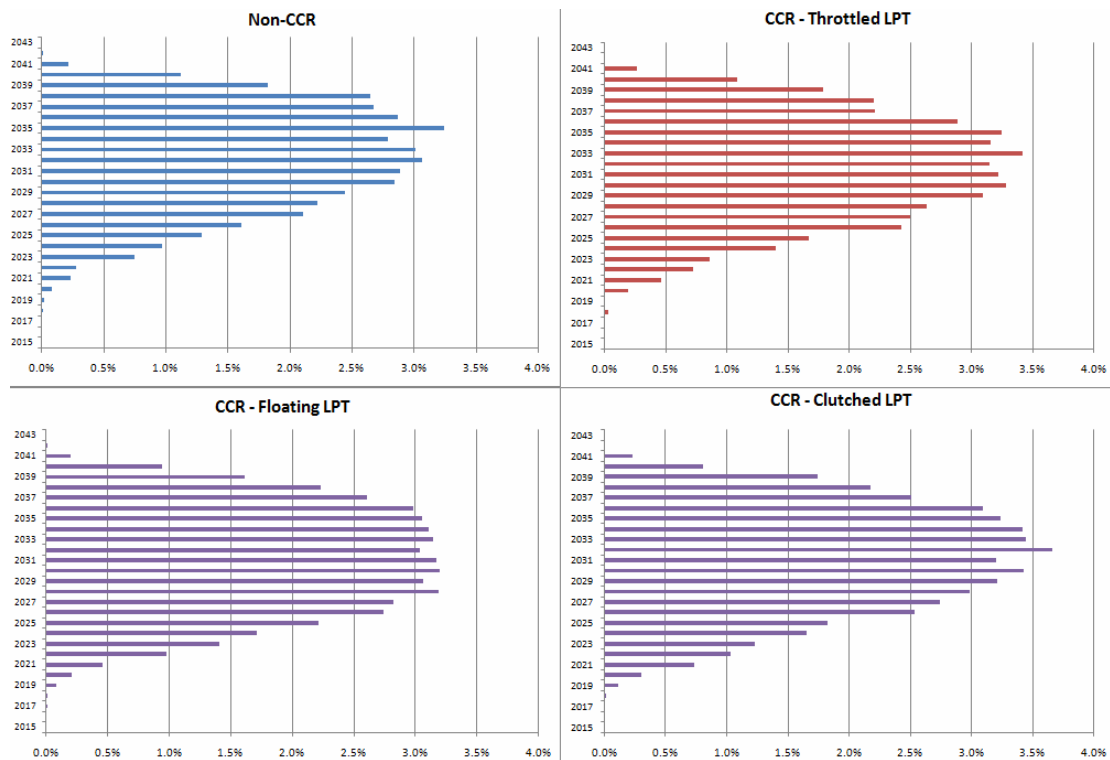
\* COE – Cost of electricity.



**Figure 3.1 Cumulative Distribution of Payoffs of Different CCSR Investments in Scenario A**



**Figure 3.2 Cumulative Probability of Payoffs of Different CCSR Investments in Scenario B**



**Figure 3.3 Probability histogram of retrofitting years with and without CCSR Investment**

In this study, the driver of the retrofitting decision is assumed to be the carbon price<sup>9</sup>. Under our assumptions, we found there is less than 1% chance to retrofit to capture each year on or before year 10, and less than 0.1% chance to retrofit on or before year 6, without CCSR investment (Figure 3.3). We found that CCSR would result in an earlier exercising of the retrofitting option: with Floating LPT, the central retrofitting year is 17.1, 1.1 years earlier than Non-Capture Ready 18.2.

### **3.4 Summary of Findings**

The modelling results shows CCSR has a number of benefits: (a) increases the probability of retrofitting by 5% to 8%; (b) provides a NPV benefit of US\$ 3.3 million to 16.9 million even if the original plant is retrofittable without CCSR investment; and (c) for a base plant which cannot be retrofit without CCSR investment, the value of CCSR could reach US\$81 million to US\$ 94 million. In addition, CCSR investment will lead to an earlier optimal retrofitting year. Our modelling results show the average retrofitting year floating LPV is 1.1 year earlier than non-CCSR investment. In addition, CCSR can significantly reduce the levelised cost of electricity in a plant's lifetime by through creating or enhancing the retrofitting options.

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<sup>9</sup> It cannot be ascertained whether or not carbon price, or some other instrument such as premium pricing for CCS electricity, will be the driver for CCS in the future, but the general principles examined here are expected to apply.

## 4. The CCS Ready Hub Concept

### 4.1 Definition and Background

In contrast with making an individual project carbon capture ready the ‘CCS Ready Hub’ is a concept which requires implementation of CCSR at a regional level. Building a CCS Ready Hub would not only require the CCSR design in new plants, but also assess the economics of retrofitting existing power plants.

A limited number of studies are also available which investigated the planning issues for CCS projects. Middleton and Bielicki (2009) developed a cost-minimizing system (SimCCS) for integrated CCS projects. By demonstrating SimCCS on 37 stationary CO<sub>2</sub> sources and 14 reservoirs in California, they found the importance of systematic planning for CCS infrastructure. Their results show that the greatest cost saving is a well-connected network rather than the economies of scale in pipeline construction.

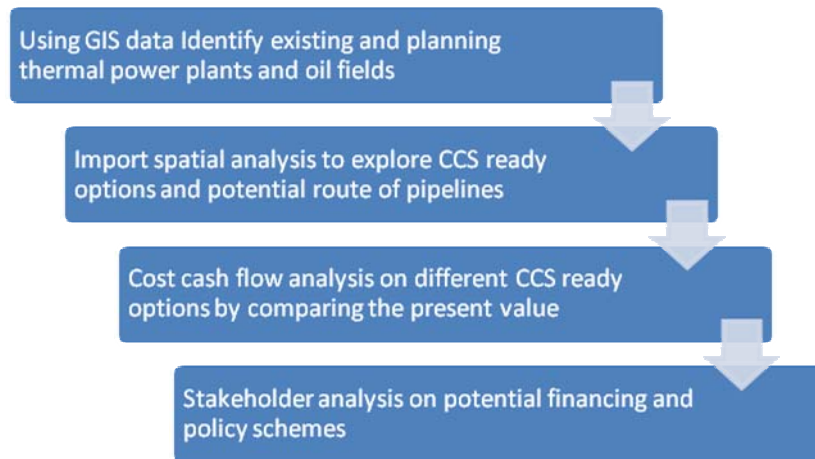
Building on existing literature, this section aims to analyse the economics of financing CCS ready in China at a regional level, with a case study of the Shenzhen area. Shenzhen city, a pioneer of economic system reform in China during the late 1970s, is now identified as one of ten pilot low carbon zones in China (NDRC, 2010). The city has a population of 8.9 million and a total of more than 11 GW power installed capacity (including 3.8GW nuclear power).

### 4.2 Methodology

Two scenarios for CCS ready investment strategies are identified in Shenzhen city based on the level of investment-decision: CCS ready at individual project and CCS ready through planning authorities (‘CCS ready hub’)<sup>10</sup>. A cost cash flow model is then developed to assess the economics of two CCS ready investment options. The valuation methodology is presented in Section Three. We also suggest potential financial strategies and evaluate immediate interests in local governments, power companies and oil companies for CCS ready investment and the CCS ready hub idea. The cost profile of CO<sub>2</sub> abatement for the whole city is assessed. The sequence in building and operating deploying CCS facilities will follow the least cost principle. When operating CCS facilities, those with the lower marginal cost of CO<sub>2</sub> abatement are assumed to have priority. The implementing process of simulation and analysis is highlighted in Figure 4.1.

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<sup>10</sup> There are some limitations due to data and resource constraint, the paper does not considered stationary emissions sources in nearby cities, such as Dongguan, Huizhou and Hong Kong. Also, the potential of EOR is not yet built in the model. The distribution of generators may affect the cost of CCS, but the paper does not consider the structure of power grids in Shenzhen and Guangdong.



**Figure 4.1 Methodology to investigate financing issues of CCS ready**

We apply a standard project cost cash flow model applied for assessing the capture readiness investment. The cost cash flow of a power plant is composed of investment cash flow which includes fixed and working capital, and the cost component of operating cash flow includes all fixed and variable operating expenses. The cost of pipelines varies with the length, capacity, route and other technical factors. The cash flow of storage includes the cost of injection and monitoring. No tax and financing cash flow is assumed in cost cash flow analysis. The decision node assumption of retrofitting is different from the study by Liang et al (2009), since we investigated scenarios for retrofitting occurring in 2020 and 2025 respectively. Two existing coal and two existing natural gas power plants are retrofittable. The baseline of CO<sub>2</sub> emissions refers to the emissions per kWh electricity generated before capture. The total CO<sub>2</sub> abated is calculated by multiplying electricity generation by the difference between emissions/kWh before and after capture at individual plants. The cost cash flow for two CCS ready scenarios in Shenzhen city are evaluated:

- A. Consider making a 4 x 1000 MW new USCPC coal-fired power plant CCS ready and the route of backbone pipeline in project planning
- B. Consider making a 4 x 1000 MW new USCPC coal-fired power plant CCS ready and the route of backbone pipeline in project planning and other stationary emissions sources in Shenzhen

### **4.3 Assumptions**

Existing thermal power plants include natural gas combined cycle, heavy oil, subcritical and supercritical units. To evaluate the retrofitting potential, the remaining lifetime of these units are assessed through discussions with plant operators, because their design lifetime may not be the actual effective lifetime. For example, some operators of coal and natural gas plants claimed their units can operate 5 to 10 years longer than the stated lifetime, but heavy oil plants will be closed within the next 2 years, much earlier than the design life, because of high operating costs and SO<sub>x</sub> emissions. The lifetime of new USCPC plants is assumed to be 30 years and the capture rate is 85%. The capital cost of a new USCPC plant is set at CNY4250/kW or US\$685/kW ( while the capital cost of retrofitting capture with CCS ready investment is assumed to be 60% of original

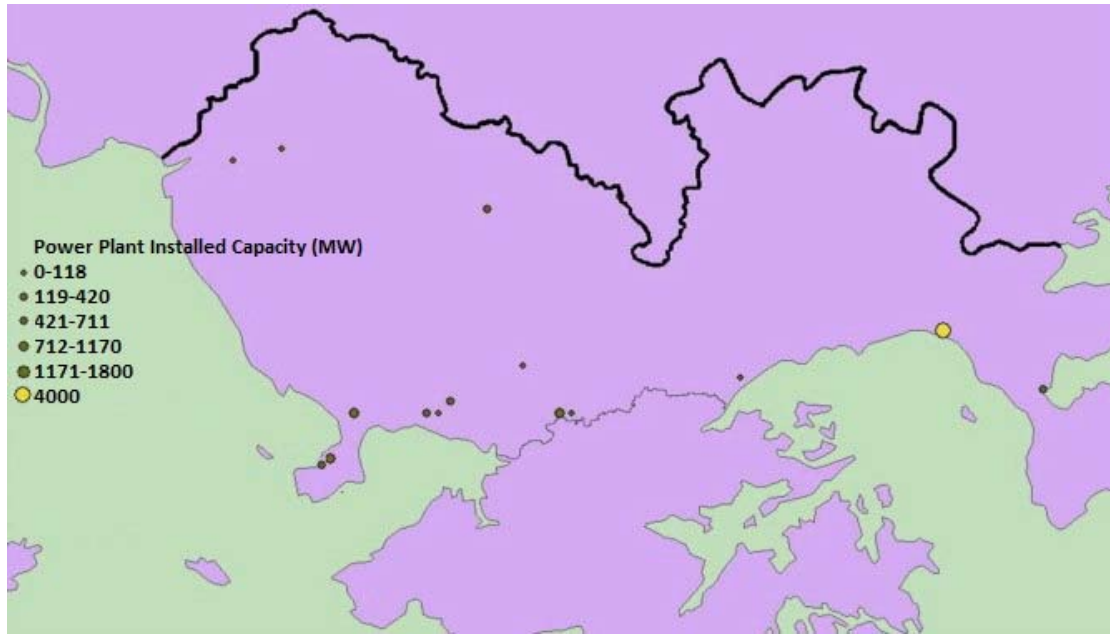
capital cost or CNY2550/kW or US\$411/kW (without capture).

The key factors considered in the model are listed in Table 4.1. We assume the capture retrofit cost advantage of CCS ready according to Table 3.2, the essential CCSR with throttled low-pressure turbine. The cost of building onshore pipeline in scenario A will be 25% higher than scenario B in the future. Two existing coal-fired power plants and two existing natural gas power plants are able to be retrofitted in 20 years time.

**Table 4.1 Key issues considered in evaluating the cost of CCS ready**

<b>Existing Power Plants</b> Fuel type Location Efficiency Total installed capacity Unit installed capacity Current utilization hours (load factor) Future utilization hours (load factor) Retrofitting feasibility Remaining Lifetime Expected average cost of retrofitting to capture Expected average retrofitting year Require rate of return (base plant, capture unit) Flexibility in capture (if applicable)	<b>New Power Plants</b> Fuel type Location Efficiency Cost of CCS ready investment Lifetime Installed capacity Estimated utilization hours Expected average cost of retrofitting to capture Expected average retrofitting year Require rate of return (base plant, capture unit) Flexibility in capture
<b>Potential Transportation (Pipeline)</b> Route options Length Capacity Capital cost Operating cost	<b>Potential Storage site</b> Type Injection capital cost Injection operating cost Monitoring cost Estimated schedule for EOR (if applicable) <sup>11</sup>

<sup>11</sup> According to the findings of CO<sub>2</sub> Storage Study in this project (Zhou et al, 2011), there is very limit CO<sub>2</sub> enhanced hydrocarbon potential in Guangdong and in South China Sea.



**Figure 4.2 Location of existing and planning power plants in Shenzhen city (Green: Existing Power Plants; Yellow: in Planning)**

The cost estimate of pipeline factors is based on the studies by McCoy and Rubin (2008), by Liu and Gallagher (2011) and by the project team, Li et al (2013)<sup>12</sup>. However, in the Chinese context, we also consulted offshore engineering companies and obtained cost estimates from local gas network operators. We assume a backbone pipeline to transport CO<sub>2</sub> from large stationary emissions sources. Scenario A, which does not consider existing emissions sources, will only require a 250km offshore pipeline, with a flow rate of 25 million tonnes pa (based on 85% CO<sub>2</sub> captured). Scenario B, which does consider existing emissions sources, will require additional onshore pipelines with a total length of 292km. The backbone onshore pipeline will be 69km with a capacity of 18 million tonnes pa (based on 40% CO<sub>2</sub> captured). The backbone offshore pipeline will be designed at 43 million tonnes pa. Under both scenarios, the operational cost of the offshore pipeline will be CNY22000/km pa while the cost of onshore pipelines is assumed at CNY11000/km pa.

From the study by Wei et al (2010) and Zhou et al (2011), sufficient offshore storage capacity is estimated to be available for CO<sub>2</sub> storage in saline aquifers. The depth of the sea area is within 200 metres or less. The capital cost of injection is assumed to be CNY57 million or US\$ 9 million in scenario A, and CNY62million in scenario B according to estimates by oil field operation companies in Shenzhen. The operational cost and monitoring cost in present value is assumed to be CNY25 or US\$4 per tonne<sup>13</sup>.

<sup>12</sup> The study completed before the GDCCSR project cost estimates are available. Therefore the study didn't apply the output of GDCCSR cost estimates.

<sup>13</sup> The assumption is consistent with and close to the sensitivity study of CO<sub>2</sub> storage cost study (Li et

Based on a study on required returns by financial officials, Reiner and Liang (2009) found that stakeholders from public or development banks perceived that the required return for capture facilities to be between 5% to 8%, but those at private banks required a return of 12% to 20% to compensate for risk. To simplify, we apply a 12% capital charge factor in real terms for all capital cost of capture, transportation and storage facilities.

#### 4.4 Summary of Results

The simulation results show that CCS ready investment will reduce the average CO<sub>2</sub> abatement cost of CCS retrofit in 2020 by approximately 20% in Shenzhen area (Figure 4.3). In addition, CCS ready scenario B (CCS Ready hub), which considers the retrofit potential for existing coal and gas power plants and an optimised pipeline network, will have a significant cost advantage when capture rises above 17 million tonnes of CO<sub>2</sub> per year, compared with scenario A, in which only 4GW of new coal plant capacity is CCS ready.

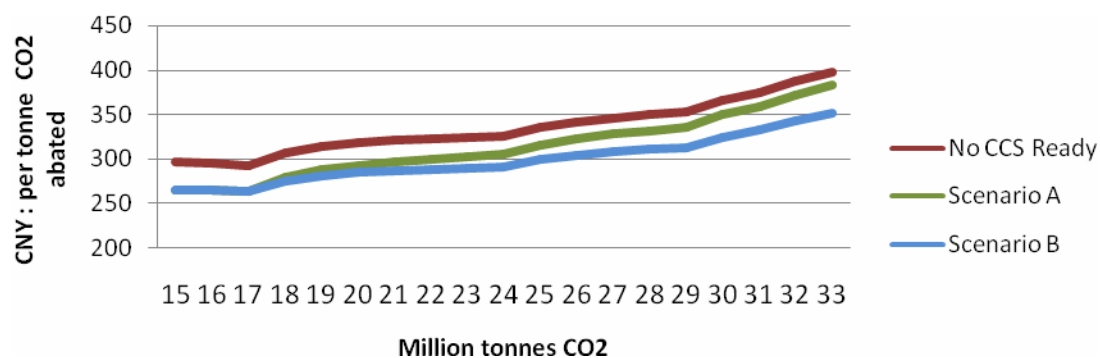
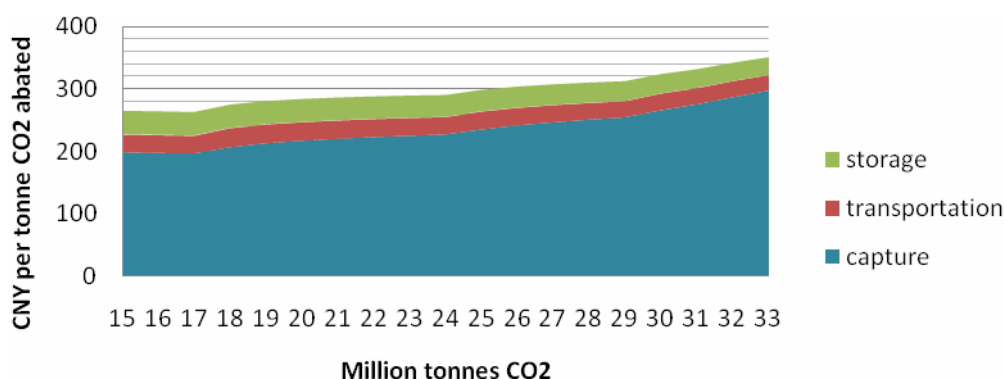


Figure 4.3 Average cost of CO<sub>2</sub> abatement of 2020 CCS retrofit

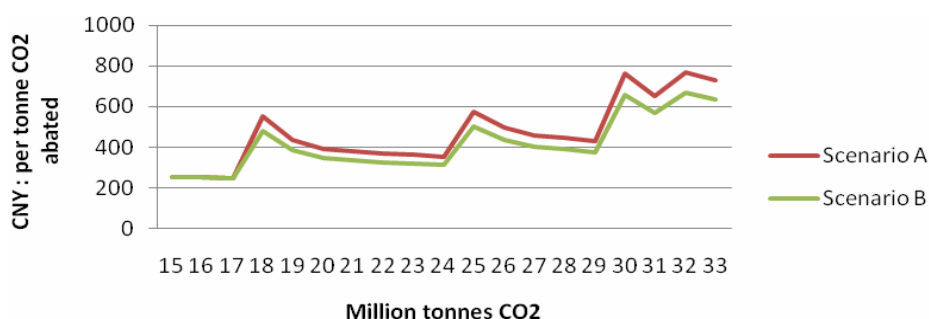
The average cost of CO<sub>2</sub> abatement rises when the total amount of CO<sub>2</sub> avoided is above 17 million tonnes (Figure 4.4), because the remaining effective lifetime of existing plants will be less than 20 years and the efficiency of existing plants is not as high as for new plants. The average cost of transportation and storage are generally lower when the total amount of CO<sub>2</sub> avoided is higher. Figure 4.5 presents the marginal cost of CO<sub>2</sub> abatement per million tonnes. The marginal abatement cost found in scenario B is lower than scenario A in retrofitting existing coal or natural gas power plants.

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al, 2013), which found the lifetime CO<sub>2</sub> storage cost at CNY34 or US\$5 per tonne CO<sub>2</sub> for a 26.4 million tonne CO<sub>2</sub> storage per year scenario.



**Figure 4.4 Structure of average cost of abatement of 2020 CCS retrofit in scenario B**



**Figure 4.5 Marginal CO<sub>2</sub> abatement cost of CCS retrofit in 2020 (assuming each decision involves an increase of 1 million tonnes)**

In order to avoid more than 29 million tonnes CO<sub>2</sub> per year through CCS in Shenzhen, retrofitting natural gas power plants for capture will be required. However, the marginal cost of CO<sub>2</sub> avoidance rises to CNY650 per tonne of CO<sub>2</sub> (about USD 100). In reality, the combination of Shenzhen's carbon emissions reduction target and expected price from international carbon markets may not be high enough for retrofits at natural gas power plants to take place. In other words, a careful evaluation of the value of CCS ready at natural gas power plants is needed before CCS ready policy or investment can be put in place.

Furthermore, as suggested by Chrysostomidis et al (2009), without sufficient incentive, project developers are likely to develop point-to-point pipelines rather than a network bringing CO<sub>2</sub> from multiple sources to multiple sinks. To build a 'CCS ready hub' which considers all emissions sources and potential CO<sub>2</sub> pipeline networks in Shenzhen, local governments need to provide sufficient financial and policy incentives.

#### 4.5 Key Findings

The 'CCS ready hub', a concept for designing CCS ready systems at a regional planning level, may have significant economic benefits. A 'CCS ready hub' considers both new plants and

existing stationary emissions sources in CCS ready planning and investment. Using simulations, we found that considering existing plants and a potential optimised pipeline network in CCS ready system designs can add significant value to CCS ready investments. To implement the CCS ready hub concept, local governments should provide planning guidelines or other guidance for CCS ready to avoid 'carbon lock-in'. Within the Chinese institutional framework, a top-down approach to implementing CCS ready by local government would be a promising path.

## 5. Power Plant Developers' Perspectives on Implementing CCSR<sup>14</sup>

### 5.1 Background of the CCSR Industrial Stakeholder Communication in Guangdong

In order to understand potential opportunities and challenges to implementing CCSR immediately in Guangdong, we conducted a survey from Feb to Jun 2010 to understand opinion-leaders' perceptions. The survey included two empirical phases: an online consultation of 31 respondents (out of a sample of 82) and three face-to-face focus group discussions, including 16 officials from five power plants and two oil companies in the Guangdong province. A majority of respondents in the online survey were officials from power companies. The objectives of the survey include:

- a. Understand opinion-leaders' willingness to implement CCSR designs in fossil fuel power plants;
- b. Identify the key engineering factors cited by interviewees which potentially affect the implementation of CCSR design;
- c. Identify cost performance expectations and the potential incentives that could trigger CO<sub>2</sub> capture ready investment.

### 5.2 Survey Methodology

The format of the study builds on the stakeholder communication for the NZEC study which used an online survey and follow-up face-to-face interviews (Liang, Reiner and Li, 2011). The online survey was conducted in Feb 2010. In March 2010, two follow-up focus groups with engineers were carried out at two proposed new supercritical power plants<sup>15</sup>, and then in Jun 2010 another focus group discussion was held in Shenzhen with engineers and managers from energy companies to discuss the potential policy and financing prospects of implementing CCSR in the short term. The aim was to explore in detail the actual drivers and barriers to the immediate implementation of CCSR.

The two criteria for selecting stakeholders were that they were (i) 'influential for others' and/or (ii) 'project specific', based on four categories suggested by Ashworth et al (2010). In other words, opinion-leaders involved must have a significant impact on CCS development in Guangdong or China and/or influence whether or not a specific power plant would have a CCSR design. The target sample for the online survey included 85 people, a majority drawn from industry such as power companies (29), power design institutes (12), petro/chemical companies (11) and thermal/chemical engineering academics (5); 8 opinion-leaders are serving on power plant authorisation bodies, or are in environmental permitting or monitoring positions within national government (e.g., National Development and Reform Commission or Ministry of Environmental Protection); and 20 opinion-leaders work in energy project approval or regulatory positions in local governments.

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<sup>14</sup> Please cite chapter 5 as Li, J., Liang, X., Cockerill, T., Gibbins, J., Reiner, D., (2012), Opportunities and Barriers for Implementing CO<sub>2</sub> Capture Ready Designs: A Case Study of Stakeholder Perceptions in Guangdong, China. Energy Policy 45, 243-251.

<sup>15</sup> Both plants are in Guangdong, scheduled be built before 2012 and near potential storage sites.

We carefully checked before finalising the invitation to make sure that, with highly probability, each government official invited would be involved in CCS planning or regulation activities in the near future. In terms of geographical locations, more than one third of opinion-leaders (29) are working in Guangdong province and a quarter of them (22) are working in Beijing. The attendees at focus group discussions were selected either through existing contacts or nominated by senior managers of their institutions. All attendees in the focus group discussions are based in Guangdong.

Taking advantage of the flexibility of an online survey, the questionnaire was designed to be path-dependent. Each opinion-leader answered 16 common questions followed by another 4 to 7 specific questions from a bank of 15 questions. In designing the questionnaire, the structure and format of previous CCS opinion-leaders' surveys in China (Reiner et al, 2007; Liang and Wu, 2009; Liang et al, 2011) was first reviewed, as well as that of a CCS opinion-leader survey in Europe (Shackley et al, 2007). However, in contrast to previous studies, the main purpose of this questionnaire was to understand opinion-leaders' ideas and concerns for implementing CCSR immediately, rather than CCS at some stage in the future. A number of 'what if' questions were therefore posed, such as 'will you accept CCSR, if it incurs an additional 1% fixed capital expenditure'.

As a final stage in its preparation, the online questionnaire was tested by six people, three CCS experts and three Chinese opinion-leaders not involved in the sample. The questionnaire was then revised according to the feedback received before being translated into Chinese and distributed to opinion-leaders via email. A total of 82 invitations were sent successfully on 1 Feb 2010.

In each email, opinion-leaders were told that an attractive token would be awarded by post after the study. At the beginning of the online survey, opinion-leaders were presented with the description of CO<sub>2</sub> capture ready by IEA GHG (2007).

To complement and calibrate the data collected through the online survey, we organised three focus group meetings in March and June 2010. There were three general purposes for holding the group discussions:

To understand the reasons behind opinion-leaders' preferences in the online survey;

To collect qualitative opinions on implementing CCSR other than the options framed by the online survey questionnaire.

To investigate drivers and barriers to immediate deployment of CCSR at their new plants.

In the focus group meetings opinion-leaders were given a Chinese translation (IEA GHG, 2007) of the CO<sub>2</sub> capture ready power plant report by IEA GHG (2007) prepared under the CAPPCCO project.

In March 2010, the first two focus group meetings were held at power companies located in Foshan and Guangzhou, both in Guangdong province. Three officials participated in each group meeting. The first two focus-group discussions started by investigating how well the plant design

for the new supercritical power plant in question would meet the engineering and geographical requirements.

The other focus group discussion was held after the Guangdong Carbon Capture and Storage Project summer assembly in June 2010 in Shenzhen, China. The 12 participants included 2 academic observers from Guangzhou; and 10 energy industry delegates (6 from power companies, 1 from a grid company and 3 from oil companies from Guangzhou, Shenzhen, Dongguan, Foshan and Huizhou). The third focus group meeting aimed to discuss regulatory issues, economics and policy acceptance among the attendants if a CO<sub>2</sub> Capture Ready design is implemented in new plants in the Pearl River Delta. The list of attendees is shown in Table 5.1 (individual and companies names are treated anonymously). Six officials participated in both the online survey and a focus-group discussion.

**Table 5.1 Demographic Information of Industry Participants in the Three Focus Group Discussions**

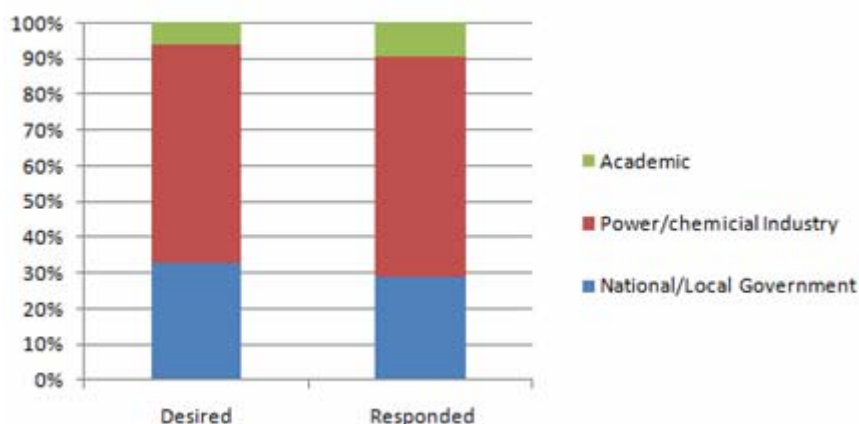
No.	Group	Ownership <sup>16</sup>	Type	Location	Position
1	1	POE	Power	Foshan	Chief Engineer
2	1	POE	Power	Foshan	Chemical Engineer
3	1	POE	Power	Foshan	Thermal Engineer
4	2	SOE (Big 5)	Power	Guangzhou	Thermal Engineer
5	2	SOE (Big 5)	Power	Guangzhou	Production Manager
6	2	SOE (Big 5)	Power	Guangzhou	Pollution Control Engineer
7	3	Private	Power	Shenzhen	Chief Financial Officer
8	3	Private	Power	Shenzhen	Chief Engineer
9	3	COE	Power	Shenzhen	Environment Manager
10	3	COE	Power	Dongguan	Vice President
11	3	POE	Power	Foshan	Deputy General Manager
12	3	SOE (Big 5)	Power	Guangzhou	Environment Manager
13	3	SOE	Oil	Huizhou	Production Director
14	3	SOE	Oil	Shenzhen	Deputy Chief
15	3	SOE	Transmission	Guangzhou	Planning Officer
16	3	FOE	Oil	Shenzhen	Business Manager

Online survey data obtained was analysed using both qualitative and quantitative methods. Descriptive analysis was first applied to determine how responses were distributed across different categories, and the average degree of acceptance. Regression analysis was then undertaken to investigate relationships between variables, for example exploring factors that might affect a respondent's general attitude towards CCSR. In-depth qualitative data was also obtained from notes and observations in the focus group meetings. In order to gain insights from these meetings the method of narrative summary analysis and interpretation (Mishler, 1986; Labov and Waletzky, 1967) was adopted. In addition, survey results with previous opinion-leaders' communication in

<sup>16</sup> Ownership is classified according to the control interest of a company. POE: provincial owned enterprise; SOE: state owned enterprise; Private: private owned enterprise; COE: city government owned enterprise; FOE: foreign government owned enterprise; Big 5: one of the five largest power companies in China.

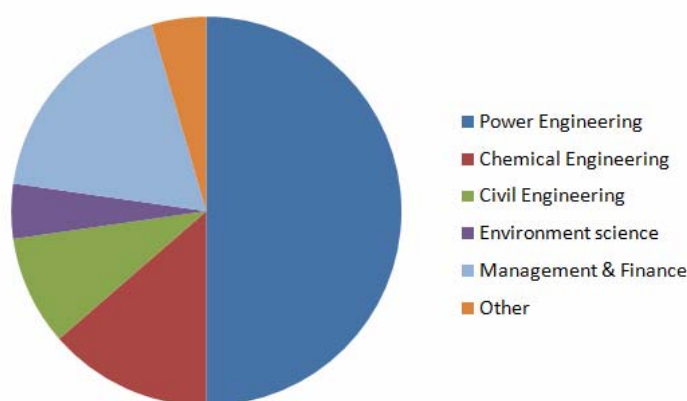
China and Europe were also compared.

A total of 31 comprehensive responses<sup>17</sup> were received by the end of February, an overall response rate of 38%. The rate was lower than for the previous NZEC (EU-UK-China Near Zero Emissions Coal Initiative) online survey (51%), perhaps because the opinion-leaders were generally less confident in answering the more technical survey questions. However, a satisfactory number of responses were received from each sector and the sector composition of responses was thus very close to the initial desired structure<sup>18</sup> (Figure 5.1). Respondents were distributed over 6 provinces, with the greatest number (13) working in Guangdong, followed by 7 located in Beijing.



**Figure 5.1 Distribution of sample versus responded by type of institution**

Three government respondents come from national institutions while six are working at local authorities. When industry and academic participants were asked for their areas of expertise, nearly half selected ‘power engineering’ (11) and four people ‘management’ (Figure 5.2)



**Figure 5.2 Distribution of industry and academic responded by claimed expertise area**

On average, opinion-leaders estimated they spent 85% of their working time on energy issues, 24% on climate change related issues and 4% of their time on CO<sub>2</sub> capture and storage. The results

<sup>17</sup> Two respondents who didn't finish the all questions are excluded in the database of respondents.

<sup>18</sup> The invitation of attend the survey was send out based on the background of the interviewee.

virtually all the respondents are not inside the CCS community. However, every opinion-leader stated they had heard of CCS before this survey and a majority (55%) said they had come across the term CCSR in Chinese as well.

### 5.3 Perspective of Plant Developers on CCSR Design

When asked their general perspectives on designing a plant to be CO<sub>2</sub> capture ready, more than half of opinion-leaders expressed either ‘strong support’ or ‘support’ (Figure 5.3). In a follow-up group discussion, a power plant manager stated a belief that removing CO<sub>2</sub> would certainly be the next environmental requirement after deNO<sub>x</sub> and deSO<sub>x</sub>. Those spending more time on climate change<sup>19</sup> and those spending more time on CCS<sup>20</sup> are more likely to be supportive of CCSR. Interestingly, opinion-leaders prioritising CCS as an important technology are *not* more likely to support CCSR, probably due to a lack of understanding or information on CCSR before the survey.

In follow-up discussions, a total of six delegates from provincial, city and private power companies explicitly expressed their concerns of the potential for ‘carbon lock-in’ because their small and inefficient plants were subject to mandatory closure in the last five years and they did not want to see mandatory closure applied to their fleets again. Two participants believed plants under construction now would be ‘very likely’ to face forced closure due to being unable to retrofit CO<sub>2</sub> capture within the next two decades. A manager with engineering background from a large chemical company expressed strong interest in applying the CCSR concept in their hydrogen production process, and he thought there was a cost advantage of partially capturing CO<sub>2</sub> in his plant in contrast with capturing CO<sub>2</sub> from conventional coal-fired power plants. A planning official from the power grid company indicated the importance of coordinating the construction CO<sub>2</sub> pipeline infrastructure, power plant locations, potential storage sites and transmission grids. He suggested CCSR should start by investigating a possible cluster rather than individual projects.

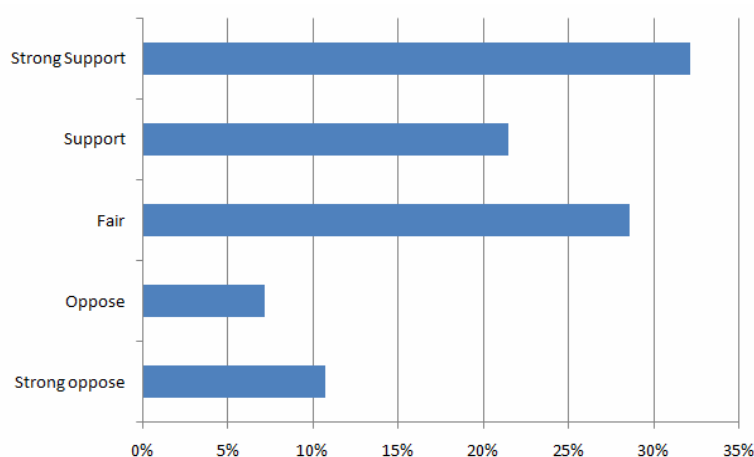


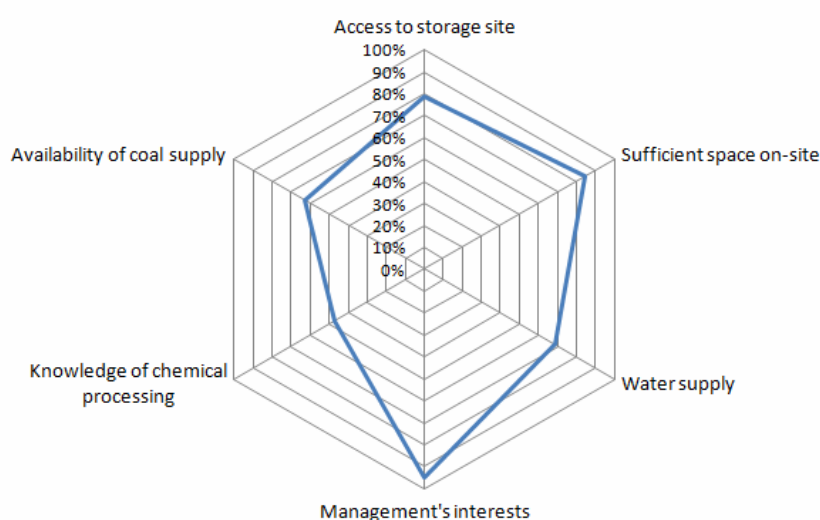
Figure 5.3 Opinion-leaders' general perceptions of CO<sub>2</sub> capture ready

To gain insights into the potential benefits of CCSR for China, participants were given four

<sup>19</sup> At 95% confidence level

<sup>20</sup> At 95% confidence level

statements, similar to those provided to opinion-leaders in the 2009 NZEC survey which was focused on CCS demonstration rather than CCSR: ‘Add credit to Chinese government in climate area’ (3.7) and ‘Attract foreign investment’ (3.5) received higher scores than ‘Benefit Chinese CCS equipment manufacturers’ (2.9) and ‘Benefit Chinese energy firms investing in CCS technologies’ (3.1). The results show a difference with respect to the perceived benefits of demonstration in the earlier study, where ‘Create advantage for Chinese energy companies to invest in CCS’ gained the highest acceptance. During the follow-up dialogue with opinion-leaders, participants from provincial-owned, city-owned and private power companies, though very interested in the technologies, were reluctant to invest in CCS due to lack of policy support and knowledge to kick-off. Therefore, foreign investments or joint-ventures might be a possible option for CCSR, though Chinese power plants are mostly owned by domestic investors.



**Figure 5.4 Opinion-leaders’ views on the relative influence of factors affecting CO2 capture ready decisions at individual power generation projects in China**

Industry opinion-leaders were asked to identify the most critical technical factors influencing CCSR decisions for individual projects (Figure 5.4). More than 90% of respondents believed a key factor is to gain ‘Management’s interest’ in CCSR. ‘Sufficient space on-site’ and ‘Access to storage site’ also received more than 80% of responses. Half of the opinion-leaders were not concerned about the lack of chemical engineering experience in electricity utility companies. During the first and second follow-up group meetings it was stated that power companies normally had a few experienced chemical engineers, working on water or flue gas treatment, and they expressed strong interest and confidence in the companies’ ability to operate CO<sub>2</sub> capture equipment. In addition to water supply issues, they also asked about the amount of waste water from CO<sub>2</sub> removal processes, because many new power plants in Guangdong are not allowed to discharge waste water into rivers and so waste water must be evaporated by a rather expensive process on-site after which waste chemicals and the dehydrated residue from the waste water are disposed of at special landfill sites. Opinion-leaders were also concerned about the efficiency penalty after retrofitting to capture and about the transport of CO<sub>2</sub> to storage sites.

For participants prioritising ‘sufficient space on-site’ and ‘water supply’, follow-up questions were asked in the online survey. More than 50% of respondents believed that ‘1/8 to 1/4 the size of the power plant’ (2\*600MW plant is used as baseline) is the reasonable extra space needed to host the capture unit and around 30% selected ‘not sure’. Most also believed extra water consumption should ideally not exceed 1/8 of the water requirement of the original plant for a capture retrofit (in water-constrained locations). The results show that opinion-leaders might not be ready for full capture at the moment. The total amount of land required is similar to the size of the power generation unit (Li, 2011), while 1/8 to 1/4 the size of the power plant is smaller than the total generation unit for a power plant. However, this was not made clear for the opinion-leaders at the time of the survey. Because the amount of carbon dioxide captured per kWh of electricity produced from coal is similar to the amount from 90% capture at natural gas power plants (and emissions are similar to unabated natural gas power plants), the possibility of partial capture could help policymakers when drawing up new regulations for different power generation technologies.

In the follow-up group meetings, it was found that some opinion-leaders would consider a side-benefit of reserving more extra space (than expected to be required by the capture facilities) in the hope that a new generation unit could also be permitted in the future. But if no extra unit could be permitted, it was felt that the capture unit should occupy as little space as possible. The extra water consumption was also considered likely to be a problem, especially for some power plants built in areas with water shortage and the strictest water regulation (i.e. zero water pollution). A manager from a city-owned power company in Shenzhen believed that, if power plants are built along rivers, or with good access to water, better cooling could be a factor to reduce the subsequent cost of adding capture device to a CCSR plant.

The survey asked which institutions would be considered as the most appropriate to suggest suitable locations to build CCSR coal-fired power plants in China. There was no consensus among industrial respondents based on the results of the online survey. A majority (58%) would select power companies, national government and local governments. Oil and gas companies, who have geological information, were, however, only prioritised by 20% of respondents.

Based on the qualitative discussions with stakeholders in the focus-group meeting in Shenzhen, we summarise the immediately perceived interests and concerns of developing CCSR by different parties in Table 5.2.

	Local government departments	Oil companies	Power or chemical companies
<b>Like</b>	demonstrate low carbon city	higher income for operation	more land in the area
	increase GDP potentially	secure CO <sub>2</sub> for EOR potential	avoid carbon lock-in
<b>Dislike</b>	consume land and money	lack of operational capacity	cost of capture in future
	efficiency penalty in future	uncertainties in operation	efficiency penalty in future

**Table 5.2 Immediate interests and concerns of developing CCSR based on a qualitative focus-group discussion with 10 power and oil industry opinion-leaders in Shenzhen city**

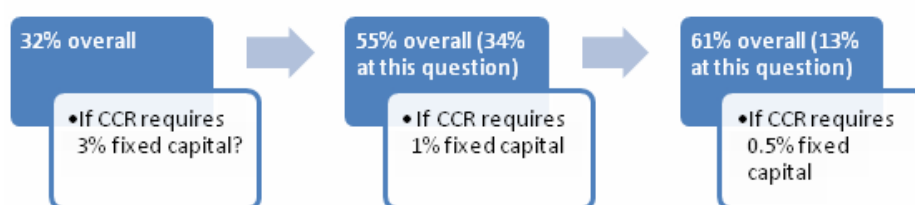
#### **5.4 Perspective of Guangdong Provincial Government on CCSR Regulation and Financing**

There were no consistent views by government officials on the strategies needed to incentivise

CCSR in the next 10 years (2010-2020). ‘Support from foreign public institutions’ (44%) and ‘Market based incentives’ (33%) were viewed as more desirable than ‘Policy mandate for new plants to retrofit capture by a certain date’ (22%) and ‘Provide direct financial subsidy on CCSR investment’ (0%). Generally, Chinese government officials probably considered it was still too early to use significant financial or political resources to accelerate the implementation of CCSR. The lack of a national policy scheme is the main barrier to implement CCSR, especially in China where most utilities companies are controlled by either the state or the local governments.

In the third group discussion with officials from energy companies, most opinion-leaders agreed that it is still early to provide a nationwide policy for CCS or CCSR deployment in China, but three senior managers from oil and power companies believed the Guangdong provincial government could encourage CCSR earlier than the country as a whole, given that a low-carbon economy is a priority in Guangdong’s development plan and CCS could provide Guangdong with an exclusive opportunity to upgrade its energy industry and enhance its offshore service industry. After acknowledging the fact that CCSR has been pioneered in the UK in 2009, a manager from a state-owned power company in Guangzhou suggested the early implementation of CCSR in Guangdong would promote the province or even China’s international image.

It is critical to understand the views and attitudes of Chinese government departments towards CCSR, especially because Chinese energy and environment related government departments have frequently adopted new functions and evolved their structures rapidly over the last ten years (Liang et al, 2008). The government respondents were invited to describe whether CCSR complies or conflicts with different departments’ objectives. The results reveal that most opinion-leaders agreed that deploying CCSR benefits the Ministry of Environment Protection, probably because it potentially strengthens its regulatory and monitoring capacity. There are divergent views on whether implementing CCSR would be consistent or conflict with the objectives of the two major national policymaking departments, the NDRC and the State Council. This could be explained by the complex often conflicting policy objectives of the NDRC and the State Council, for example, the target of reducing energy intensity of GDP may discourage the increased fuel consumption needed to capture CO<sub>2</sub>, but the Chinese carbon intensity target may encourage deployment of CCS. A majority of opinion-leaders believed that local governments would benefit from implementing CCSR.



**Figure 5.5 Responses to questions on the acceptable costs of CCSR in China**

With regard to willingness to pay to implement CCSR, a third of opinion-leaders said they would

be prepared to pay up to 3% on the plant capital cost<sup>21</sup>, more than half agreed to 1% and 60% agreed to 0.5%. The finding by Reiner and Liang (2009) that power industry opinion-leaders are more reluctant to accept the extra fixed capital cost was confirmed, with only 44% accepting 1% extra fixed capital cost and 17% accepting 3%. The overall acceptance is weaker than found in the NZEC study, where 58% of industry opinion-leaders were willing to pay an additional 1%. This discrepancy could be due to the different order of the questions: in this study they started with a higher cost assumption, 3%, while the previous study started with 1% as an example, and then 0.5% or 2% depending on the response (Figure 5.5).

However, in the third focus group discussion, a great majority of opinion-leaders did not consider the additional capital investment as being a key constraint in implementing CCSR at their projects, but they seem worried about the lack of knowledge on CCSR design and land requirement. The CFO from a private power company in Shenzhen suggested that the first few plants with CCSR design may be entitled to a favourable tax rate scheme for hi-tech and innovative enterprises (25% instead of 15% corporate tax rate). This existing incentive could be strong enough to support an extra 3% of initial capital cost to achieve CCSR and formulate retrofitting strategies.

Finally, those responses supporting CCSR advocated as priorities 'Provide incentive for land reservation for on-site for capture unit' (1.9<sup>22</sup>) and 'Consider access to CO<sub>2</sub> storage site' (2.1) as priorities. In group discussions, both (non-CCSR) plants that were investigated were viewed as having very limited space for future full scale retrofit.

Officials from both plants in the first and second focus groups complained that there were currently very strict controls on land use for thermal power plants in China. However, they would be very pleased if CCSR design proposals could help them to reserve more land on-site. It may be due to the fact that both power plants are willing to develop a next phase and therefore they wished to secure the extra land before formal approvals of new units. In the third focus group there were very heated debates on whether or not Chinese coal plants should rely on international financial support. Oil companies and SOE power firms believe it would be more realistic to use domestic resources to support CCSR, but officials from private and city-owned enterprises tend to believe that developed countries should create incentives for China to act on CCSR. Interestingly, we found none of the power companies participating in our face-to-face discussion have investigated the value of a retrofitting option and they have not yet applied any carbon emissions cost in their project appraisal processes.

## **5.5 Discussion and Summary of Findings**

A majority of respondents expressed interest or supportive attitudes towards CCSR, especially those opinion-leaders spending more time on climate change and/or CCS. To implement CCSR in Guangdong, it is urgent to influence project management as well as senior local government officials, with 90% of opinion-leaders from industry considering this factor critical.

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<sup>21</sup> The rationale of 3% is based on the estimation of IEA GHG study on CCR essential design with a clutched low pressure turbine, which is 2.89% (IEA GHG, 2007).

<sup>22</sup> 1 is strongly agreed, 3 is neutral and 5 is strongly disagree.

Besides making sufficient space available on-site and considering access to storage sites from plant locations it is also necessary to investigate local plant design conventions and regulations, such as water constraints and cooling technology. There is no clear signal as to which government departments may have the strongest interest in CCSR, but most of the government officials in this study believed CCSR would be consistent with the objectives of Ministry of Environmental Protection. More than half of the opinion-leaders perceived that 1% extra cost for CCSR would be acceptable, consistent with the NZEC study, but government officials believed that market-based mechanisms or foreign support would be the key driver for CCSR from 2010 to 2020.

*What are potential opportunities of implementing CCSR in Guangdong?*

- (1) Provincial low-carbon energy and industry policy. ‘Low-carbon’ is an important development target for Guangdong province by 2020. In addition, Guangdong is rapidly upgrading its industry structure towards one that is less carbon intensive and more innovative. CCSR policy would provide the Guangdong with the opportunity to develop CCS related industry and strengthen its offshore operation and service industry.
- (2) Diversity of electricity supply. Guangdong is the largest electricity importing province in China. If Chinese domestic carbon emissions policy is tightened or some developed countries impose a carbon-based border tax adjustment or nuclear power projects are delayed, then CCSR can provide some degree of protection by easing the retrofitting of coal-fired power plants and keeping the diverse fuel option open.
- (3) Reluctance to impose mandatory early closure of power plants. The policy of ‘mandatory closing down less efficient plants early’ was a painful experience for many power companies. Guangdong has set a carbon emissions intensity target (i.e. carbon emissions/GDP). The least painful response could be a possible driver to deploy CCSR in new coal-fired power plants in Guangdong, because both power companies and provincial governments would like to minimise the chance that power plants built in the near future are forced to close down early due to the impossibility of retrofitting to CO<sub>2</sub> capture (or ‘carbon lock-in’).
- (4) Applying CCSR design for partial capture. Some opinion-leaders suggest partial capture should be considered rather than full capture in a capture ready plant. As most power plant operators are more willing to spare part of the power plant site for capture ready design, while interest is not significant for full capture at the moment. If a 50% capture ratio is defined, the amount of carbon dioxide captured per kWh of electricity produced from coal is similar to the amount from 90% capture at natural gas power plants.
- (5) Existing innovation incentives. A plant with CCSR design and a clear retrofitting strategy may be entitled to the more favourable 15% tax rate for hi-tech and innovation enterprise whereas the standard corporate tax rate in China is 25%. If applicable, this strategy could be a very strong incentive for the early-movers of CCSR.
- (6) Attracting foreign Investment. Opinion-leaders from power companies and governments in Guangdong strongly believed a benefit of CCSR is that it could attract additional foreign investment to capture CO<sub>2</sub> in a plant’s life time, in contrast with an earlier study finding that relatively few agreed CCS demonstration projects could attract foreign investment. It seems opinion-leaders believed foreign investment should be used to

support the capture and storage elements of a project but is not necessary to support construction of the base power plants. In addition, the recent decision to include CCS in the clean development mechanism (CDM) of the United Nation Framework Convention on Climate Change (UNFCCC) may encourage plant owners to invest in CCSR and to expect a higher income through the flexible mechanism.

*What are potential barriers to implementing CCSR?*

- (1) Lack of policy support schemes. Opinion-leaders consider the lack of policy support for CCSR design in new plants as the main barrier to implement CCSR. In addition, there is no policy signal with regard to the deployment of CCS in China (i.e. when will capture retrofit become mandatory).
- (2) Strict land control. Chinese national government has very strict on land use by power plants, hence the opinion-leaders from power industry concern whether it is possible to have sufficient land for future retrofit. If the land regulation for CCSR is resolved, the extra land reserved on-site could be a strong incentive for implementing CCSR by power plants.
- (3) Lack of information on CCSR design. Given the existing awareness of CCSR and the sub-issues involved in its implementation it would probably be feasible to implement a regular and effective communication framework (Li and Liang, 2010) to further explore and address opinion-leaders' concerns, including through links to the development of CCSR expertise and experience elsewhere (such as in the UK, where CCSR is now a requirement for new power plant permitting (DECC, 2009)). Such a programme has the potential to help accelerate the implementation of CO<sub>2</sub> capture ready designs for new Chinese coal-fired power plants.
- (4) Uncertainties about access to storage site. Some opinion-leaders expressed concerns over the lack of information on the potential storage site.
- (5) Lack of awareness regarding carbon market. A majority of opinion-leaders have no idea how a retrofitting investment may be driven by potential international and domestic carbon market. They are not aware of the option value of retrofitting by investing in CCSR.

## 6. Conclusions and Implications

Technical analyses undertaken for this study show that typical 1GW supercritical steam plant in China can be made carbon capture-ready without compromising performance before CO<sub>2</sub> capture is added to the plant. Carbon capture-readiness would not penalise efficiency.

Typical 1GW supercritical Chinese power plant steam cycles also present the ability to be retrofitted and subsequently upgraded with a range of solvents and meet the principles of good performance with capture, capacity to operate without capture and to be retrofitted with a range of future improved solvents.

Limited additional capital costs (i.e. 0.5% to 3%) would be necessary to implement the following capture-ready measures to ensure that the principles above are met. These low-cost measures would not significantly affect capital costs. The principle additional items to implement carbon capture-readiness to the steam cycle are:

- Access to steam extraction from the IP/LP crossover within the turbine hall
- A tee-piece with a flange for a suitably sized steam off-take to be connected at the IP/LP crossover and a spool piece for the valve (or a spool piece for both),
- Allocate space for a throttling valve in the extraction line downstream of the steam off-take tee,
- Reinforcement of the last IP turbine blades to tolerate pressure and temperature variations at the IP/LP crossover
- Reinforcement of turbine hall foundation for the future addition of a back pressure turbine, ideally at the free end of the alternator (see below)
- Provision for a clutch for connection of an additional back-pressure turbine to the main alternator shaft free end

Economic modelling indicates there is significant value from investing in CCSR at a generic power plant. The potential benefits of CCSR to power companies and to society as a whole include a higher possibility of retrofitting, an earlier mean optimal retrofitting year, significant option value and a lower levelised cost of electricity for power plant investors. Furthermore, the concept of a 'CCS Ready Hub' was assessed, and we found there is significant synergy in implementing CCSR at the regional level rather than for individual power plants. Improving awareness of CCSR amongst local government officials would therefore be valuable.

With regard to financing, though the economic results show investment in CCSR is beneficial, most power companies have not yet included the potential cost of CO<sub>2</sub> emissions in their cash flow analysis of power plant feasibility studies. There is an urgent need to develop awareness amongst power plant investors of the possibility of future carbon prices. This 'price discovery' process could be driven by the interest of senior local government officials or by communication with power companies about the international carbon market. In addition, although CCSR itself does not reduce carbon emissions directly, the prospect of CCS being financed by the CDM may encourage power companies to make a modest investment in CCSR.

The extent to which CCSR is valued in Guangdong is likely dependent on a number of site-specific engineering and market assumptions. Thus, it is crucial to have a detailed engineering survey on one or more specific power plants in Guangdong and geological surveys of potential storage sites around the region. The follow-up studies would also address some concerns by opinion-leaders in power companies. Even though this study focuses on Guangdong province, the results and methodologies may provide a reference for studies investigating CCS and the implementation of CCSR in other regions of China.

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## **Appendix I - List of Papers Published or Presented**

Li, J., Liang, X., Cockerill, T., (2011), Getting ready for carbon capture and storage through a ‘CCS Ready Hub’: a case study of Shenzhen City in Guangdong Province, China. *Energy* 36, 5916–24.

Li, J., Liang, X., Cockerill, T., Gibbins, J., Reiner, D., (2012), Opportunities and Barriers for Implementing CO<sub>2</sub> Capture Ready Designs: A Case Study of Stakeholder Perceptions in Guangdong, China. *Energy Policy* 45, 243-251.

Liang, X., Li, J., (2012), Assessing the value of retrofitting cement plants for carbon capture: A case study of a cement plant in Guangdong, China. *Energy Conversion and Management* 64, 454-465.

Li, J., Liang, X., Gibbins, J., Lucquiaud, M., Reiner, D., Zhou, D., (2012), The Techno-economic Prospect of Retrofitting Natural Gas Combined Cycle Power Plants in China: a case study of CCGT power plants in Huizhou and Shenzhen, Guangdong. (will be submitted to an academic journal)

Liang, X., Pang, Z., Lucquiaud, M., Gibbins, J., Li, J., Zhou, D., (2012), Valuing CCS Ready with Upgrade and Operational Flexibilities in Coal-fired Power Plants in Guangdong, China. (will be submitted to an academic journal)

## **Appendix II Guangdong Cement Plant Study**

Please cite the following article as

Liang, X., Li, J., 2012. Assessing the Value of Retrofitting Cement Plants for Carbon Capture: A Case Study of a cement plant in Guangdong, China. *Energy Conversion and Management* 64, 454-465.

### **Assessing the Value of Retrofitting Cement Plants for Carbon Capture: A case study of a cement plant in Guangdong, China**

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## Abstract

The cement manufacturing sector is the second largest source of anthropogenic greenhouse gas emissions in the world. Carbon capture and storage (CCS) is one of the most important technologies to decarbonise the cement manufacturing process. China has accounted for more than half of global cement production since 2008. This study suggests criteria to assess the potential to retrofit cement plants and analyses the economics of retrofitting cement plants for CCS with a case study of a modern dry process cement plant locating in Guangdong province, China. The study assumes the extra heat and power for CO<sub>2</sub> capture and compression is provided by a new 200MW combined heat and power unit (CHP) (US\$17.5/MWth for the cost of coal). The estimated cost of CO<sub>2</sub> avoidance by retrofitting a cement plant for carbon capture in 2012 is US\$70/tonne at a 14% discount rate with 25 years remaining lifetime. Through a stochastic cash flow analysis with a real option model and Monte Carlo simulation, the study found the value of an option to retrofit to be US\$1.2 million with a 7.3% probability of economic viability. The estimate is very sensitive to the assumptions in the carbon price model (i.e. base carbon price is US\$12.00/tCO<sub>2</sub>e in 2012 and the mean growth rate is 8%). The option value and the probability can reach US\$20 million and 67% respectively, if a 10% mean carbon price growth is assumed. Compared with post-combustion carbon capture retrofitting prospect in existing coal-fired power plants, the economics of retrofitting cement plants to carbon capture is less attractive. However, given the uncertainties in climate policy, regulation and carbon market, new-build cement plants in China, with long lifetime, should consider an essential level of “CCS Ready” to reduce the cost of retrofit and keep the retrofitting option open.

**Key Words:** CO<sub>2</sub> capture, Cement, Economics, Finance, Retrofit, China, optimisation

## 1. Introduction

Carbon Capture and Storage (CCS) is recognised as one of the most important technologies to reduce greenhouse gas emissions [1]. After power generation, cement production is the second largest source of anthropogenic CO<sub>2</sub> emissions accounting for approximately 7% of total emissions in the world [2]. Growing at an average rate of 11% in the last three decades, Chinese cement production reached 1.87 billion tonne in 2010, equivalent to 55% of the world's cement production [3, 4]. Most Chinese cement plants were built in the last decade. The lifetime of modern cement plants is usually 30 to 50 years [5]. Therefore, retrofitting existing cement plants to CO<sub>2</sub> capture is an important strategy to decarbonise the cement production process.

Since 2005, though no large-scale CO<sub>2</sub> capture project has been implemented on cement plants, a number of studies have been conducted to investigate the engineering requirements of new build CO<sub>2</sub> capture plant in the cement industry [5-11]. However, only limited estimates have been made of the cost of CO<sub>2</sub> capture in the cement industry [2, 12-14]. Hassan [12] investigated the costs of capturing CO<sub>2</sub> from a hypothetical cement plant in Canada with high flue gas CO<sub>2</sub> concentration and found a cost of US\$49/tonne CO<sub>2</sub> captured. Ho et al [14] through analysing a hypothetical monoethanolamine-based (MEA) post-combustion CO<sub>2</sub> capture process equipped cement plant in Australia calculated a cost of CO<sub>2</sub> avoidance of US\$68/tonne, 15% less than the cost of CO<sub>2</sub> avoidance of capturing CO<sub>2</sub> from a pulverised coal-fired power plant. Kuramochi et al identified post-combustion as the only commercial technology in the short term and the costs

are above €65/tCO<sub>2</sub>e, but they believed the capture costs from cement plants with improved technologies could be reduced to €25 to €55 /tCO<sub>2</sub>e in the long term [15]. On the other hand, even though International Energy Agency (IEA) and United Nations Industrial Development Organisation (UNIDO) estimated that two thirds of global CCS projects in the cement industry are in Africa or developing Asia by 2050 [16]. Cement plants have been identified as key stationary sources for installing CO<sub>2</sub> capture in the Chinese Carbon Capture, Utilisation and Storage (CCUS) technology roadmap [17]. However, all of these studies focused on cement plants in developed countries. To bridge the literature gap, this paper analyses the economics of retrofitting a cement plant for CO<sub>2</sub> capture, using a cement plant in Guangdong China as a case study.

The paper aims to address the following three research questions.

- 1) What is the cost of CO<sub>2</sub> avoided to retrofit a cement plant for carbon capture, through a case study of a large cement plant in China?
- 2) How possible is it to retrofit a cement plant to carbon capture during its lifetime?
- 3) What are the policy implications for new build cement plants in China?

## 2. Methodology

The methodology of this study includes four steps: (a) Assessing the retrofitting potential of large cement plants to shortlist a cement plant for this study; (b) Designing the post-combustion CO<sub>2</sub> capture process located next to the underlying cement plant; (c) Evaluating the cost of CO<sub>2</sub> avoidance and the cost structure by a discounted cash flow (DCF) approach; (d) Assessing the economics of retrofitting for CO<sub>2</sub> capture through a real option analysis.

A number of studies have investigated the technical and engineering design requirements to retrofit thermal power plants to CO<sub>2</sub> capture [18-23], but very few studies have focused on the prospect of retrofitting cement plants. Building on the literatures in retrofitting coal-fired power plants to CO<sub>2</sub> capture, and a survey of cement plants in Guangdong, China, it is suggested that the following six categories of criteria are relevant in evaluating the CO<sub>2</sub> capture retrofit potential of a cement plant (listed in Table 1). Categories A, B, C, and D are essential, and must be considered when assessing the retrofitting potential. Categories E and F are desirable requirements in the evaluation. These criteria are applied to assess the retrofitting potential of cement plants in Guangdong, China.<sup>24</sup>

We develop a process model of CO<sub>2</sub> capture plant building on an existing post-combustion CO<sub>2</sub> capture model for retrofitting an ultra-supercritical coal-fired power plants to CO<sub>2</sub> capture in China[20]. The first step is to define the properties of the mix of flue gas streams from the base cement plant. The second step is to add extra FGD and SCR units for purifying the flue gas stream before CO<sub>2</sub> capture. Then a post-combustion CO<sub>2</sub> capture model using monoethanolamine (MEA) as solvent is added after the additional FGD and SCR units. The auxiliary load for producing extra heat for CO<sub>2</sub> separation and electricity for CO<sub>2</sub> compression is assumed to be provided by an extra combined heat and power (CHP) plant. The CO<sub>2</sub> emissions in the flue gas of the CHP plant (after the electrostatic precipitator process, ESP) will be mixed with flue gas

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<sup>24</sup> The study surveyed modern cement plants larger than 2500t/day in Guangdong, China and shortlisted the New Guangzhou Cement plant for this study.

streams from the existing CHP and the cement process. The mixed flue gas is then fed into purification (i.e. SCR, FGD) and CO<sub>2</sub> separation facilities with MEA.

Table 1 List of Criteria for Assessing the Potential to Retrofit Cement Plants

<b>A. Extra space on site (Essential)</b>	<ul style="list-style-type: none"> <li>➤ Sufficient space for building a post-combustion capture unit including a possible combined heat and power (CHP) plant</li> <li>➤ The space to accommodate CO<sub>2</sub> capture facilities should be close to the preheater and kiln</li> <li>➤ Sufficient space for compressing and temporarily storing CO<sub>2</sub></li> </ul>
<b>B. Access to storage site (Essential)</b>	<ul style="list-style-type: none"> <li>➤ Transport of the captured carbon dioxide to potential storage site</li> <li>➤ The method selected for the transportation of CO<sub>2</sub> will not cause major health and safety concerns along the proposed route to the storage site</li> </ul>
<b>C. Water supply and process water treatment issue (Essential)</b>	<ul style="list-style-type: none"> <li>➤ Process and cooling water supply for the post-combustion capture plant</li> <li>➤ Cooling water supply for new-build energy generation plant (e.g. CHP)</li> <li>➤ Waste water treatment requirement</li> </ul>
<b>D. Sufficient power and steam supply (Essential)</b>	<ul style="list-style-type: none"> <li>➤ Existing power supply for cement plant</li> <li>➤ Distance from the existing power plant to preheater and kiln (if applicable)</li> <li>➤ Potential of co-locating with other large power plants for retrofit (if applicable)</li> </ul>
<b>E. Technology for cement production (Desired)</b>	<ul style="list-style-type: none"> <li>➤ Raw meal type (dry, semi-dry, semi-wet or wet)</li> <li>➤ Kiln design</li> <li>➤ Plant size</li> <li>➤ Remaining plant life</li> <li>➤ Electrostatic precipitator (ESP)</li> <li>➤ Selected catalytic reduction (SCR)</li> <li>➤ Flue gas desulphurisation (FGD)</li> </ul>
<b>F. Flue Gas properties (Desired)</b>	<ul style="list-style-type: none"> <li>➤ Concentration of CO<sub>2</sub> in the waste gas stream</li> <li>➤ Concentration of other gases that might poison the solvent (in post combustion capture, SO<sub>x</sub>, NO<sub>x</sub> and dust level should be considered)</li> <li>➤ Other impurities in the waste gas stream</li> <li>➤ Identify strategies to capture CO<sub>2</sub> from the additional energy generation facilities (e.g. CHP)</li> </ul>

In regard to the cost estimate for retrofit, building a conventional cash flow model, the cost of CO<sub>2</sub> avoidance (in US\$/tCO<sub>2</sub>e) is analysed in the hypothetical CO<sub>2</sub> capture retrofit case in the cement plant (given by 2-1). It is a better indicator when a make-up plant is used to maintain the original output. The disadvantage of using the cost of CO<sub>2</sub> avoidance is that it does not take into account the opportunity cost of losing output. However, the cost of CO<sub>2</sub> avoidance is easier to compare across industries and countries. The cost assumptions of each component in the post-combustion capture process are set out in section 3. The investment cost data was projected based on public information sources as well as consultations with the cement plant owner, two local design institutes with experience in designing flue gas clean-up process and chemical plant

design, and a consultant company who has conducted CCS cost studies for thermal power plants in Guangdong. The equipment cost for CO<sub>2</sub> capture and compression was also based on communication with colleagues in designing large CO<sub>2</sub> capture pilot plants in China (Table 3). Because the perceived required return for CCS projects in China are divergent<sup>25</sup> [24], we conducted a sensitivity analysis on discount rate assumptions.

$$Q = \frac{\sum_{i=1}^n (I_i + O_i) / (1+r)^i}{\sum_{i=1}^n (E_{c,i} - E_{b,i}) \times Y_i / (1+r)^i} \quad (2-1)$$

where  $I_i$  is the investment cash flow for CO<sub>2</sub> capture at year  $i$ , including all the capital investment;  $O_i$  is the operating cash flow for CO<sub>2</sub> capture at year  $i$ ;  $E_{c,i}$  is the emissions factor with CO<sub>2</sub> capture at year  $i$ ,  $E_{b,i}$  is the baseline emissions factor (i.e. a plant without CO<sub>2</sub> capture or an acknowledged baseline) at year  $i$ ;  $Y_i$  is the total production at year  $i$ ;  $r$  is the required rate of return of total capital (i.e. discount rate).

### ***Economics of Retrofitting to CO<sub>2</sub> Capture***

Because a deterministic approach (such as annuity, DCF) fails to consider the value of inherent flexibilities and uncertainties of running an energy technology, a real option approach (ROA) is often applied by scholars in evaluating a project investment decision taking into account uncertainties [25-26]. In this case, the retrofitting decision is a real option problem. At each decision node<sup>26</sup> (assumed the end of each year), investors could exercise the option of retrofitting the cement plant to capture CO<sub>2</sub> or defer the option to a later date. In order to inform the retrofit decision, a real option analysis is conducted through a stochastic cash flow model to understand the value of retrofitting options in the cement plants, and to derive the probability that the plant will be retrofitted for CO<sub>2</sub> capture.

The ROA framework with American style claims (i.e. options could be exercised anytime from now to any expiry date) is applied and therefore a backward looking algorithm is needed to find the optimal exercise boundary. The evaluation process includes three steps. First, we identify the sample paths of the case; second, we apply a heuristic approach, using a least square method with Monte-Carlo simulation (40,000 trials in this case) to estimate the value and probability of retrofitting and continuing at each decision node on each sample path through a backward deduction process. If the plant is not retrofitted before year  $t$ , the estimated present value of subsequent retrofitting options at year  $t$  is given by 2-2. If a cement plant is retrofitted at year  $t$ , the present value of the mean marginal benefit of capturing CO<sub>2</sub> (if the retrofitting option is

<sup>25</sup> UK-EU-China near zero emission coal (NZE) project interviewed 16 financial stakeholders and found that the required returns for power plants and development banks were below 8%, but the rates for other energy companies and commercial banks are above 12%.

<sup>26</sup> The timing, at which, the management would investigate the economics of carbon capture retrofitting option, and decide whether or not exercising the retrofitting option. In a theoretical model, there could be continuous decision nodes in the power plant's life. However, because assessing the retrofitting option may incur significant sunk cost in reality, the study assumes the retrofitting decision is made once a year until the plant retrofitted or the end of plant life.

anticipated to be exercised in year  $t$ ) is given by 2-3. Finally, the value of retrofitting option is identified. The initial value of the retrofitting option will be equal to the estimated present value with subsequent retrofitting options held at the year 0.

$$V_t^c = \frac{1}{d_1} (p_{t+1}^r V_{t+1}^r + p_{t+1}^c V_{t+1}^c) \quad (2-2)$$

where  $d_1$  denotes the discount rate in the option analysis,  $p_{t+1}^r$  is the estimated probability of retrofit at year  $t+1$  estimated through simulations,  $p_{t+1}^c$  is the estimated probability of continuation at year  $t+1$ ,  $V_{t+1}^r$  is the estimated present value of marginal cost cash flow of retrofitting at year  $t+1$ ,  $V_{t+1}^c$  is the estimated value of continuation with remained retrofit options at year  $t+1$

$$V_t^r = \sum_{n=t}^L \left[ \left( \frac{1}{d_2} \right)^{n-t} (F_n^{r,t} - F_n^b) \right] - K_t \quad (2-3)$$

where  $d_2$  denotes the discount rate for carbon capture investment,  $F_n^{r,t}$  is the estimated mean expected cash flow of retrofit at year  $n$  affected by the retrofit investment at year  $t$ ,  $F_n^b$  is the estimated baseline cash flow at year  $n$  without the retrofit option and  $K_t$  is the one-off investment for retrofit at year  $t$ .

The initial carbon price in 2010 is taken as US\$12/tCO<sub>2</sub>e, by reference to the then prevailing approximate price in the CDM (Clean Development Mechanism) market<sup>27</sup> [27]. The hypothetical cost for transport, storage and monitoring is assumed as US\$10 per tonne CO<sub>2</sub> captured under the assumption that the CO<sub>2</sub> will be transported through a potential CO<sub>2</sub> pipeline network in the Pearl River Delta CCS ready hub. The assumption considers factors and scenarios identified in existing literatures [28, 29]. The initial coal price is taken as US\$17.5/MWh<sub>therm</sub>, by reference to the average coal price in Guangdong in 2010 [30]. The ROA model normally applies a risk-free rate or a lower discount rate. Consequently a 6% real discount rate ( $d_1$ ) has been applied to calculate the option value while 8% real discount rate ( $d_2$ ) has been applied for discounting cost cash flow after retrofit. The study assumes that both the price of CO<sub>2</sub> emissions and the annual average price of coal follow a GBM (Geometric Brownian Motion) process with mean reverting, given by 2-4. The standard deviation and mean reverting ratio of coal price is estimated based on Guangdong coal price during the past 10 years [30]. There is very limited information on annual carbon price in China; hence the assumptions of standard deviation and mean reversion ratio of carbon prices are hypothetical.

$$P_t = P_{t-1}(1 + \alpha) + \pi(P_L - P_{t-1}) + Z \quad (2-4)$$

Where  $\alpha$  is the drift,  $\pi$  is the mean reverting rate,  $P_t$  is the price at year  $t$ ,  $P_L$  is the long run equilibrium price,  $Z$  follows a standard Wiener process.

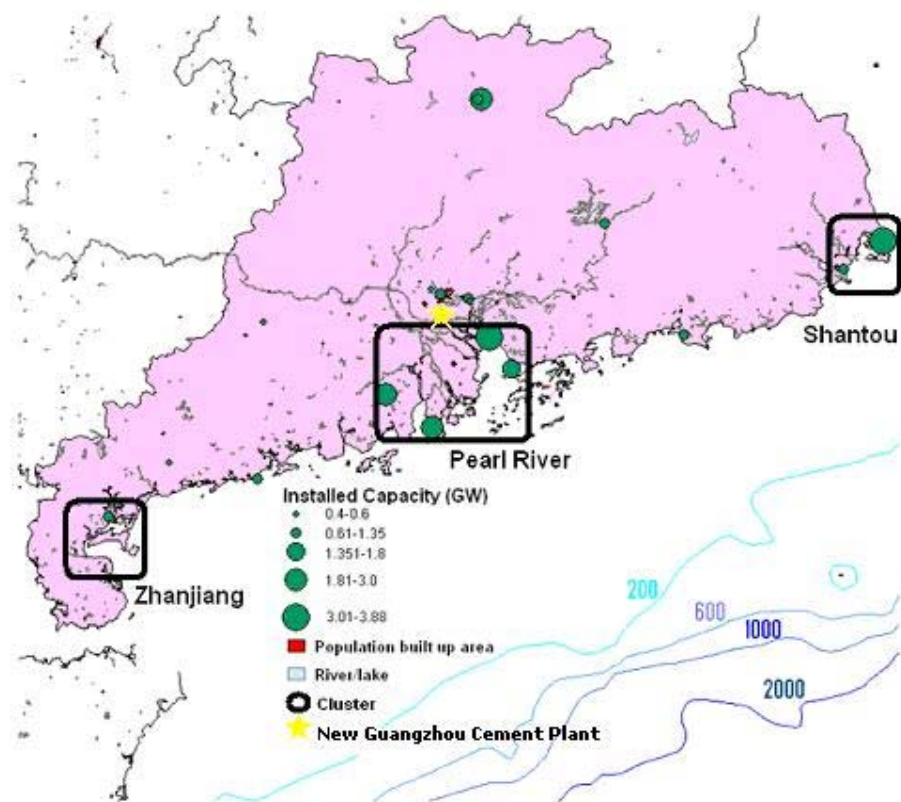
### 3. Technical and Economic Assumptions

#### Base Cement Plant

The New Guangzhou Cement Plant in Huadu district is chosen for a case study, because it is

<sup>27</sup> The floor carbon price for CDM price set by the Chinese government was €7/tCO<sub>2</sub>e in 2011.

the only large modern cement plant located next to the Pearl River Delta CCS Ready Hub<sup>28</sup> in Guangdong [29] (location shown in Figure 1). Zhou et al [31] estimated there is significant CO<sub>2</sub> storage capacity with an estimate of 308 Gt on average in the Pearl River Delta Mouth Basin. The cement plant was commissioning in 2007, with investment from the Heidelberg Cement and Yue Xiu Group<sup>29</sup>.



Note: New Guangzhou Cement Plant (Star); Installed Capacity of Large Thermal Power Plants (Green Dot)

Figure 1 Three Proposed CCS Ready Hubs in Guangdong and the location of the underlying cement plant investigated in this study

The baseline annual dry cement output of the new Guangzhou Cement Plant is 2 million tonnes per year (i.e. 6000 tonne/day and running full capacity for 333 days a year). The lifetime of the plant was assumed to be 30 years, from 2007 to 2036. The design parameters and emissions of the plant can be found in Table 2 and Figure 2. After raw material is prepared and sent to the raw mill, the moisture content is less than 0.5% (w/w) and more than 13.3% of the meal has a size of less than 80µm in diameter. The plant has a 5-stage twin pre-heater with precalciner design. The cement plant is designed for anthracite coal, but it is actually operated with a blend of anthracite

<sup>28</sup> CCS ready hub is a capture ready concept to maximise the benefits of deploying 'CCS Ready' design at a regional planning level instead of an individual project with consideration of both existing plants and new plants (20).

<sup>29</sup> The cement business of Yue Xiu group was purchased by China Resources Cement Holding Limited in January 2011.

and bituminous coal. The regulated limit of SO<sub>x</sub> and NO<sub>x</sub> emissions from cement plants in China are 400 mg/N<sup>3</sup> and 800 mg/N<sup>3</sup> respectively [32]. The monitored SO<sub>x</sub> and NO<sub>x</sub> emissions are 160-260 mg/N<sup>3</sup> and 420-545 mg/N<sup>3</sup>, with the estimated CO<sub>2</sub> emissions of 1.66 million ton per year. Approximately 60% of the carbon dioxide comes from the calcination of limestone, and the rest from the combustion of coal.

**Table 2 Design Parameters and Emissions of the New Guangzhou Cement Plant**

	Parameters	Value
Site Conditions	Ambient air Temperature	25°C
	Ambient air pressure	1.013 bar
Operational Conditions	Capacity	6000 t/d or approximately 2 million tonne per year (the actual production could reach 6500 t/d)
Raw Mill	Moisture content (Raw meal existing raw mill)	≤0.5% (w/w)
	Size (Raw meal existing raw mill)	R80μm≤13.3%
	Electricity consumption:	19.6kwh/t generated by a 100MW self-supplied combined heat and power (CHP) plant
	Feed capacity (dry base)	560t/h
Preheater	Supplied by KHD (Germany)	5 stages double train (includes precalciner)
Rotary Kiln	Feed	Anthracite coal (designed coal) Blend of Anthracite and Bituminous coal (actual consumption)
	Moisture content of dried coal	Between 1.48% to 3.95%
Main Products	Type A	86% Clinker; 4% Gypsum; 10% Coal Ash
	Type B	86% Clinker; 4% Gypsum; 10% Limestone
	Type C	88% Clinker; 4% Gypsum; 3% Limestone
	Type D	90% Clinker; 4% Gypsum; 6% Limestone
Emissions	SO <sub>x</sub>	160-260 mg/N <sup>3</sup>
	NO <sub>x</sub>	420-545 mg/N <sup>3</sup>
	CO <sub>2</sub>	1.66 million tonne pa (estimated total)

A simplified process flow diagram (PFD) for the capture plant is shown in Figure 2. The clinker and cement production plants both already exist on site. Raw meal is first heated to 220°C at 7 to 9 mini bar below atmospheric pressure. The meal then enters the mill at a rate of 560t/h. The fine meal exits the mill at 80-110 °C and goes into the 5-stage twin preheater with precalciner, operating at 855-865 °C. The treated meal is then fed into the rotary kiln, but at a reduced rate of 230t/h due to the calcination of limestone. Reacting with coal in the kiln, the clinker is produced at approximately 250t/h. After the cooling process, cement is produced and packaged on the same site. An existing onsite plant using waste heat from the kiln produces electricity for the raw mill, coal mill and kiln.

### Carbon Dioxide Capture Plant

In terms of the design of CO<sub>2</sub> capture plant, the proposed post combustion CO<sub>2</sub> capture plant (Figure 2) should be close to the preheater and kiln, because it saves energy required to transport the waste gas to the CO<sub>2</sub> treatment plant. The SO<sub>x</sub> and NO<sub>x</sub> concentration in the raw mixed flue gas is much higher than the requirement of the MEA separation process, thus extra SCR and FGD facilities are installed after the ESP unit on the site to reduce the SO<sub>x</sub> and NO<sub>x</sub> level to below 10ppm at 3% O<sub>2</sub>. After the SO<sub>x</sub> and NO<sub>x</sub> removal treatment, the waste gas will then enter the absorber and react with MEA. Thereafter, the CO<sub>2</sub>-rich MEA will be fed into the desorber and the waste gas, mainly nitrogen, can be vented into the atmosphere. After the CO<sub>2</sub> is separated from the MEA, it will be compressed and transported to the storage site.

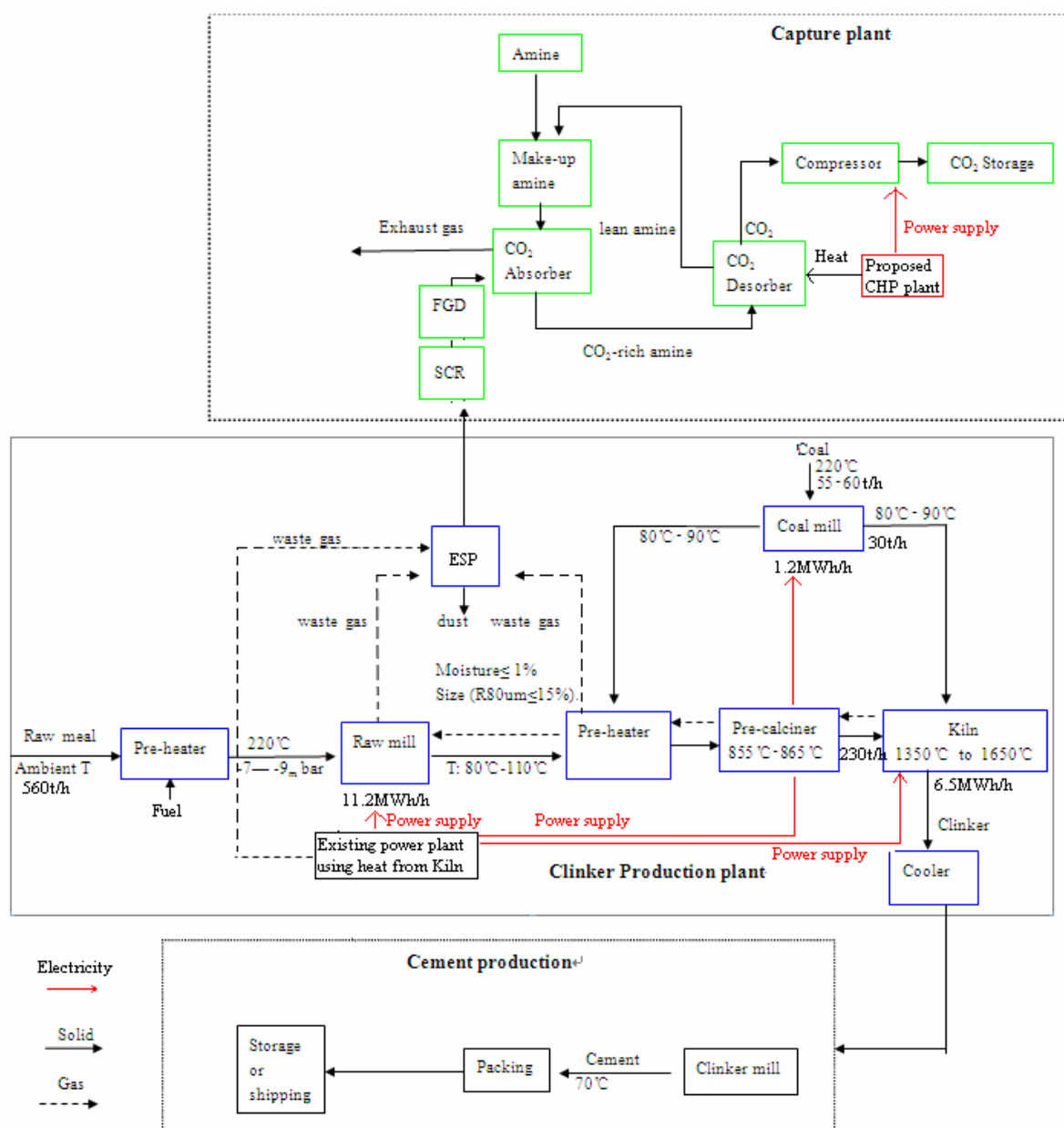


Figure 2 Block Flow Diagram of Post-combustion CO<sub>2</sub> Capture Retrofit Process in the New Guangzhou Cement Plant

In this design, we assume the extra power requirements (for compression) and steam requirement (for CO<sub>2</sub> separation) comes from a new-build 200MW CHP plant. However, co-locating a new-build thermal power plant within 5km of the cement plant is another possible approach. The thermal power plant co-location design can provide a convenient source of steam for the desorber and other CO<sub>2</sub> capture facilities. A longer term possibility is to co-locate the plant with a higher efficiency calcium looping power plant [33-36].

The additional capital cost of post-combustion CO<sub>2</sub> capture in a cement plant is estimated to be US\$ 210.4 million, including US\$126.4 million for post-combustion plant and US\$84 million for CHP (Table 3). The post-combustion CO<sub>2</sub> capture facility includes 4 key components: selective catalytic reduction, flue gas desulphurisation, CO<sub>2</sub> capture stripper and absorption tower, and compression and purification units. The estimated total cost of equipment is US\$59 million (as shown in Table 3). The cost of design, construction and other services (e.g. staff supervision, training, construction staff insurance) is estimated at US\$50 million.

**Table 3 Estimated Investment Cost for CO<sub>2</sub> Capture Retrofit in the Cement Plant (excl. CHP)**

	Estimated Cost (million US\$)
<i>Selective catalytic reduction (SCR)</i>	5.1
<i>Flue gas desulphurisation (FGD)</i>	20.9
<i>CO<sub>2</sub> capture stripper, reboiler, absorption tower</i>	27.1
<i>Compression and purification units</i>	6.4
<b>Estimated Total Equipment Cost</b>	<b>59.5</b>
<i>Design costs</i>	14.7
<i>Construction costs</i>	26.0
<i>Other costs</i>	9.3
<b>Estimated EPC Cost</b>	<b>109.0</b>
<i>Contingency</i>	8.9
<i>Owners costs</i>	4.6
<i>Fees</i>	3.4
<b>Total Investment Cost</b>	<b>126.4</b>

The estimated total fixed operating and maintenance costs (O&M) for CO<sub>2</sub> capture is \$8.9 million per year (as shown in Table 4). The fixed O&M includes the maintenance expenditure, the cost of labour (i.e. 40 est. staffs), the management expense and insurance. The estimated variable costs for CO<sub>2</sub> capture are US\$61.4 million/year (of which US\$49.5m/yr. cost of electricity is offset by the electricity supplied from CHP) and the variable cost of CHP is US\$41.3 million/year (as shown in Table 5 and Table 6).

**Table 4 Estimated Fixed O&M Cost for CO2 Capture Retrofit in the Cement Plant (excl. CHP)**

	Estimated Cost (million US\$ /year)
<i>Plant maintenance</i>	5.0
<i>Labour</i>	2.4
<i>Management and supervision</i>	1.0
<i>Insurance</i>	0.5
<b>Estimated Total Fixed Operating Cost</b>	<b>8.9</b>

**Table 5 Estimated Variable Costs for CO2 Capture Retrofit in the Cement Plant (excl. CHP)**

	Unit Cost (US\$)	Annual Consumption	Cost US\$/year)	(million
<i>Limestone for an extra FGD</i>	6.5/tonne	24400 tonne		0.16
<i>Ammonia for SCR</i>	715/tonne	4200 tonne		3.00
<i>MEA</i>	1690/tonne	5000 tonne		8.45
<i>Electricity - post combustion (mainly for CO2 compression)</i>	110/MWh (average)	450,000 MWh		49.50
<i>Cooling water for post-combustion</i>	0.3/tonne	500,000 tonne		0.15
<i>Process water and treatment for post-combustion</i>	0.6/tonne	300,000 tonne		0.18
<b>Total Variable Operating Costs</b>				<b>61.4</b>

**Table 6 Estimated Costs and Revenue for a new-build 200MW Combined Heat and Power Plant for CO2  
Post-combustion Capture Retrofit**

	Unit Cost or Price	Annual Total	Cost or Revenue (million US\$/year)
<i>Annual Electricity Production</i>	US\$ 110/MWh (average)	479,500 MWh	52.75
<i>Annual Heat Production</i>	n/a	1,118,000MWh (thermal)	n/a
<i>Total Investment Cost</i>	420/kW		84.00
<i>Coal Cost</i>	US\$17.5/MWth	2,219,900 MWth	38.85
<i>Cooling Water Cost</i>	US\$0.3/tonne	8,200,000 tonne	2.46
<i>Fixed O&amp;M Cost</i>			2.50
<b>Total CHP Operating Cost</b>			<b>43.80</b>

The annual emissions from the base cement plant are assumed to be 1.66 million tonne and those from the new-build CHP to be 0.87 million tonne (Table 7). A total of 85% of CO2 emissions or 2.15 million tonnes are assumed to be captured annually. The emission factor is reduced from 0.831 to 0.183. The study uses the original base plant emission factor as the baseline, thus the emissions avoided are 0.648 tCO2e/tonne cement or 77.9%. On average, 0.52 MWth

heat (steam) 0.21 MWh electricity is required to capture and compress per tonne of CO<sub>2</sub> from the cement plants.

**Table 7 Baseline CO<sub>2</sub> emission and estimated CO<sub>2</sub> emission with CO<sub>2</sub> Capture**

Parameters	Performance
Annual Cement Production	1.998 million tonne
Baseline Total CO <sub>2</sub> Emissions	1.660 million tonne
Baseline CO <sub>2</sub> Emissions Factor	0.831 tCO <sub>2</sub> e/tonne cement
Estimated CO <sub>2</sub> emissions from new-build CHP	0.87 million tonne
CO <sub>2</sub> Captured (85% capture ratio)	2.151 million tonne
Adjust: CO <sub>2</sub> emission in exported electricity*	0.0133 million tonne
CO <sub>2</sub> emitted due to cement production	0.366 million tonne
Emission factor with CCS	0.183 tCO <sub>2</sub> e/tonne cement
CO <sub>2</sub> Avoided	0.648 tCO <sub>2</sub> e/tonne cement
Percentage of CO <sub>2</sub> Avoided	77.94%

\* CO<sub>2</sub> emissions of 295,000MWh net export electricity is deducted to calculate the CO<sub>2</sub> emission due to cement production (the 2010 build margin emission factor in Guangdong set by NDRC, RMB 0.45/kWh) is applied

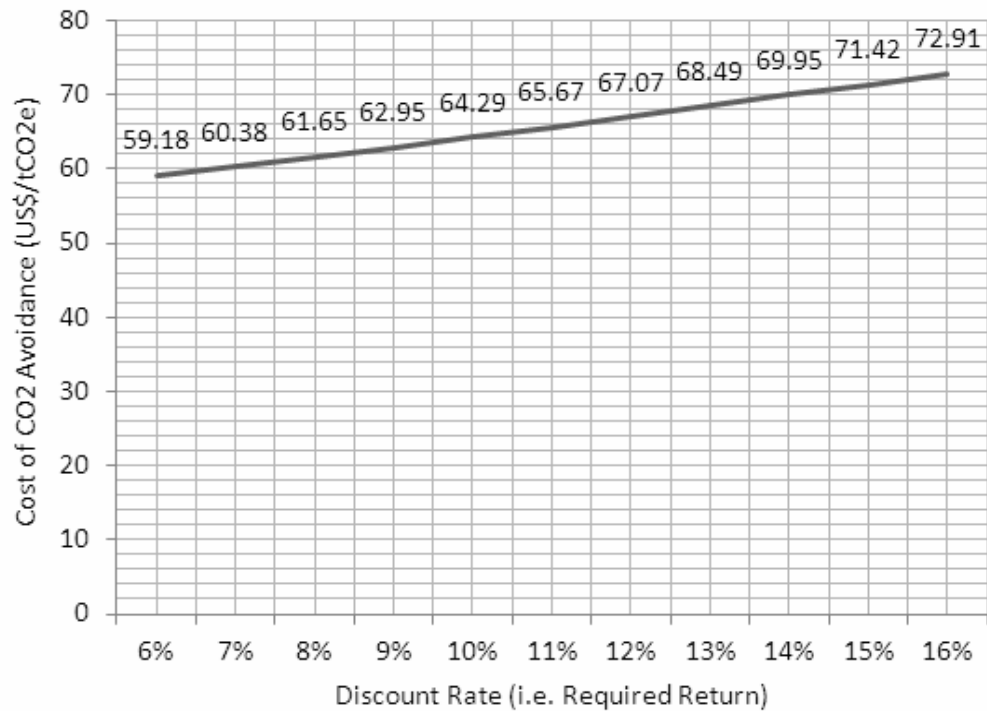
## 4. Results and Discussions

### Costs of Retrofitting to Capture

Through a static cash flow analysis, we found the cost of CO<sub>2</sub> avoidance assuming retrofitting in 2012 to be US\$70 at a 14% discount rate (Figure 3). The variable cost, mainly the cost of purchasing coal, contributed 51% of the cost of CO<sub>2</sub> avoidance. If the retrofit is decided in 2019 and takes place in 2020, the cost of carbon avoidance rises 2% to \$71.3/tCO<sub>2</sub>e. Furthermore, when a US\$10/tonne levelised cost of CO<sub>2</sub> transport, storage and monitoring (in US\$/tCO<sub>2</sub>e) is added, the cost of carbon avoidance will increase to US\$86.1/tCO<sub>2</sub>e.

As illustrated in Figure 3, the cost of CO<sub>2</sub> avoidance is very sensitive to the total capital discount rate assumption. Using a 10% discount rate, the cost of CO<sub>2</sub> avoidance will be reduced to US\$64.3/tCO<sub>2</sub>e. This is much lower than the estimate of new build post-combustion CO<sub>2</sub> capture in the IEA GHG study in 2008 [7] (as shown in Table 8), because (1) the capital investment (construction cost) and fixed O&M is lower in China (2) the baseline emission factor is higher in this study. However, the cost in Guangzhou China is approximately 4% higher than the estimate of new-build CO<sub>2</sub> capture in a generic cement plant in Australia [14], because the lower capital cost advantage is offset by a higher coal price in Guangdong, a higher discount rate assumption in this study, and the cost disadvantage of retrofit instead of new-build. On the other hand, the cost of CO<sub>2</sub> avoidance in post-combustion CO<sub>2</sub> capture cement plants is estimated US\$41/tCO<sub>2</sub>e higher than that of post-combustion capture coal-fired power plants in China<sup>30</sup> [37].

<sup>30</sup> Estimates are based on MEA post-combustion capture from a 621MWe supercritical power plant according to the UK-China Near Zero Emission Coal (NZE) study.



**Figure 3 Estimated Cost of CO2 Avoidance (assuming decision made by the end of 2011 and retrofit in 2012) versus Discount Rate Assumptions**

**Table 8 Comparisons of Forecasted Costs of CO2 Avoidance in CO2 Capture Cement Plants**

Study	This study (2011)	IEA GHG 2008 Study [7]	Study by Ho et al in 2011 [14]
<b>Location</b>	Guangdong, China	North East Scotland UK	Australia
<b>Capture Technology</b>	PC-MEA, Retrofit	PC – MEA New Build	PC – MEA New Build
Source of extra energy for CO2 capture	Coal CHP with capture	Coal CHP with capture	Natural Gas CHP with capture
CO2 Capture Rate	85%	85%	89%
CO2 Captured (million tonne)	2.15	1.07	0.77
<b>Discount Rate</b>	14%	10%	7%
<b>Cost of CO<sub>2</sub> emissions Avoided (€/tCO<sub>2</sub>e)</b>		107	
<b>Cost of CO<sub>2</sub> emissions Avoided (AU\$/tCO<sub>2</sub>e)</b>			76
<b>Cost of CO<sub>2</sub> emissions Avoided (US\$/tCO<sub>2</sub>e)</b>	70	161 <sup>31</sup>	68 <sup>32</sup>

Note: Transportation, storage monitoring costs are not included in the estimates above.

<sup>31</sup> The original estimate is in euro.

<sup>32</sup> The original estimate is in Australian dollar.

## Value of Retrofitting Options

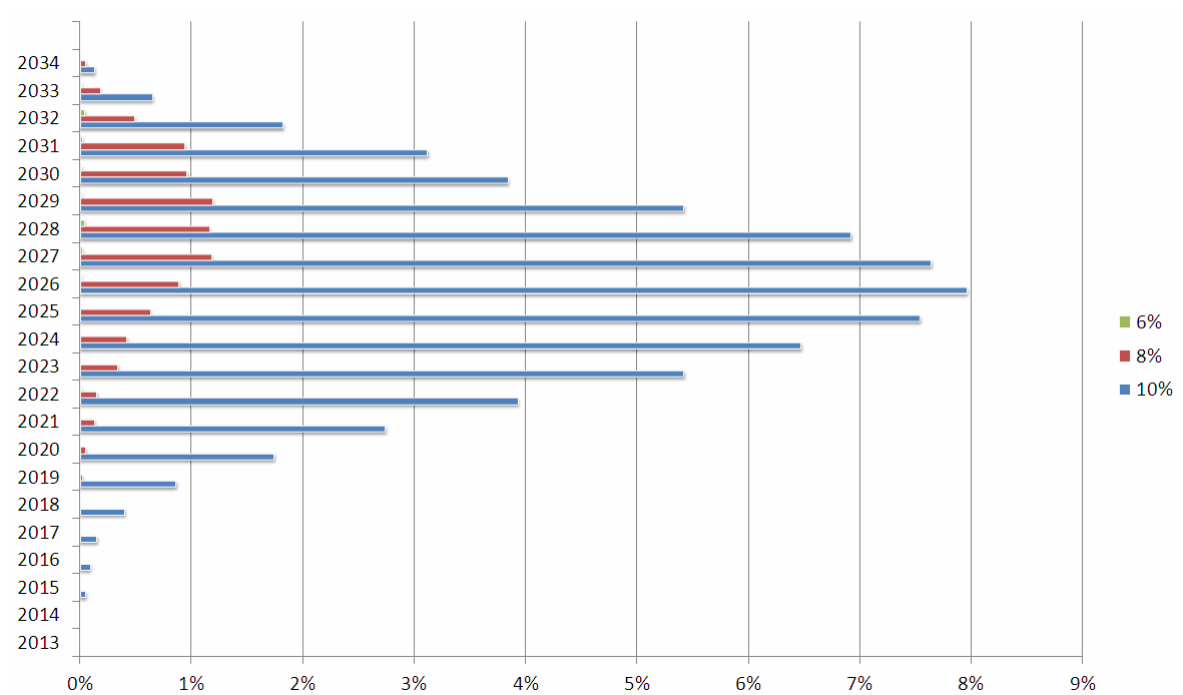
When assuming the price growth of certified carbon emission reduction units (CERs or carbon credits) is below 6%, the present value of the retrofitting option is zero and there is almost no chance of making an economically viable retrofit during a cement plant's lifetime. Even if the growth of the carbon price is assumed to be 8% (implying a mean carbon price of US\$24.0/tCO<sub>2</sub>e in 2020 and US\$51.8/tCO<sub>2</sub>e in 2030, as demonstrated in Figure A.1 in Appendix), the value of retrofitting is only US\$1.2 million and the economic viability probability of retrofitting is 7.3% (mainly takes place after 2020, as shown in Figure 4). The one percentile maximum option payoff is US\$ 14.9 million.

In a sensitivity analysis (Table 9), we found the coal price assumption has a moderate impact on retrofitting probability, as a 10% reduction of coal price will increase the probability of retrofit by 2.1%. Because of the transportation bottleneck, the average delivered coal price in Guangdong is significantly higher than the west or the north part of China. On the other hand, the cost assumption for CO<sub>2</sub> transportation, store and monitoring (TSM) has significant impact on the option value and retrofitting probability. A 10% reduction in TSM cost can result in a US\$5.2 million increase in the option value with a 10.9% higher economic viable possibility for retrofitting to CO<sub>2</sub> capture.

The underlying cement plant in this study is assumed to have 30 years lifetime and is currently with 25 years left. If the life of the plant can be extended by 5 years, the economic viable odd will be increased by 72% to 79% (Table 9). Therefore, the option value and the probability of retrofitting to CO<sub>2</sub> capture in new modern cement plants with long lifetime could be significantly higher.

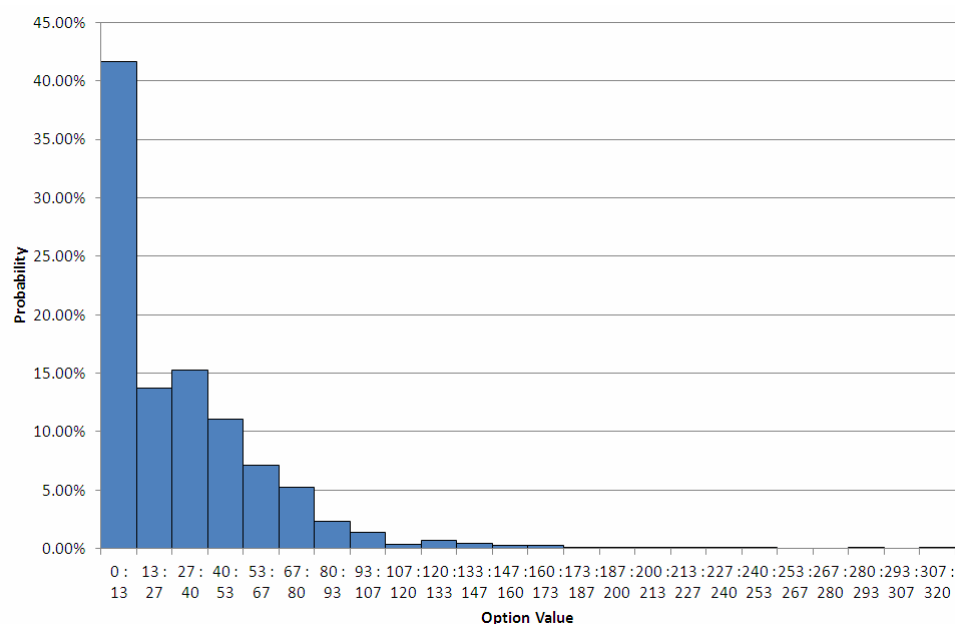
The value of the retrofitting option can reach US\$20.1 million under a high carbon price growth scenario (10% per year, implying a mean carbon price of US\$28.4/tCO<sub>2</sub>e in 2020 and US\$73.5/tCO<sub>2</sub>e in 2030). The distribution of retrofit option payoff is shown in Figure 5. At the 10% carbon price growth assumption, the possibility of retrofitting to capture will be 66.9% over the plant's lifetime. The one percentile maximum option payoff is US\$ 122 million. Under this scenario, the economic viability probability of retrofitting before 2020 is less than 10% while the probability of retrofit between 2020 and 2030 is 58%.

In the baseline scenario, the estimated retrofitting option value and economically viable retrofit possibility in cement plant (US\$1.2 million and 7.3%) is much lower than recent estimates by a recent study on the retrofitting option value (US\$ 99 million and 39%) in a 600MW supercritical coal-fired power plant in China [38]. However, this current study is limited by the fact that the possibility of mandatory CO<sub>2</sub> capture from cement plants has not yet been evaluated. This limitation may cause underestimation on the possibility of retrofit. Therefore, new modern cement plants should consider an essential and minimal level of CCS Ready design to enable their retrofitting potential [39, 40].



Carbon Price: standard deviation 20%; mean reverting ratio 0.3; Coal price: drift 0%; standard deviation 16%; mean reversion ratio 0.3.

**Figure 4 Simulated economic viability probability of retrofitting the underlying cement plant to CCS under three carbon price growth scenarios (6%, 8%, 10% pa)**



**Figure 5 Simulated distribution of retrofit option payoff in the underlying cement plant at a high carbon price growth scenario (10% pa)**

**Table 9 Sensitivity of Retrofitting Option Value and Economic Viable Retrofitting Probability to Carbon Price Growth, Mean Coal Price, Plant Life Assumptions**

	Change	Change of Retrofit Option Value (US\$ m)	Change of Retrofit Probability
Mean Coal Price	+10%	-0.4	-1.6%
	-10%	+0.7	+2.1%
Carbon Price Growth	+1%	+11.3	+26%
	-1%	-1.1	-7.1%
Transportation, Storage and Monitoring Cost	+10%	-0.8	-5.5%
	-10%	+5.2	+10.9%
Lifetime of Cement Plants (years)	+5	24.3	72.0%
	-5	-1.2	-7.2%

### Conclusions

Conducting a case study of a 6000t/day typical modern dry process cement plant in China, the cost of CO<sub>2</sub> avoidance, (measured in terms of the carbon price required to trigger a CCS retrofit investment in 2012), is estimated at US\$70/tCO<sub>2</sub>e with 85% capture ratio. In other word, a carbon tax level of US\$70/tCO<sub>2</sub>e can immediately trigger CCS retrofit in the cement plant. A stochastic model with Monte-Carlo simulation is applied to investigate the value and distribution of retrofitting options in the cement plants. The result shows that the option value of CO<sub>2</sub> capture retrofit in a Chinese cement plant's lifetime is only US\$ 1.2 million with a 7% probability that the retrofit will be economically viable. However, the value of the retrofitting option can reach US\$20 million at a 10% annual carbon price growth assumption. Compared with the economics of CO<sub>2</sub> retrofit in thermal power plants, retrofitting existing cement plants to CO<sub>2</sub> capture is less attractive. However, the sensitivity study shows that new cement plants with longer lifetime may have much higher economic viable probability of retrofitting to CO<sub>2</sub> capture.

Although the Chinese cement manufacturing industry produces approximately 4% of global greenhouse gas emissions, it lacks research, development or demonstration activities of carbon capture technologies. The study identifies three policy implications for developing and deploying CCS technologies at existing and new-build cement plants. First, it would be necessary to conduct a survey to understand the retrofitting potential of existing large and modern cement plants in China. Second, given the lack of regulatory incentives and significant uncertainties in both the carbon and energy commodities market, new-build cement plants in China should consider an essential level of Capture Ready design to keep the retrofitting option open. Finally, new large cement plants should consider to co-locate with large thermal plants and other large stationary emission sources that can potentially reduce the cost of CO<sub>2</sub> capture [7, 15]

### Limitations and Scope for Future Work

The following limitations are identified in this study:

- The cost of retrofitting to capture could be reduced due to the learning effect. For example, improved performance of solvent in the future can reduce the energy consumption (i.e. extra required heat) for the CO<sub>2</sub> capture plant [41]. However, the learning effect is not evaluated in the model. In this context, the economic viability could be understated.
- The study assumes that the retrofit decision is driven by a carbon market. The probability of policy mandatory retrofitting cement plants to CO<sub>2</sub> capture is not yet evaluated in this study.
- Because there is no large-scale CO<sub>2</sub> capture plant in the cement industry in the world, the cost estimate is – derive from our understandings on the cost of post-combustion capture in Chinese coal-fired power plants. In the stochastic model, the annual average carbon price is assumed to evolve with an average growth rate and follows a mean reverting process. In reality, the carbon price is driven by policy decisions. Any change of policy regime can affect the pricing of carbon emissions and therefore impact the economics of investing CCS for cement plants.

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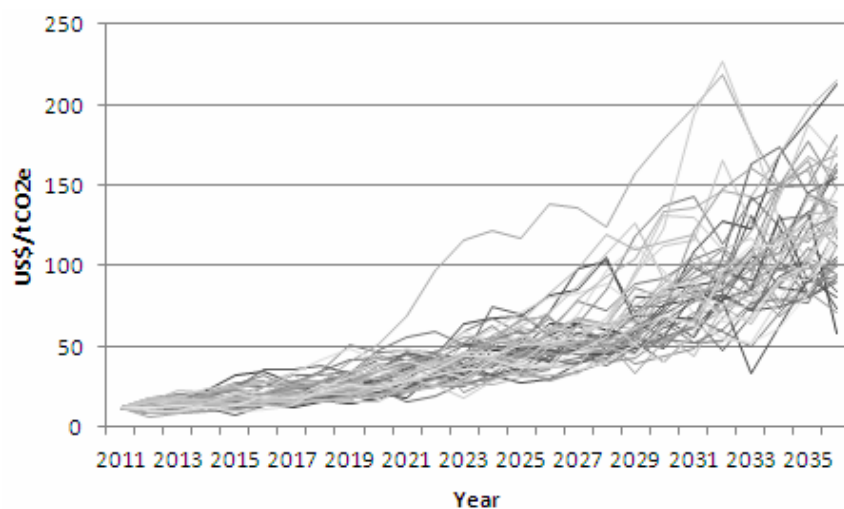
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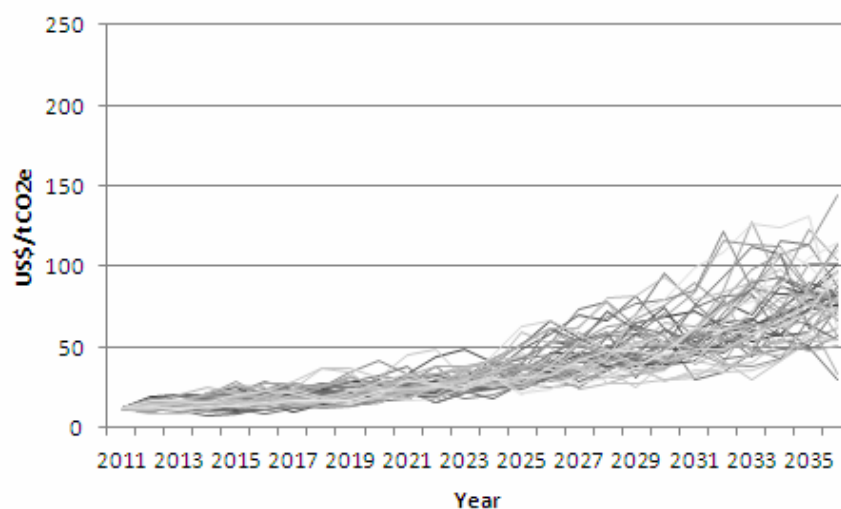
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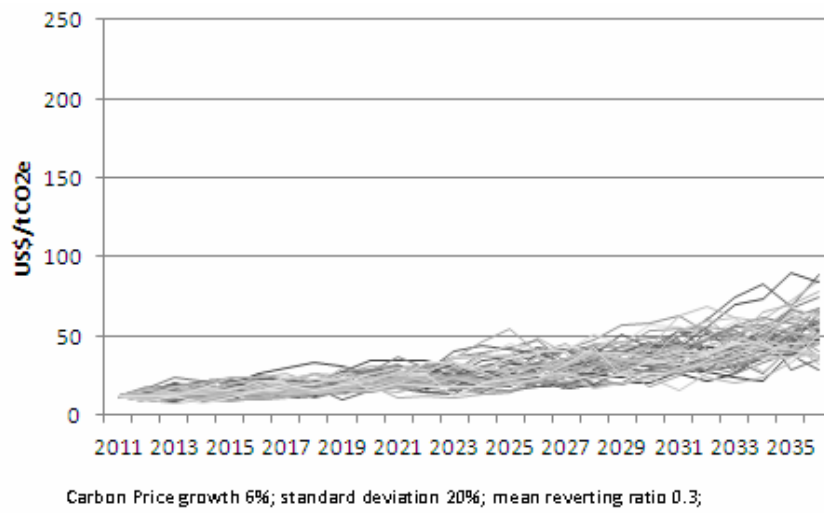
## Appendix. Simulated Paths of Carbon Emission Reduction Units (CERs) Prices



Carbon Price growth 10%; standard deviation 20%; mean reverting ratio 0.3;



Carbon Price growth 8%; standard deviation 20%; mean reverting ratio 0.3;



**Figure A.1 Demonstration of simulated mean annual carbon prices (50 trials, 6%, 8% and 10% annual growth scenarios)**