CARBON PRICES AND CCS INVESTMENT: COMPARATIVE STUDY BETWEEN THE EUROPEAN UNION AND CHINA

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Abstract

As policy makers assess strategies to reduce greenhouse gas emissions (GHG), they need to know the available technical options and the conditions under which these options become economically attractive. Carbon Capture and Storage (CCS) techniques are considered as a key option for climate change mitigation. But integrating CCS techniques in a commercial scale power plant adds significant costs to the capital expenditure at the start of the project and the operating expenditure throughout its lifetime. Its additional costs can be offset by a sufficient CO_2 price but most markets have failed to put a (sufficient) price on CO_2 emissions: currently, the weak Emission Unit Allowances price threatens CCS demonstration and deployment in the European Union (EU). A different dynamic is rising in Asia: a carbon regulation seems to appear in China where these techniques seem to encounter a rising interest. However, there are very few in-depth techno-economic studies on CCS costs. This study investigates two related questions: how much is the extra-cost of a CCS plant in the EU in comparison with China? And then, what is the CO_2 price beyond which CCS power plants become more profitable/economically attractive than classic power plants, in the EU and in China? To answer these questions, I first review, analyze and compare public studies on CCS techniques in order to draw an objective techno-economic panorama in the EU and China. Then, I develop a net present value (NPV) model for coal and gas plants, with and without CCS, in order to assess the CO_2 price beyond which CCS plants become the most profitable power plant type. This CO_2 value is called CO_2 switching price. I also run some sensitivity analyses to assess the impact of different parameter variations on this CO_2 switching price. We show that CCS power plants become the most profitable baseload power plant type with a CO_2 price higher than 70 €/t[1] in the EU against 30 €/t in China. When the CO_2 price is high enough, CCS gas plants are the most profitable power plant type in the EU whereas these are CCS coal plants in China. Through this study, we advise investors on the optimal power plant type choice depending on the CO_2 market price, and suggest an optimal timing for CCS investment in the UE and China.

Introduction

To reduce anthropogenic greenhouse gas (GHG) emissions responsible for climate change and limit long-term global temperature increase to 2°C (COP 15), the four main technical options to be combined are: (1) a massive development of clean energies (renewable and nuclear), (2) the reduction of fossil fuel consumption by switching to lower-carbon alternatives (E.g.: coal to gas), (3) improvements of the energy efficiency of technologies used to convert fossils fuels into energy, particularly in power generation, and (4) carbon capture and storage techniques (CCS) (BERNSTEIN L. et al., 2006). CCS is a suite of techniques designed to intercept the CO_2 contained in industrial flue gases from large point sources (fossil fuel plants, blast furnaces, cement manufacturing…) before it enters the atmosphere, to transport it (by trucks, ships, pipelines) and then to inject it into a suitable storage facility (depleted oil and gas fields and deep saline aquifers).

International organizations like the European Commission (Roadmap 2050, 2011), the IPCC (2005, 2007), the IEA (2010, 2012, 2013)[2], the ZEP (2011)[3]… present CCS as the only current mitigation

[1] Transport and storage costs are not taken into account.
[2] International Energy Agency.

technology that would allow industrial sectors (such as iron and steel, cement and fossil fueled power plant) to meet deep emission reduction targets. Thus, energy scenarios with ambitious climatic goals use CCS techniques. In its[4] analysis (IEA, 2013), the IEA develops a 2DS scenario in which CCS play an important part in the energy system that permits to meet the 2°C goal: CCS could account for up to 20% of the total emission reductions globally through 2050. About half of the total volume of the captured carbon comes from the industry and the other half from the power sector.

CCS techniques applied to the power sector offer a significant potential to reduce GHG emissions: in 2009, power generation contributed to 40% of total CO_2 atmospheric emissions (IEA, 2012b; IFPEN 2013). Around two thirds of the world's electricity was generated from fossil fuels, with 40% from coal, 21% from natural gas and 5% from oil, and the use of coal and gas to generate electricity is still rising (IEA, 2012b). That's why this study focuses on the power sector.

Abandoning CCS as a mitigation option would increase the investment requested in the power sector by 40%, which means an extra cost of USD 2 trillion over 40 years (IEA, 2012a). Even if CCS techniques remain capital intensive and costly, they can be "competitive on a levelised cost of electricity (LCoE) basis with solar, wind (...)" (IEA, 2012d). Indeed, one can tend to focus on the high extra-costs of CCS power plants without replacing them in the merit order of low carbon energies. Moreover, CCS power plants present a significant advantage upon renewable energies: the electricity can be supplied on demand and do not suffer intermittency.

Therefore, while their energy demand is still growing and their energy mix fossil fuel dependent, the European Union and China consider CCS as an important technology to reduce CO_2 emissions from power plants (GRIMSTON et al., 2001). Indeed, CCS could play a critical role in meeting European Union climate targets well known as the "20-20-20" in the climate and energy package framework (2009)[5]. To fulfill its commitments, the UE has set different programs/initiatives to sustain CCS deployment. Among them, one can mention the seventh Framework Program Research and Technological Development (FP7) that has funded several CCS projects: Octavius, SiteChar or Ultimate CO_2 and the European Energy Program for Recovery (EEPR)[6]. One can also emphasize the NER300; in 2008, the EU agreed to set aside 300 million Emission Unit Allowances (EUA) from the New Entrant Reserve (NER) under the European Union-Emission Trading System (EU-ETS) Directive. This financing instrument is dedicated to subsidy installations of innovative renewable energy technology and CCS. However, the current weak EUA price weakens CCS demonstration and deployment. As a result, the European Union could lose its leadership[7] in the CCS field.

If a CCS cooling has been observed in the UE over the past few months, CCS seem to have received a fresh boost in China. Indeed, China has recently shown the willingness to reduce its GHG emissions with the goal to reduce its carbon intensity by 40% to 45% from 2005 levels by 2020 (WU N. et al., 2013). But coal share in the Chinese power mix was 78% in 2010 and will remain dominant in 2020 with 60% (IEA, 2012b). Thus, CCS has a high potential market in China. The inclusion of CCS in China's 12th Five-Year Plan reflects a strong commitment in CCS development and deployment. China has now 12 projects spread across all stages of development planning compared to five in 2010, ranking second to the United States (20 projects) (GCCSI, 2013). Moreover, Chinese investment and Operation and Maintenance (O&M) costs

[3] Zero Emission Platform. Founded in 2005, the European Technology Platform for Zero Emission Fossil Fuel Power Plants is a coalition of stakeholders united in their support for CCS as a key technology for combating climate change. ZEP serves as advisor to the European Commission on the research, demonstration and deployment of CCS. 300 experts from 19 countries and around 40 companies and organizations contribute to ZEP's activities.

[4] Energy Technology Perspectives.

[5] (1) a 20% reduction in GHG emissions from 1990 levels, (2) raising the share of EU energy consumption produced from renewable resources to 20%, (3) a 20% improvement in the EU's energy efficiency.

[6] http://www.developpement-durable.gouv.fr/IMG/pdf/26-_captage_et_le_stockage_du_CO2.pdf

[7] Alstom, for instance, has namely been involved in these pilots: Lacq (France), Le Havre (France), the Technology Center Mongstad (TCM) (Norway) which is the world's largest facility for testing CO_2 capture, or the White Rose project (United Kingdom (UK)).

are lower than in OECD countries. So CCS plants could be profitable at a lower cost than in the EU. Besides, a Chinese carbon regulation could happen in the next few years; different designs of carbon market are currently tested in 7 Chinese cities.

And the carbon price plays a key role in CCS profitability and thus its deployment (GIOVANNI E. et al., 2010). Indeed, if there is a carbon regulation, decision makers for power plants would face this choice: either they invest in a CCS power plant to reduce their CO_2 emissions and then their carbon burden, or they decide not to install CCS and pay for every ton of CO_2 emitted by the power plant. The higher the CO_2 price, the higher the interest of CCS investment. But this implies the existence of a CO_2 cost pass through to electricity prices. It exists in Europe (SIJM J. et al., 2006 and JOUVET P.-A. et al., 2013) but is currently impossible in China because of regulated electricity prices. Nonetheless, reforms are currently undergone to partly deregulate gas prices (IEA, 2012c); thus an electricity reform is perfectly conceivable.

The European Parliament has recently adopted the back-loading proposal, which could be seen as the first step to further structural measures to revitalize the EU-ETS. In the United States, to Barack Obama's request (Climate Action Plan), the Environmental Protection Agency (EPA) released in September 2013 its proposed Clear Air Act standards to significantly reduce CO_2 emissions from new power plants (CCS will be required): a carbon binding regulation could be implemented in the near future. These recent measures show that policy makers and investors should keep in mind the idea of a possible future carbon regulation/legislation when they make their investment decisions.

Power plant costs strongly differ from China to the EU. Therefore, one can expect that CCS costs vary a lot between China and the EU. Two questions arise: how much is the extra-cost of a CCS plant in the EU in comparison with China? And then, what is the CO_2 price beyond which CCS power plants become more profitable than power plants without CCS, in the EU and in China?

To answer these two questions, I carry out a literature review on public studies about techno-economic CCS costs in the EU and China. CCS cost studies necessarily employ a host of technical and economic assumptions that can dramatically affect results (RUBIN E. et al., 2007). This paper summarizes the results of the most recent public studies of current CCS costs for fossil fueled power plants and gives an updated and objective comparison of coal and gas power plants with and without CCS, covering a range of assumptions for key parameters. To assess objectively the profitability of a CCS power plant, I calculate two key metrics: the levelised cost of electricity (LCoE) and the CO_2 switching price (the CO_2 price beyond which a CCS power plant becomes more profitable than another power plant type). In other words, I build a net present value model that take into account the CO_2 price in order to calculate the breakeven CO_2 price. If techno-economic studies on CO_2 capture from power generation are numerous in OECD countries, particularly in EU, they are scarce in China (WU N. et al., 2013). But they have in common the fact that very few of them assess the CO_2 switching price. My study fills these gaps by providing an objective CCS cost comparison in the EU and in China, and by giving implications for European and Chinese power plant investors/policy makers.

In section 2, I give the state of art about CCS techniques in the power sector, then, in section 3, I describe the methodology I have used to draw an economic panorama of CCS power plants, section 4. In section 5, I run sensitivity analysis and in section 5, I assess CCS costs by 2030 to advise investors on the optimal power plant type choice depending on the CO_2 market price, and suggest an optimal timing for CCS investment in the UE and China

1. State of art: CCS and electricity generation

1.1. CCS techniques readiness

As their name suggests, CCS techniques are a 3 links chain: carbon capture, carbon transport and carbon storage. If the carbon transport and storage links are often considered as ready, namely thanks to the American Enhanced Oil recovery (EOR) experience[8], it is not the same for the carbon capture link.

The CO_2 capturing or separation is already performed as part of the standard process in industries with high-purity sources of CO_2. These industries include: natural gas processing, chemical production, coal gasification, coal to liquid, synthetic natural gas, fertilizer production, hydrogen production and ethanol production. However, capturing CO_2 emissions from fossil fuel power plants, blast furnaces or cement kilns has not been deployed yet because their flue gases have low carbon content. Flue gases are a mixture of CO_2 but also oxygen, steam, or nitrogen. Thus, depending on the industry concerned, the carbon content varies from a few percentage points to nearly 20%. For instance, the CO_2 content is around 10-12% for coal plants and only 3-5% for gas plants. The effort required for CO_2 capture is proportional to the purity of the gas stream: CO_2 capture is easier and less expensive when flue gases are CO_2 rich. Thus, to reduce their CO_2 emissions, utilities, cement and steel manufacturers have to develop specific techniques to capture CO_2. In 2013, the Global CCS Institute has identified 65 large scale integrated CCS projects around the world, and only 12 projects in operation. We are far away from the 7 000 industrial sites[9] that could be equipped with CCS (GIEC, 2005).

Currently, three main processes are being developed to capture CO_2:

- **Pre-combustion carbon capture**

  The carbon contained in the fossil fuel is removed **before the combustion process**. The problem is tackled at its root.

  It's the most complex carbon capture process. The feedstock (coal for instance) is turned into a synthesis gas (mixture of hydrogen H_2 and carbon monoxide CO). Then, the syngas undergoes the water-gas shift reaction to produce a H_2 and CO_2-rich gas mixture. The CO_2 concentration can range from 15-50%. The CO_2 is separated from H_2 in a similar way as in post-combustion process[10]. H_2 can be used directly (in refineries namely) or as a fuel in combined-cycle gas plant (electricity or heat without CO_2) or to produce synthetic fluids.

  Pre-combustion capture technology is only applicable to new fossil fuel power plants (Integrated Coal Gasification Combined cycle or IGCC) because the capture process requires significant modifications of the power plant.

- **Oxy-combustion carbon capture**

  In traditional fossil fuelled power plants, combustion is carried out by using air; the flue gas has a low CO_2 content so it is costly to separate it. In the oxyfuel combustion process, the combustion is carried out with pure oxygen; as a result, the flue gas contains only steam and CO_2 with a high concentration (greater than 90% by volume). These two components are then easily separated through cooling; the water condenses and a CO_2 rich gas-stream is formed.

  Oxy-combustion is the most promising carbon capture process; innovations are expected to reduce the cost of pure oxygen production (chemical looping).

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[8] 6200 km pipelines currently handle about 50 Mt of CO2, in a supercritical state, per year (IEA ETSAP, 2010). 4 storage sites (>1MtCO2 per year) are currently in operation around the world.

[9] CO_2 emissions higher than 100 000 t/year.

[10] In the post-combustion process, the flue gas stream is at low pressure and with a low CO_2 content (5-15%). In the pre-combustion process, the shifted synthesis gas stream is rich in CO_2 and at higher pressure; so the CO_2 removal is easier.

- **Post-combustion carbon capture**

  The process consists in separating and removing the CO_2 diluted in the flue gas produced by the combustion of a fossil fuel. Several options are available. The most common process is absorption which is based on a chemical reaction between CO_2 and a suitable chemical, also called an absorbent. The absorbed CO_2 is separated from the absorbent through a thermal regeneration process. Typical absorbents that are used today are amines and carbonates. Cryogenic separation, calcium looping and adsorption are the three other processes.

  Positioned downstream, the post combustion capture process can be added to existing coal or gas power plants, blast furnaces, cemeteries... or factories that emit large CO_2 amounts.

  Post-combustion carbon capture is the most mature and widely used process.

Within each of these three main capture categories, there are several pathways using different technologies which may find particular application more favorably in certain climate conditions, locations and fuel types. None of those capture processes are used at an industrial scale in the power/cement/steel sector.

1.2. Uncertainty on CCS costs

As said before, CCS applied to fossil fuel power plants is an emerging technology. Consequently cost data come from CCS pilot projects in operation (only 12 large scale integrated CCS projects around the world (GCCSI, 2013)), and from engineering and feasibility studies. These cost data correspond to First-of-a-Kind Projects[11] that is to say projects with technologies at early stage of development. From these cost data, N^{th} of a Kind CCS plants[12] costs are deduced. These costs take into account learning effects and economies of scale.

Thus, economic data for CCS plant remain uncertain. Besides, the literature overview has raised two questions: (1) are studies influenced by the national energy context? (2) how much independent are public studies about CCS costs? Indeed, for the first question, by comparing public studies two discernable trends appear: American studies (WorleyParsons, 2009, 2011 and NETL, 2010a, 2010b) tend to favor gas plants relatively to coal plants and on the contrary, the European study (ZEP, 2011) tends to favor coal plants relatively to gas plants. Are the American studies influenced by the national energy context, the *dash for gas* linked with the shale gas exploration and development? This might be a bias. Note that like the DECC, the IEA, sometimes criticized for its too optimistic scenarios, has a median position. The second issue, about public studies independence, is raised by two factors: for most studies, cost data sources are kept secret or lack transparency, and a rather high cost data homogeneity is observed after the standardization of several techno-economic parameters and calculation methodologies (for more details, see 3.3.). One can wonder whether these cost data are rather similar because studies refer to one another and eventually use the same data. The cross analysis of bibliographies shows that most studies refer to others (table 1). Consequently, it is pretty hard to conclude about the independency of these public studies.

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[11] The technology is at an early stage of development/deployment.
[12] The technology is mature.

Quotes / Is quoted by	EPRI	GCCSI	IEA	Worley Parsons	DoE-NETL	ZEP	Alstom	NZEC	WU N.et al.	DECC
EPRI		X		X	X	X			X	
GCCSI						X				
IEA		X		X		X	X		X	X
WorleyP.		X				X				X
DoE	X	X	X	X					X	
ZEP		X							X	X
Alstom						X				X
NZEC			X						X	
WU N.al.										
DECC										
IPCC		X	X						X	
Rubin		X	X	X	X	X	X		X	X
IEA-GHG		X	X		X					

Table 1 : Cross analysis of studies' bibliographies

The current economic and financial crisis has reinforced this CCS cost uncertainty. Indeed, investors are more risk averse, and national/regional subsidies have been drastically cut (E.g.: NER300). But as CCS projects are not funded, economies of scale and learning effects required to reduce CCS costs don't happen.

Moreover, this cost uncertainty is exacerbated by the heterogeneity of techno-economic studies on CCS. Indeed, each study has different methodologies to estimate economic data such as the capital cost, the levelised cost of electricity… and uses different sets of financial and boundary conditions such as lifetime, discount rate, fuel prices… This heterogeneity leads, *de facto*, to important differences in CCS costs from one study to another. Their results cannot be compared straightforward. And then, it reinforces the uncertainty on the true costs of CCS techniques.

2. Methodology and data

In order to assess more precisely the potential of CCS as a key option for climate change mitigation, this study aims at reviewing, analyzing and comparing public studies in the purpose of drawing an objective techno-economic panorama of CCS applied to the power sector in the EU and in China. It implies: (1) studying the profitability of CCS plants respect to power plants without CCS (marginal economic analysis), (2) assessing the costs and performance of carbon capture techniques - pre-combustion, oxy-combustion, post-combustion - to indicate which one is the most profitable, (3) determining the CO_2 price beyond which CCS power plants become more profitable than non-CCS power plants also called reference coal plants.

To perform this comparative analysis of CCS costs and assess the profitability of these techniques, the literature review will be done though three intermediate targets:

- Using available data, decomposing/re-evaluating, the full cost of power plants defined as the sum of the levelised investment cost, operation and maintenance (O&M) costs, fuel cost, carbon transport and storage costs, and CO_2 cost.

This fine decomposition is currently used and facilitates the comparison of these different cost items in and between studies.

- Thanks to this fine decomposition of the full cost, comparing and identifying differences in methodologies (in the LCoE/emission factor/constant investment annuity/CO_2 switching price…calculation) and in financial and operating boundaries (lifetime, construction time, discount rate…) between studies is easier.
  This comparison allows us to select calculation methodologies and financial and operating boundaries that make consensus or seem the most relevant. They are used…
- …in the standardized calculation of two key metrics: the LCoE and the CO_2 switching price (see below).

2.1. Two key metrics to assess CCS power plant profitability

CCS techniques will be deployed if and only if they are a profitable option for industrials/investors. CCS power plant profitability is directly linked to CCS extra-costs. These are of two kinds:

- Fixed: at the start of the project,
- Variable: during the operation time, because of:
  - Net efficiency penalties (from 8 to 10 points) which means higher fuel consumption.
  - Higher operating and maintenance expenditure.

The extra-costs induced by CCS devices are assessed through the two following key metrics:

- The Levelised Cost of Electricity (LCoE).
  The LCoE is equal to the minimum selling price of electricity for which the power plant becomes profitable (the NPV is null). It is an uniform annual value giving the same net present value as the year-by-year case. The LCoE is expressed in €/MWh and is equal to the present value of the sum of discounted costs divided by total production adjusted for its economic time value.
- The CO_2 switching price.
  When the CO_2 price is not null, power plants without CCS are significantly charged for their CO_2 emissions on the contrary to CCS power plants.
  So there exists a CO_2 price that equals the LCoE of CCS and non-CCS power plants. In other words, there exists a CO_2 price beyond which CCS power plants become more profitable than the same plants without CCS[13] (Figure 1).
  It also can be seen as the CO_2 price for which the NPV of the differential project (NPV CCS - NPV ref) is null.

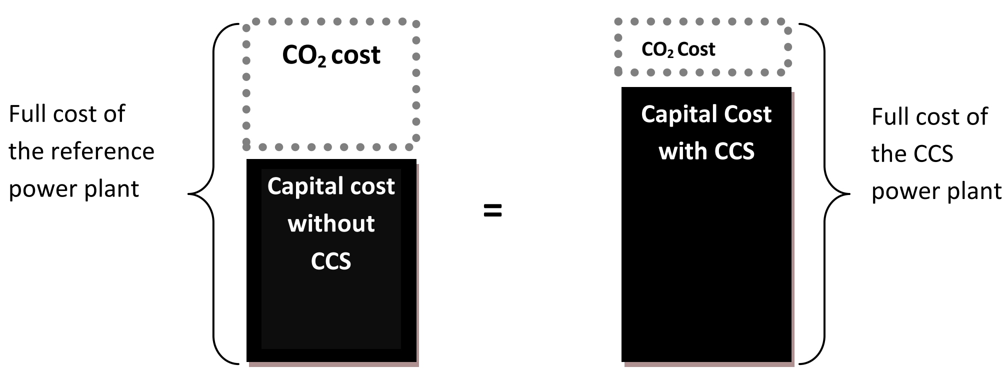

Figure 1 : The CO_2 switching price concept

[13] Also called reference plants.

It can be noticed that there is still a CO_2 cost box for the CCS power plant. Indeed, the carbon capture rate is 90% not 100%.

These two key metrics will allow us to establish a merit order between CCS and non-CCS power plant LCoEs according to different CO_2 price scenarios.

2.2. Public studies selection and scope of analysis

The public studies selected in this paper are the following: IEA (2010, 2011, 2012b, 2012d), Alstom (2011), DECC (2012, 2013), Global CCS Institute (2011, 2013), ZEP (2011a, 2011b, 2011c), NETL (2010a, 2010b) WorleyParsons (2009, 2011), NZEC (2009) and WU N. et al. (2013).

These studies have been selected because they are considered as references in the "CCS sphere" and were published over the last five years. Indeed, as suggests the Global CCS Institute (GCCSI, 2011) public studies have been conduced to highly increase CCS costs: "The levelised cost estimates in the studies [NETL, WorleyParsons, IEA, ZEP] are consistently higher than those estimated three or more years ago. Due to changing methodologies and the inclusion of previously omitted items, costs are now suggested to be 15 to 30 per cent higher than earlier estimates" (p66).

This study focuses on:

- new-built large-scale coal and gas plants (more than 350 MW),
- mature CCS techniques (not pilot projects). Thus, provided costs are rather relative to NOAK (N^{th} Of A Kind) than FOAK (F^{st} Of A Kind) power plants.
  It as to be said that cost data presented in this study do not intend to represent the costs of specific projects, but try to indicate a global trend.
- capture techniques whose capture rate is larger than 85%.

2.3. How can we turn techno-economic information from different studies into a comparable set of data?

As previously said, most studies have their own methodology to calculate economic data such as the LCoE. Moreover, there is not a set of commonly agreed on boundary conditions such as the discount rate, the fuel cost… As a consequence, it is very tricky to compare straightforward CCS cost data from different studies. Indeed, the LCoE is very sensitive to parameters such as the fuel price, the discount rate… (Figure 2).

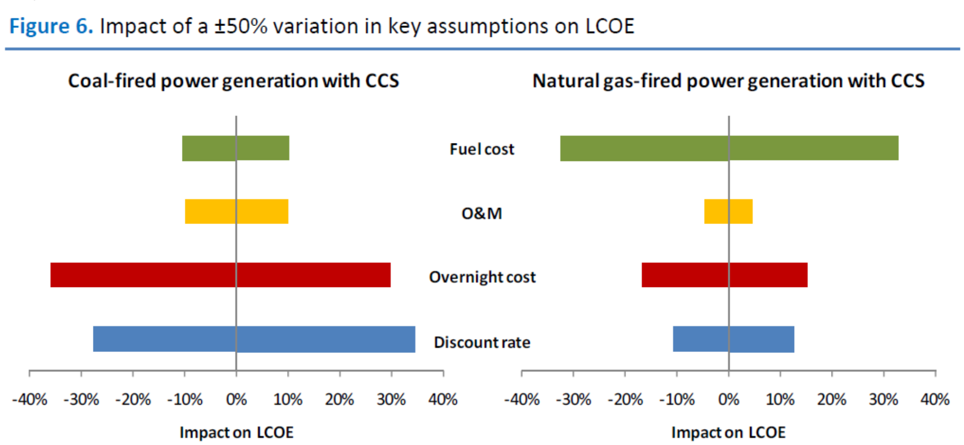

Figure 2: LCoE sensibility to key parameters (From IEA, 2011)

To address this issue and objectively compare LCoE and CO_2 switching prices from different studies, we only keep 4 data from the selected public studies: Overnight cost[14], Operating and maintenance costs, CO_2 emission factor and net power (table 2).

Several techno-economic parameters (table 4) and calculation methodologies (table 3) are standardized.

Unchanged techno-economic parameters	**Unit**	**European value range [min; max]**	**Chinese value range[15] [min; max]**
Overnight cost	€$_{2011}$/kW		
Ultra-supercritical coal plant[16]		[1283; 1659] [ZEP; Alstom]	[589; 913] [IEA; WU N.]
IGCC plant			
CCS coal plant		[1660-1923; 2235] [DoE; DECC]	[618; 2102] [IEA; WU N.]
Post-combustion		[2145; 2858] [ZEP; WorleyP.]	
Oxy-combustion		[2436; 3142] [AIE; DECC]	[1208; 1469] [NZEC; WU N.]
Pre-combustion		[507; 654] [DoE; AIE]	
Combined Cycle Gas plant		[2618; 3045] [AIE; ZEP]	[1272; 3154] [IEA; WU N.]
CCS gas plant		[1064; 1430] [DoE; ZEP]	436 [IEA]
			785 [IEA]
Operation and Maintenance costs	€$_{2011}$/MWh		
Ultra-supercritical coal plant		[5; 12] [Alstom; DoE]	[1.7; 5.3] [IEA; NZEC]
IGCC plant		[7.5; 23] [DECC; DoE]	[2; 9.8] [IEA; MIT]
CCS coal plant		[7; 19] [DECC; DoE]	[3.3; 17.7] [IEA; NZEC]
Combined Cycle Gas plant		[2; 6] [DECC; ZEP]	1.3 [IEA]
CCS gas plant		[4; 13] DECC; ZEP]	2.5 [IEA]
CO_2 emission factor	tCO_2/MWh		
Coal plant without CCS		[0.7; 0.8]	
Gas plant without CCS		[0.33; 0.37]	
Net power	MW	[400; 800]	

Table 2: Unchanged techno-economic parameters

Calculation methodology	**Applied to studies since the beginning**	**Applied to studies at the standardization time**
CO_2 emission factor	X	X
Constant investment annuity[17]	X	X
LCoE	X	X
CO_2 switching price	X	X
CO_2 cost		X
Fuel cost		X

Table 3: Standardized calculation methodologies

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[14] IDC are calculated in a very simplified way. Let's assume that the construction time is 4 years and that the life time is 20 years. The annuity is levelised from year 4 to 23 instead of 0 to 19. It means that during the four first years the power plant pays interests and starts its production from the fourth year. Some studies, the ZEP's one for instance, provide capital costs with IDC and/or owners' costs. It implies the recalibration of capital costs by subtracting IDC and/or owner's costs. Note that net power outputs are unchanged. Indeed, studies might take into account scale effects.

[15] Only three studies analyze Chinese CCS costs: NZEC (2009), IEA (2010), WU N. et al. (2013).

[16] We divide into ultra-supercritical coal plants and IGCC plants for IGCC remain little used (there are less than 10 IGCC around the world and the technology is still a demonstration and experimental stage) and have different investment and operating and maintenance costs. IGCC are very well fitted for pre-combustion capture.

[17] PARK Chans S. [*Analyse économique en ingénierie*, Editions du renouveau pédagogique, 2009, p63-64] donne la formule suivante :

$$Constant\ Investment\ Annuity = \frac{Investment}{\sum_{k=0}^{n}\frac{1}{(1+discoun\ rtae)^k}}\ [1]$$

so: $$Constant\ Investment\ Annuity = \frac{Total\ Plant\ Cost\ (€/_{kW})\times 1000*}{8760\ hours\times Capacity\ Factor\ (\%)*\sum_{k=0}^{n}\frac{1}{(1+discoun\ rtae)^k}}\ [2].$$

Standardized techno-economic parameters	Unit	European values	Chinese values
Currency[18]		€$_{2011}$	
Capacity factor	%	85 [7 446 hours/yr] = BASE	
Capture rate	%	90[19]	
Yield		*[9 pts of penalty]*	
Coal plant (PCI)	%	*45% (2015)*	
CCS coal plant	%	*36% (2015)*	
		[8 pts of penalty]	
Gas plant	%	60% (2015)	
CCS gas plant	%	52% (2015)	
Construction time			
Coal plant (PCI)	*years*	*4*	
CCS coal plant	*years*	*5*	
Gas plant	*years*	*2*	
CCS gas plant	*years*	*3*	
Lifetime			
Coal plant	*years*	*40*	
Gas plant	*years*	*25*	
Fuel price[20]			
Black coal (Illinois n°6)	*$$_{2011}$/GJ*	*2015 : 4.34 (108.5 $/t)*	2015: 3.8 (95 $/t)
Natural gas	*$$_{2011}$/GJ*	*2015 : 11.61 (11 $/MBtu)*	2015: 10.55 (10$/MBtu)
CO_2 price	€/t	0	
Owner's cost[21]	Overnight cost %	15	
Discount rate [real and after tax]	%	8	

Table 4: Standardized techno-economic parameters

[18] Cost data are calibrated to 2011 cost levels by using cost indices (Price index Consumer from http://stats.oecd.org/, Eurostat, Oxford Economic (Forecast) and Asia Pacific Consensus Forecast (April 2013)). Then cost data are converted from the original currency to EUR$_{2011}$. Exchange rates are from OECD stat.

[19] According to public studies, the CO_2 capture rate ranges from 70% (Alstom, 2011, for gas) to 95% (AIE, 2010, oxy-combustion capture on a gas plant). A 90% value is chosen because it is the most widely used value (DoE-NETL, WorleyParsons, IEA and ZEP).

[20]Standardizing fuel prices means that fuels are homogeneous. Comparability between studies is higher. European fuel price hypothesis come from the World Energy Outlook 2012 (IEA). Chinese fuel price assumptions come from the comparison of several studies (bibliography). Indeed, there are no official fuel prices in China, for prices are partly/totally administered.

[21] O*wners' costs* are calculated as a fraction of the overnight cost. According to studies, owners' costs range from 5% (EPRI) to 25% (DoE-NETL). A 15% value is chosen.

This standardization process allows a rigorous calculation and comparison of LCoEs and CO_2 switching prices between studies. After this standardization, cost data from studies are less heterogeneous. Across studies, LCoE values could:

- Range from 30 to 75% for a specific coal power plant type (Figure 4),
- Reach 75% for a specific post-combustion gas plant type.

After the standardization, we can observe that LCoEs:

- Range from 12 to 25% for a specific coal power plant type (Figure 4),
- Range 0 to 15% for a specific post-combustion gas plant type.

This higher homogeneity in cost data is in accordance to the GCCSI (2011): "*The different cost estimates observed in the various studies arise due to differences in assumptions regarding technology performance, cost of inputs or the methodology used to convert the inputs into levelised costs. Many of these differences disappear when the assumptions are normalized and a common methodology is applied".*

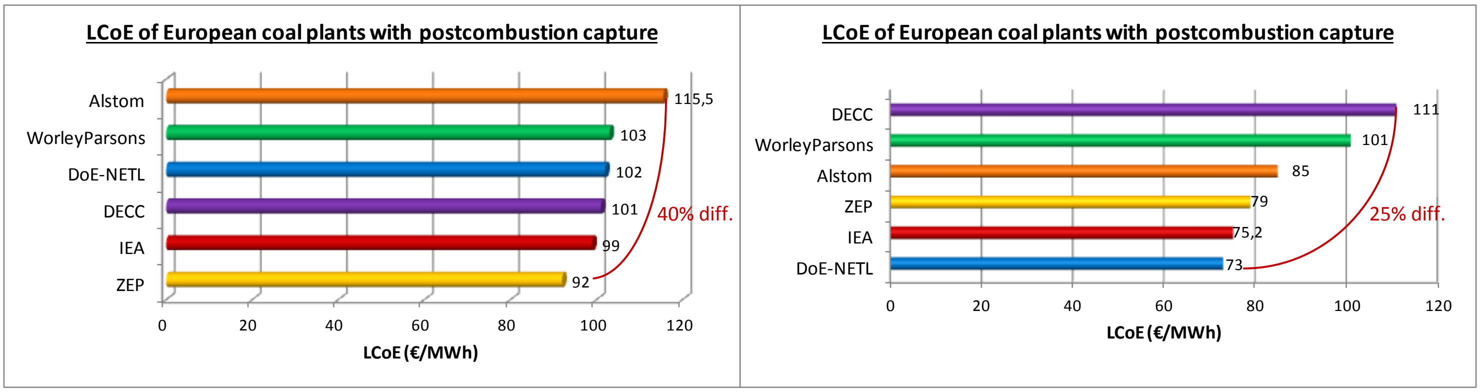

Figure 3: LCoE of European coal plants with post-combustion capture, before and after standardization

LCoE residual differences between studies for a specific power plant type are mainly due to discrepancies in O&M assumptions (they can vary substantially by a factor of more than 2 or 3). For instance, LCoE residual differences are reduced by 70% when IEA O&M assumptions are applied.

2.4. Chinese cost calculation

As table 4 suggests, only very few studies compare CCS costs in China: the NZEC's study (2009), the IEA's (2010) and the WU N. et al.'s (2013). In fact, there are many studies about Chinese IGCC and ultra-supercritical coal plant cost comparison, but they neither consider CCS nor the CO_2 price beyond which a particular kind of power plant become profitable regarding another kinds of power plants.

However, by using cost location factors, it is possible to assess CCS costs in China. Indeed, WorleyParsons (2011) has defined cost location factors[22] using data from Richardson Products' International Cost Factor Location Manual 2009-2010 Edition. Richardson is usually considered as the reference in the field of regional cost indices. Thus this study uses cost location factors[23] from WorleyParsons' study (Table 6).

[22] "To support conversion of the reference case costs from USGC [US Gulf Coast] to location specific costs (expressed in US dollars) for the selected cities/countries, conversion indices were developed for three major cost elements. These include imported equipment and materials, locally sourced equipment and materials, and labour."

[23] When data costs refer to European power plants [ZEP, Alstom, DECC], we apply the cost location factor to move a power plant from Europe to the USGC and then we apply the cost location factor to move the plant from the USGC to China. Note that for the NZEC's study, we only convert cost data from CNY_{2009} to EUR_{2011}. Cost location factors can be applied straightforward for two studies: DoE-NETL's and WorleyParsons'. Indeed,

	Capital and O&M Costs		
Region	**Equipment**	**Materials**	**Labor**
United States (USGC)	1	1	1
Europe (Euro Region)	1.19	1.16	1.33
China	0.81	0.81	0.05

Table 5 : Regional indices used to transfer projects from USGC to specific locations

Thanks to this cost location factor approach, we can assess CCS costs in China through 8 studies instead of 3. So this study fills the current gap by providing and comparing CCS costs data in China.

3. Economic panorama of CCS power plants

3.1. None carbon capture technique have a clear cost advantage

For gas plants, only one carbon capture technique is studied: post-combustion capture. Note that if all OECD studies analyze CCS gas plants, only one of the three studies about Chinese CCS costs analyzes CCS gas plants: IEA (2010). It's hardly surprising. Indeed, in 2010, gas power plants generated only 2% of the Chinese electricity. In 2015, their share could rise to 3.5% (IEA, 2012b).

For coal plants, none carbon capture technique have a clear cost advantage[24]. This observation is shared by the Global CCS Institute (2011, p66): "*Given the uncertainties, at this stage, it is difficult to identify any single technology with a clear cost advantage*". Although post-combustion capture techniques do not have a clear cost advantage, they should be the first to be deployed at a commercial scale for they are the most mature. Pre-combustion capture only concerns IGCC plants which are still little used and at the demonstration stage. Oxy-combustion capture is the most promising technique but still needs research and development efforts to reduce energy consumption for the oxygen production (chemical looping could be part of the solution).

3.2. Extra-costs due to CCS device

A CCS plant undergoes an increase in both investment and O&M costs.

- Fixed costs:
    - The coal overnight cost increases on average by 70% in Europe *vs* 60% in China.
    - The gas overnight cost increases on average by 100% both in Europe and China.
- Variable costs:
    - Net efficiency penalties of 9 percentage points for coal plants *vs* 8 points for gas plants which imply an increase of respectively 25% *vs* 15 % in the budget dedicated to fuel costs.
    - O&M costs increase on average by 80% for coal plants and 100% for gas plants.

By adding carbon capture, coal LCoE increases on average by 60% in European countries (95 €/MWh) *vs* by 50% in (60 €/MWh). Chinese LCoEs for CCS coal plants are 35 €/MWh lower than European's.

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in these two studies, the Labour/Equipment/Raw Materials items clearly appear. But the ZEP, DECC and Alstom studies, provide global/concatenated investment and O&M cost data. Thus, thanks to DoE and WorleyParsons' studies, an allocation key [one for investment cost and one for O&M costs] has been determined and then applied to ZEP, Alstom and DECC's studies.
Note that cost location factors are applied to studies after the standardization of cost data (see 3.3.).

[24] For The EU: for ZEP, the capture technique which have the lowest LCoE is post-combustion for ZEP (92 €/MWh), pre-combustion for the IEA (98 €/MWh), and oxy-combustion for the DECC, WorleyParsons and Alstom (that doesn't study pre-combustion capture) (respectively 95, 97 and 109 €/MWh). Note that the DoE-NETL doesn't study oxy-combustion capture and doesn't give a clear rank between carbon capture techniques. Rankings are exactly the same for China. Indeed, Chinese CCS costs are directly given by 3 studies (NZEC, IEA, WU N. et al.) and derived from 5 US or European studies (ZEP, Alstom, DoE, WorleyParsons, DECC) through cost location factors. Thus, for China too, it is not possible to identify one carbon capture technique with a clear cost advantage.

By adding carbon capture, gas LCoE increases on average by 40% in European countries (90 €/MWh) *vs* 25% in China (70 €/MWh). The relative increase of European LCoE is 15 percentage points higher than in China. As a result, Chinese LCoEs for CCS gas plants are 20 €/MWh lower than European.

3.3. CO_2 price and breakeven point

Chinese CO_2 switching price are almost twice as low than European.

CCS coal power plants become more profitable than reference[25] coal plants beyond an average CO_2 price estimated to 30 €/t for China *vs* 55 €/t for European countries[26].

CCS gas power plants become more profitable than reference[27] gas plants beyond an average CO_2 price estimated to 45 €/t for China *vs* 70 €/t[28] for European countries.

3.4. The investor's vision on CCS: depending on the CO_2 price, in which power plant type invest?

Until now, we have calculated intra-technique CO_2 switching price (CCS coal plant *vs* reference coal plant// CCS gas plant *vs* reference gas plant). However, in practice, whatever the CO_2 price, an investor will compare all the possible arbitrations: **reference coal plant *vs* reference gas plant, reference coal plant *vs* CCS gas plant, reference gas plant *vs* CCS coal plant** and as seen before, reference coal plant *vs* CCS coal plant and reference gas plant *vs* CCS gas plant. Then he will choose the power plant with the lowest LCoE. The power plant type with the lowest LCoE varies with the CO_2 price.

Arbitrations in bold correspond to inter-technique CO_2 switching price the others to intra-technique CO_2 switching price. Inter-technique CO_2 switching price are absent from CCS literature. By taking into account all the possible arbitrations, intra and inter-technique CO_2 switching prices better represent the complex reality of an investor.

Results vary a lot between European countries and China. Thus, we'll first study Europe, then China and eventually, we'll quickly compare them.

3.4.1. In European countries

When the CO_2 price is low (less than 20 €/t)

Coal and gas reference power plants are the most competitive, that is to say they have the lowest LCoE. Then, the main decisive factors for investment are relative fossil fuel prices. It echoes the "fuel switch" concept.

What happened in Europe a few months ago is a good illustration. Indeed, because of the shale gas exploration, the United States have increased their coal exportations to Europe. Thus, the European coal price has become even lower than the gas price. Moreover, the European CO_2 price is less than 5 €/t. Thus, coal plants have increased their competitiveness compared to gas plants. As a consequence, in April 2013, GDF Suez mothballed three out of four CCG: two for summer time (Combigolfe and Spem) and one for indeterminate period (Cycofos).

[25] Coal plant without CCS.
[26] The specialized literature that assesses OECD CCS costs gives 60 €/tCO_2 because it includes carbon transport and storage costs.
[27] Gas plant without CCS.
[28] The specialized literature about CCS costs in OECD countries gives 90 €/tCO_2 because it includes the cost of carbon transport and storage.

When the CO_2 price is more significant: from 20 € to 55 €/t

When the CO_2 price increases beyond 20 €, the carbon burden becomes significant for power plants without CCS[29].

Beyond 20 €/t[30], it is more interesting to invest in a gas plant than in a coal plant.

This coal to gas CO_2 switching price is highly sensitive to fossil fuel prices. The table below illustrates it for European countries. *Ceteris paribus*, when the coal price varies by +/-20%, the CO_2 switching price varies more than proportionally by +/-50%. This switching CO_2 price is even more sensitive to gas price: when it varies by +/-20%, the CO_2 switching price varies by +/-95%.

To summarize, beyond 20 €/tCO_2 until 55 €/tCO_2, gas plants are the most profitable power plant type.

	Gas/Coal Prices Ratio	Coal plant LCoEs	Gaz plant LCoEs	Coal minus Gas LCoEs
Reference case	2.7	59 €/MWh	70 €/MWh	11 €/MWh
Coal price reduced by 20%	3.3	53 €/MWh	70 €/MWh	17 €/MWh
Coal price increased by 20%	2.2	64 €/MWh	70 €/MWh	6 €/MWh
Gas price reduced by 20%	2.1	59 €/MWh	59 €/MWh	0 €/MWh
Gas price increased by 20%	3.2	59 €/MWh	82 €/MWh	23 €/MWh

Table 6: Relative competitiveness of coal and gas plants depending on different scenarios of fuel prices in Europe, IEA 2011

When the CO_2 price ranges from 55 to 70 €/t

CCS coal plants become more profitable than reference coal plants (relative cost-effectiveness). However, the reference gas plant is still the most profitable power plant type *ie* they have the lowest LCoE.

When the CO_2 price is higher than 70 €/t

CCS power plants are more cost-effective than reference power plants. More precisely, CCS gas plants and not CCS coal plants have the lowest LCoE, except for ZEP. It could be surprising because the intra-technique CO_2 switching price is higher for gas than for coal plants. Recent declarations seem to confirm this result. During the ZEP's Assembly (September 2012), it was said that funding CCS gas pilots was a priority. In England, the Peterhead CCS project is a CCS gas plant.

To summarize, in European countries, the investment choice first depends on the switch induced by fossil fuel prices. Currently, from 0 to 20 €/tCO_2, coal plants are the most cost-effective power plant type, and from 20 to 70 €/tCO_2, gas plants become the most profitable. Then, when the CO_2 price exceeds 70 €/t, a second switch, favorable to (gas) CCS power plants, dominates.

[29] For instance, with a CO_2 price at 40 €/t, the LCoE of reference coal plants increase by 40% (+30 €/MWh) and the LCoE of reference gas plants increase by 15% (+15 €/MWh).

[30] Note that this CO_2 switching price varies widely between studies: from 10 € (DECC) to 40 € (ZEP). The value indicated is the mean between the studies.

3.4.2. In China

It is simpler. Indeed, when the CO_2 price is lower than 30 €/t, coal plants are the most profitable power plant type. When the CO_2 price is higher than 30 €/t, CCS coal plants become the most cost-effective power plant type.

Note that beyond 60 €/tCO_2, CCS gas plants become more profitable than reference gas plants, but are still less competitive than CCS coal plants.

Thus, in China, the investment choice only depends on the CO_2 price. When it is lower than 30 €/t, reference coal plants are the most profitable power plant type, beyond, these are CCS coal plants.

3.4.3. China and EU CCS costs comparison

To conclude, in China, gas plants, with or without CCS, are never the most profitable option. On the contrary, in European countries, gas plants, without and then with CCS are the most cost-effective power plant type beyond 20 €/tCO_2.

The CO_2 switching price beyond which CCS power plants become more profitable than all the other power plant types is 70 €/tCO_2 in Europe (LCoE around 90 €/MWh) against only 30 €/tCO_2 in China (LCoE around 50 €/MWh).

This result is mainly due to lower investment and O&M costs in China than in European countries and, in a lesser extent, to cheaper raw materials and fuel prices.

4. Sensitivity analysis

We assess the sensitivity of European and Chinese LCoEs and CO_2 switching prices to variations of the standardized techno-economic parameters. We use the DECC's study data. Indeed, it is the most recent techno-economic study about CCS so its cost data are the most updated and the literature review has shown that in comparison with other public studies, the DECC (like the IEA) has a rather median position.

Standardized techno-economic parameters	Unit	Value	Variations
Capture rate	%	90	- 5 points (85%)
Construction time			
Coal plant	*Year*	*4*	*Coal plant: +1 year*
CCS coal plant	*Year*	*5*	
Gas plant	*Year*	*2*	*Gas plant : +1 year*
CCS Gas plant	*Year*	*3*	
Lifetime			
Coal plant	*Year*	*40*	*- 5 years*
Gas plant	*Year*	*25*	*[-5 years; +5 years]*
Fuel price			
Hard coal	*$\$_{2011}$/GJ*	*Europe in 2015: 108.5 $/t* *China in 2015: 95 $/t*	[-20% ; +20%]
Natural gas	*$\$_{2011}$/GJ*	*Europe in 2015: 11 $/MBtu* *China in 2015: 10 $/MBtu*	[-20% ; +20%]
Discount rate [real and post tax]	%	8	[-4 points ; +4 points]
Yield			
Centrales charbon (PCI)	%	*45%*	*49%*
Centrales charbon avec CCS	%	*36%*	*40%*
Centrales gaz	%	60%	*63%*
Centrales gaz avec CCS	%	52%	*55%*

Table 7: Parameters used to run sensitivity analyses

Results of sensitivity analyses reveal that only the discount rate, fuel prices and load factor variations have a real impact on the LCoE merit order and CO_2 switching prices. Results are presented in tables 8 to 11.

European LCoE	BAU [ref case]	Discount rate: 4%	Discount rate: 12%	Coal price: +/-20%	Gas price: +/-20%	Mid peak load
Reference coal plant	64 €/MWh	-20%	+28%	+/-9%	-	+59%
CCS coal plant	101 €/MWh	-28%	+38%	+/-7%	-	+66%
Reference gas plant	68 €/MWh	-6%	+7%	-	+/-16%	+20%
CCS gas plant	93 €/MWh	-9%	+12%	-	+/-14%	+32%

Table 8: Sensitivity analysis results on European LCoEs

Chinese LCoE	BAU [ref case]	Discount rate: 4%	Discount rate: 12%	Coal price: +/-20%	Gas price: +/-20%	Mid peak load
Reference coal plant	41 €/MWh	-15%	+22%	+/-12%	-	+44%
CCS coal plant	60 €/MWh	-20%	+30%	+/-10%	-	+52%
Reference gas plant	57 €/MWh	-4%	+5%	-	+/-18%	+12%
CCS gas plant	74 €/MWh	-7%	+8%	-	+/-16%	+22%

Table 9: Sensitivity analysis results on Chinese LCoEs

Coal LCoEs (with and without CCS) are more sensitive to standardized parameters variations than gas LCoEs (with and without CCS) except for fuel prices. It can mostly be explained by the fact that the share of the capital cost in the LCoE is higher for coal plants (45% for EU, 30% for China) than for gas plants (15% for EU, 11% for China). Discount rate and load factor play a significant role in the capital cost calculation. Consequently, the more capitalistic power plants are, the higher their influence.

Note that in the EU, for reference coal plants, the capital cost share in the LCoE is higher than the fuel cost share (45% *vs* 41%) whereas in China the capital cost share is lower (30% *vs* 62%) than the fuel cost. For gas plants, the fuel cost share in the LCoE is much higher than the capital cost share: 80% *vs* 15% in European countries and 87% *vs* 11% in China. The fuel cost share in the LCoE is higher in China than in European countries, mostly because Chinese capital and labor costs are lower which mechanically increases the fuel cost share in the LCoE.

EU - 2015		BAU [ref case]	Discount rate: 4%	Discount rate: 12%	Coal price: +/-20%	Gas price: +/-20%	Mid peak load
Intra-technique CO_2 switching price	Coal to CCS coal	55 €/tCO_2	-40%	56%	+/-4%	-	82%
	Gas to CCS gas	84 €/tCO_2	-18%	21%	-	+/-7%	68%
Inter-technique CO_2 switching price	Coal to gas	9 €/tCO_2	255%	X	X/144%	300%/X	X
	Coal to CCS gas	40 €/tCO_2	17.5%	-25%	-/+20%	+/-45%	-27.5%
	Gas to CCS coal	134 €/tCO_2	4%	703%	379%/209%	159%/429%	959%

Table 10: Sensitivity analysis results on European CO_2 switching prices

China - 2015		BAU [ref case]	Discount rate: 4%	Discount rate: 12%	Coal price: +/-20%	Gas price: +/-20%	Mid peak load
Intra-technique CO_2 switching price	Coal to CCS coal	29 €/tCO_2	-21%	45%	+/-5%	-	66%
	Gas to CCS gas	56 €/tCO_2	-15%	18%	-	+/-9%	55%
Inter-technique CO_2 switching price	Coal to gas	38 €/tCO_2	26%	-34%	+/-30%	-/+63%	-66%
	Coal to CCS gas	46 €/tCO_2	4%	-9%	+9%/-15%	-37%/34%	-4%
	Gas to CCS coal	12 €/tCO_2	X	508%	X/208%	350%/X	817%

Table 11: Sensitivity analysis results on Chinese CO_2 switching prices

Intra-technique switching prices are more sensitive for coal plants than for gas plants except for fuel prices. The explanation is the same as above: the share of the capital cost in the LCoE is higher for coal plants than for gas plants.

In European countries, when the CO_2 price is null, the reference gas plant (and not coal plant) is the most profitable power plant type for 4 scenarios: mid peak load, gas price reduced by 20%, coal price increased by 20% and a 12% discount rate. In China, when the CO_2 price is null, whatever the scenario, the reference coal plant is always the most profitable power plant type.

In European countries, we have shown that when the CO_2 price is high enough, the CCS gas plant (and not CCS coal plants) is the most profitable power plant type. Sensitivity analyses show there are only two scenarios for which CCS coal plant and not CCS gas plant is the most profitable power plant type: a gas price increased by 20% and a 4% discount rate which corresponds to the public policy rate.

In China, it's the opposite: in the reference case, when the CO_2 price is high enough, the CCS coal plant is the most profitable power plant type. There are 3 scenarios for which the CCS gas plant is the most profitable power plant type: a 12% discount rate, a gas price reduced by 20% and a mid peak load. In fact, whatever the geographic region, in mid peak load, when the CO_2 price is null, the most profitable power plant type is always a reference gas plant. When the CO_2 price is high enough, the most profitable option is a CCS gas plant. The mid peak load CO_2 switching price is much higher than the base load CO_2 switching price.

In European countries and in China, the CO_2 price to switch from a reference plant to a CCS plant varies widely. However, a general trend appears. In Europe, the CO_2 price to switch from a reference to a CCS plant ranges from 80 to 90 €/tCO_2 except for the discount rate and the mid peak load scenarios. In China, when techno-economic conditions do not allow gas plants to be the most profitable power plant type whatever the CO_2 price, the CO_2 price to switch from a reference to a CCS plant ranges from 23 to 29 €. When gas plants are the most profitable power plant type for a given range of CO_2 prices, the CO_2 price to switch from a reference to a CCS plant is higher and ranges from 44 to 66 €.

5. *What about 2030?*

According to many studies, CCS techniques could be mature in 2030. It means that, thanks to R&D investments, economies of scale and learning by doing effects, CCS investment and operating costs should have decreased significantly in 2030. Mechanically, the CO_2 price beyond which CCS plants become the most profitable power plant type should have decreased too. As a consequence, CCS power plant attractivity should be higher in 2030.

Thus the question is: how much cheaper advanced CO_2 capture systems will be compared to current technology. To assess CCS costs in 2030, we use the DECC's study for the reasons exposed above and because, with the IEA, it's the only study that projects CCS costs in 2030[31].

WU N. et al.'s paper (2013) considers CCS costs by 2030 by reducing capital and O&M costs but do not modify fuel prices assumptions. This scenario of constant fuel prices has the advantage to isolate the learning by doing and economies of scale effects (Scenario 1). However, this assumption of constant fuel prices is rather unrealistic.

That's why, we have also made a fuel price scenario based on the WEO 2012 projections by 2030 ("New Policies scenario", 2012d) (Scenario 2). For steam coal prices by 2030, according to the IEA, the OECD coal price is "a proxy for international coal prices"; thus we adopt this value for the EU and China. For natural gas prices, we directly use the IEA projection for the EU, since there is none for China. There is currently an uncertainty on Chinese fuel prices effectively paid by utilities because prices are administered and often kept lower to avoid triggering high inflation rates. Moreover, there is a high fuel price heterogeneity between regions. Thus, for the future, the uncertainty is very high and, to our knowledge, there are no public projections on the future level of Chinese fuel prices. We assume that, by 2030, Chinese gas prices follow either Japanese prices (in 2011, 54% of Chinese imports were liquefied natural gas whose price is supposed to follow the Japanese price (IEA, 2012c)) or European prices (relatively to the high volumes of natural gas which are imported, China has a bargaining power).

[31] To project CCS costs in 2030, the DECC refers to Rubin'studies (2007, 2010) which are considered as references. They use historical experience curves as the basis for estimating future cost trends for CCS power plants. They first assess the rates of cost reductions achieved by other energy and environmental process technologies in the past. Then by analogy with leading capture plant designs, they estimate future cost reductions that might be achieved by power plants with CO_2 capture.

	Scenario 1: Constant fuel prices		Scenario 2: fuel prices based on IEA (2012d)		
	UE	*China*	*UE*	*China - European prices*	*China - Japanese prices*
Natural gas imports in 2030 ($\$_{2011}$/MBtu)	11	10	12.2	12.2	14.7
Steam coal imports in 2030 ($\$_{2011}$/t)	108.5	95	114	114	

Table 12: Fuel price assumptions for UE and China in 2030

UE		***2015***	**2030 - Scenario 1**	**2030 - Scenario 2**
Intra-technique CO_2 switching price	Coal to CCS coal	*55*	42	42
	Gas to CCS gas	***84***	**72**	75
Inter-technique CO_2 switching price	Coal to gas	***9***	**13**	**25**
	Coal to CCS gas	*40*	38	47
	Gas to CCS coal	*134*	88	**70**

Table 13: European Union CO_2 switching prices by 2030

China		***2015***	**2030 - Scenario 1**	**2030 - Scenario 2 European prices**	**2030 - Scenario 2 Japanese prices**
Intra-technique CO_2 switching price	Coal to CCS coal	***29***	**22**	**24**	**24**
	Gas to CCS gas	*56*	49	55	62
Inter-technique CO_2 switching price	Coal to gas	*38*	52	70	105
	Coal to CCS gas	*46*	51	63	86
	Gas to CCS coal	*12*	X	X	X

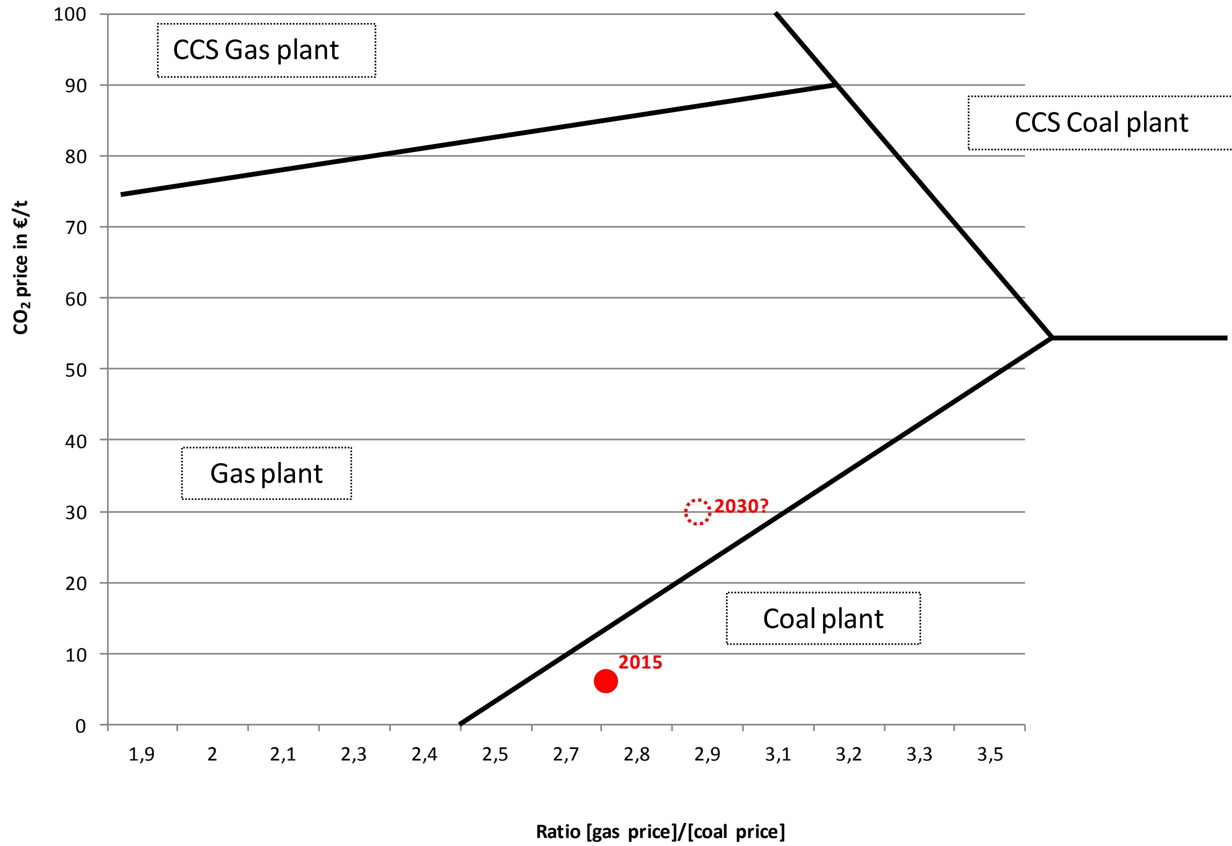
Table 14: Chinese CO_2 switching prices by 2030

In the EU, if fuel prices are constant over the time, the CCS gas plant is the most profitable power plant type when the CO_2 price is high enough (above 70 €/tCO_2). But if fuel prices follow the IEA trends, the most profitable power plant type will be a CCS coal plant (above 70 €/tCO_2). The same result is obtained with the IEA's study (2011). Indeed, by 2030, the profitability frontier that divides CCS gas plants from CCS coal plants is thin.

It also should be noticed that the CO_2 price that causes the switch from a coal plant to a gas plant is lower in the first scenario than in the second (which is more realistic) and both are higher than the 2015 value.

As a consequence, by 2030, European actors should invest in gas plants rather than coal plants, since the IEA forecasts a CO_2 price above 30 €/t (2012d) (Figure 4). On the opposite, in China in 2030, CCS power plants are still not profitable because of the low CO_2 prices that are forecast.

Figure 4: Profitability areas for power plant types based on fuel price ratio[32] and CO_2 price in the European Union. Simulations on the DECC study.



As figure 4 suggests, coal plants have still a bright future in Europe. CCS plants (coal or gas) are far away from being competitive (very high CO_2 price compared to IEA forecasts: red points).

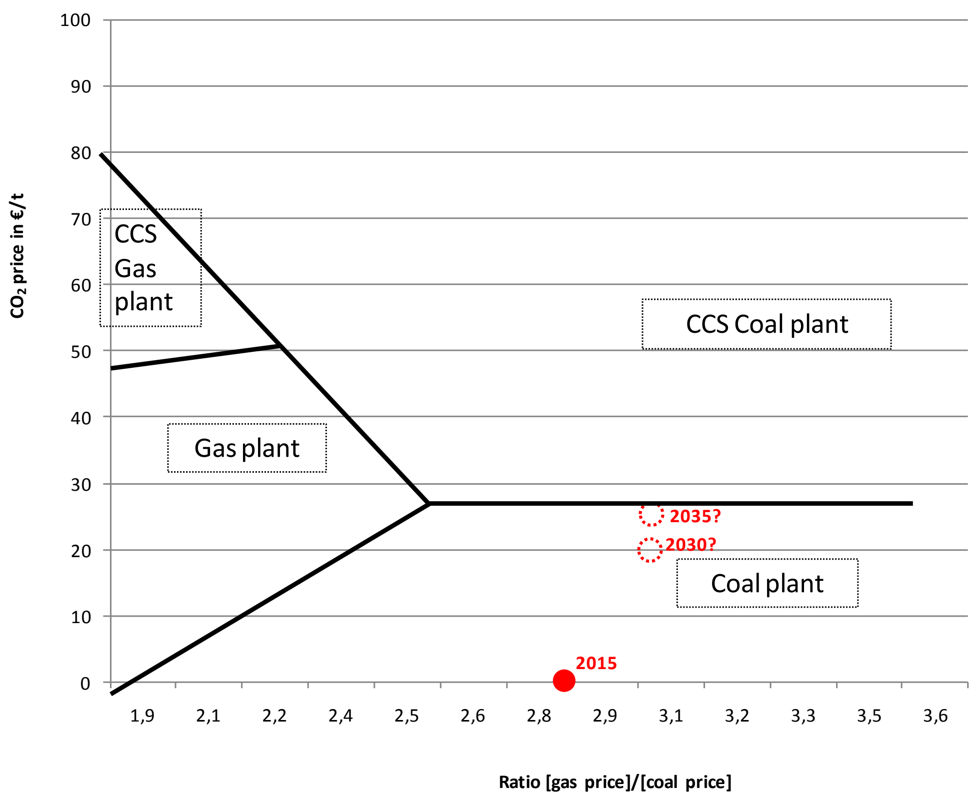
For China, results are similar in 2015 and in 2030: the CCS coal plant is still the most profitable power plant when the CO_2 price is high enough. In comparison with 2015, the CO_2 price to switch from a reference to a CCS plant decreases by 20% when fuel prices remain constant over time (24 €/tCO_2), or decreases by 30% when fuel prices follow the IEA trends (22 €/ tCO_2). This CO_2 price beyond which CCS power plants become the most profitable power plant type is very low in comparison with the EU: less than 30 € *vs* more than 70€. This CO_2 price level could be reached realistically in China: the IEA (2012b) forecasts a CO_2 price at 20 €/t in 2030 and 25 €/t in 2035.

Thus Chinese actors should keep in mind this and invest in CCS coal power plants in the early 2020s[33] (Figure 5).

[32] We have a similar approach to BLYTH W. and YANG M. (2006). Coal price is fixed and gas price varies.

[33] At least in the early 2020s because coal power plants have a lifetime of 40 years: with a rising CO_2 price, reference coal plants would not be profitable for the lifetime project, contrary to CCS coal plants (not profitable in the early 2020s, but highly profitable in the early 2060s, at the end of the lifetime).

Figure 5: Profitability areas for power plant types based on fuel price ratio[34] and CO_2 price in China. Simulations on the DECC study.



As Figure 5 suggests, CCS coal plants could become the most profitable power plant type in the late 2030s. The IEA (2012d) forecasts a CO_2 price at 20 €/t in 2030 and 25 €/t in 2035 (dotted circles).

6. Conclusion

This study shows that, given current power plant costs, with and without CCS, a CO_2 price of 70 €/t (respectively 30 €/t) is required for CCS power plants to become the most profitable power plant type in the EU (respectively in China). In the EU, CCS gas plants are the most profitable power plant type when the CO_2 price is higher than 70 €/t, whereas in China, these are CCS coal plants that are the most profitable power plant type when CO_2 price is higher than 30 €/t.

The WEO 2012 (New policy scenario) forecasts a CO_2 price at 40 $/t in the EU and 30 $/t in China by 2030. Thus, it can be said that in the UE, investors should choose gas plants without CCS and that in China, investors should choose CCS coal plants in the early 2020s by considering the lifetime of a coal plant. Note that Chinese electricity prices are regulated; it could cause difficulties to CCS deployment. However structural reform could happen quickly. Last year, because of the coal price increase, many utilities lost money and there were several electricity shortages.

In this study, I have developed a methodology to objectively compare CCS costs provided by public studies. I have also shown that when CCS costs for a specific region, here China, are not given, a cost location factor approach can be adopted. Then, I have demonstrated that there exists several CO_2

[34] We have a similar approach to BLYTH W. and YANG M. (2006). Gas price is fixed and coal price varies.

switching price; to be sure that a CCS power plant is the most profitable investment, both intra and inter-technique CO_2 switching price have to be considered. This distinction have pointed out that in UE, contrary to common beliefs, CCS coal plants are not profitable when the CO_2 price is higher than 55 €/t. Indeed, at 55 €/tCO_2, CCS coal plants become more profitable than reference coal plants but they are not the most profitable power plant type. Gas plants are the most profitable power plant type from 20 to 70 €/tCO_2.

To make it more valuable for investment decisions and policy making, this study could be extended with the assessment of investment risk under uncertainty (relatively to the CO_2 price, CCS techniques maturity…).

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