Carbon Capture & Storage: Assessing the Economics

McKinsey&Company

Preface

McKinsey has worked with leading institutions over the last 3 years to develop an understanding of the costs and potential of the options for reducing greenhouse gas emissions at both a global and regional level.

This report takes a deeper look at one of these options, CO_2 capture and storage (CCS). It has been independently developed by McKinsey over the last few months, with extensive input from a number of leading institutions, in response to a perceived need for a transparent and 'readily accessible' fact base for CCS.

Our research has been greatly strengthened by contributions from over 50 companies (electricity production, oil, gas transportation and industrial equipment sectors), NGOs, and other stakeholders and experts in CCS. In particular we could like to acknowledge the access to expertise provided by Alstom, Enel, the European Climate Foundation, RWE, Shell and Vattenfall.

This report does not attempt to be comprehensive—for example the focus is on Europe, and the detailed cost reference cases are based on new build coal power applications. It is an attempt, in an objective and clear way, to provide basic facts and transparency regarding current costs and possible future development of CCS. It also explains key issues affecting the longer-term deployment of CCS and finally the barriers that currently exist to this deployment. It does not make policy recommendations or conclusions.

McKinsey & Company takes sole responsibility for the content of this report.

Contents

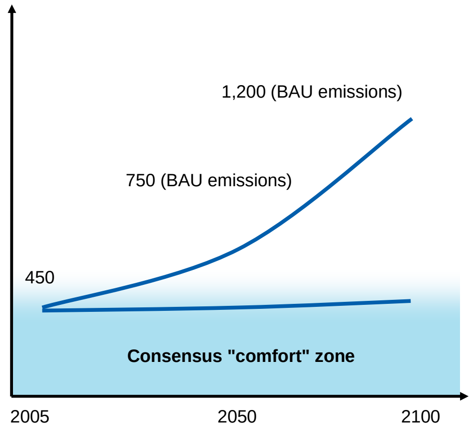
1. Introduction

There is a growing consensus among climate scientists, economists and policy makers that the link between man-made emissions of greenhouse gases (GHG) and climate change is sufficiently likely to motivate global actions. [Exhibit 1]

Exhibit 1

Forecasts of CO_2e* concentrations in business-as-usual scenario

Average forecast of CO_2e concentration**, parts per million



* CO2 equivalent emissions: greenhouse gas concentrations are converted to CO2 equivalent for comparability
** Excluding ranges for alternatives and uncertainties
Source: Stern Review, IPCC, CCSI

Energy use and energy generation are at the heart of the problem, with the International Energy Agency (IEA) forecasting that global electricity generation will nearly double from 2005 to 2030. The Agency says that fossil fuels will remain a significant part of the energy mix up to 2030, comprising roughly 70 percent of global and 60 percent of European electricity generation.

One of the solutions being discussed to reduce GHG emissions from fossil fuel energy generation is CO_2 Capture and Storage (CCS). CCS is a group of technologies for capturing the CO_2 emitted from power plants and industrial sites; compressing this CO_2; and transporting it to suitable permanent storage sites, such as deep underground[1].

CCS is in a relatively early phase of development, with several key questions remaining, including about its costs, timing, and relative attractiveness versus other low carbon

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[1] European Commission / Climate Change: http://ec.europa.eu/environment/climat/ccs/what_en.htm

opportunities. Public understanding of CCS is low[2], and there is some confusion around its true economics, exacerbated by the wide range of cost numbers quoted and the limited information on how they are derived.

Hence this report, which aims to provide a brief, objective, fact-based, and generally accessible overview of CCS, focusing on the economics and key issues, to help stakeholders understand and assess the technology. This overview looks ahead as far as 2030.

As far as possible, the report has built on existing knowledge—from publicly available sources and from our interaction with more than 50 companies, NGOs, and other stakeholders and experts in CCS, who contributed through interviews and participation in workshops.

The report's findings are based on technologies and measures that are currently relatively well known and understood, and that are likely to be commercially available within the next two decades. These findings have been reconciled with reports on CCS recently published by the IEA, the Massachusetts Institute of Technology (MIT) and the United Nations Intergovernmental Panel on Climate Change (IPCC).

The report aims for complete transparency on the methodology and assumptions used in reaching its findings. Details of these are provided in the relevant chapters. In addition, the appendix contains a full bibliography and glossary of terms.

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[2] For example, a survey in April 2007 by the Massachusetts Institute of Technology (MIT) showed low public awareness of CCS in the US.

2. Summary of findings

This section provides a summary of the report's key findings; each is elaborated and substantiated further in the report itself.

Recent high profile reports, such as those by IPCC, Lord Stern and IEA have described CCS as a key potential abatement measure to help slow climate change.

Fossil fuels are forecasted to continue to play a major part of the energy mix to at least 2050, and CCS provides the main abatement lever for stationary fossil fuel sources. CCS could also provide the main means of curbing emissions from heavy industrial sectors such as steel, cement and refineries, which together account for around 10-15 percent of Europe's CO_2 emissions.

Renewables such as wind and solar, and other abatement measures such as improved energy efficiency, are other opportunities to reduce CO_2 emissions. But it is unlikely that these alone will enable the EU to reach its GHG abatement targets by 2030. By most accounts, additional measures will be required – such as CCS.

Previous reports have estimated the potential impact of CCS in 2030 at between 1.5 and 4 Gt/year of abatement globally. The McKinsey/Vattenfall cost curve 1.0[3] estimated the global potential at 3.6 Gt/year, and in Europe at 0.4 Gt/year – around 20 percent of the total European abatement potential in 2030.

In addition to its direct abatement potential, including CCS in the portfolio of actions could help meet Europe's broader energy needs. On the one hand, it could provide greater energy security, by making the burning of Europe's abundant coal more environmentally acceptable and so reducing the dependency on imported natural gas. On the other, it could potentially improve the environmental impact of new energy forms such as electric cars and hydrogen, which could be produced with CCS-based electricity.

For the reference case of new coal power installations, CCS costs could come down to around € 30-45 per tonne of CO_2 abated in 2030 – which is in line with expected carbon prices in that period. Early demonstration projects will typically have a significantly higher cost of € 60-90 per tonne.

A reference case has been defined for new coal power installations, which is the basis for the cost calculations. For this reference case, early full commercial scale CCS projects are

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[3] http://www.vattenfall.com/www/ccc/ccc/577730downl/index.jsp

expected to cost in the range of € 35 to 50 per tonne CO_2 abated. With operating experience and scale effects, it is estimated that these costs can drop to € 30 to 45 per tonne CO_2 abated by 2030. Costs at these levels would make such CCS installations economically self-sustaining at a carbon price of € 30-48 per tonne CO_2 as forecasted by various financial institutions[4]. There is potential for even lower costs if a global roll-out of CCS takes hold, or if some breakthrough technologies, now still in the laboratory stage, emerge.

Early demonstration projects will typically be more costly (€ 60 to 90 per tonne CO_2 abated), due to their smaller scale and lower efficiency, and their focus on proving the technology rather than commercial optimisation.

Individual project costs can vary from the reference case costs, depending on their specific characteristics. The costs of different capture technologies are at this stage quite similar, while retrofit and industrial CCS applications will typically have higher costs than new build coal power applications.

The reference case costs are especially sensitive to deviations from the assumed risk of capital and the capital investments required for CCS. In addition, actual costs are likely to vary significantly between individual projects, depending on their scale, their location, and the technologies being tested. For a demonstration project, for instance, a transportation distance 200 km longer than the reference case would add € 10 per tonne CO_2.

The differences in cost between the three main capture technologies are relatively small today, suggesting that multiple technologies should be tested at this early stage of development. Retrofitting of existing power plants is likely to be more expensive than new installations, and economically feasible only for relatively new plants (with high efficiencies).

There are feasible paths for the European CCS industry to develop from the demonstration phase to substantial scale in 2030; however, this requires storage and business model challenges to be resolved.

Achieving 0.4 Gt CO_2 abatement per year from CCS in Europe, by 2030, would require the installation of between 80 and 120 commercial-scale CCS projects. These are likely to develop as a series of capture clusters, which would typically consist of newly built power plants and adjacent retrofit and industrial capture projects, all connected into a common transport and storage network.

The timing of the roll-out of CCS would have a major impact on the level of abatement achieved by 2030. If the first commercial projects do not start until well after the demonstration phase, or if projects are delayed due to difficulties with permits or other uncertainties, CCS could struggle

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[4] Estimates from Deutsche Bank, New Carbon Finance, Soc Gen, UBS and Point Carbon

to reach large scale in 2030. To achieve that, the first commercial projects would have to be started shortly after the demonstration phase or a fast roll-out programme would be needed.

Storage is a key uncertainty that will determine the shape of the CCS roll-out. Experts believe there is sufficient storage potential in Europe for at least several decades. Depleted oil and gas fields, one key option, are well known and lie mostly in the North Sea, while deep saline aquifers, the other key option, are more widespread but also less researched and understood. In an ideal case, deep saline aquifers will be available locally for main emission clusters, but it is possible that longer transport and offshore storage may be required for some areas.

Capturing the CCS abatement potential in Europe would require rapid deployment of a demonstration programme and planning for a subsequent commercial roll-out. Several barriers and uncertainties would need to be addressed.

A demonstration programme of commercial-scale, integrated CCS projects would make it possible to prove the range of CCS technologies at scale, identify risks and achieve public and industry confidence in CCS. A sufficient number of such projects would be required to test different capture technologies and different storage geologies across a range of fuel applications and geographies. Given the higher costs of typical demonstration projects, there is likely to be an “economic gap” between the expected carbon price and lifecycle costs, amounting to some € 0.5 - 1.1 billion per project (in NPV terms).

In parallel to these demonstration projects, and to some extent as part of them, further efforts would be required to prove local storage potential, particularly in deep saline aquifers. The current “GeoCapacity” surveys are a good start, but further steps would be required to prove the local feasibility of aquifers.

Subsequent scaling up of CCS to a substantial level by 2030 would require that a way be found to ensure rapid commercial deployment after the demonstration phase. The implication is that early attention must be given to the prerequisites for commercial roll-out beyond the first 10-15 projects – including cluster development, infrastructure networks, permits, industry preparations, and possible business models and commercial approaches to the next stage of development.

Regulatory issues, particularly around storage liability and the legality of storage, will need to be resolved; and funding solutions will need to be found to support the demonstration project phase. To ensure a “level playing field” and to share lessons learned this CCS framework and some form of coordination should be on a European level. Public awareness of CSS must also be improved – and support for it strengthened.

Such actions require the joint and coordinated efforts of all stakeholders in CCS – including industry players, governments, NGOs and academia.

3. CCS abatement potential

This section outlines what CCS is, how it works, and the logic of its role in CO_2 abatement.

3.1 What is CCS?

CO_2 is produced whenever we burn any type of fossil fuel from power generation to using our cars. Certain industrial processes, such as steel and cement production or oil refining, also produce significant quantities of CO_2. This is currently released into the atmosphere, contributing to the build up of atmospheric CO_2, which scientists' link to climate change and an increase in average global temperatures.

CO_2 Capture and Storage (CCS) is a technology that aims to prevent the CO_2 generated by large stationary sources, such as coal-fired power plants, from entering the atmosphere. The technology aims to capture around 90 percent of CO_2 emissions from these sources and permanently[5] prevent their release into the atmosphere. CCS is designed to accomplish this in three steps. Firstly, CO_2 is captured and compressed at the emission site. Secondly, it is transported to a storage location, where, thirdly, it is permanently stored.

Each of these steps can be accomplished in several ways. Consider, for instance, the several different options available for the capture process. In simplified terms, the capture process must solve the following problem. The combustion of a fossil fuel produces CO_2 and water vapour. These two gases are present in the flue gas emitted by a power plant, together with large quantities of nitrogen originating from the air used in combustion. In order to be stored, CO_2 has to be removed from this stream.

The three principal capture processes available today work in different ways:

- **Oxy-fuel combustion:** The fuel is burned with oxygen instead of air, producing a flue stream of CO_2 and water vapour without nitrogen. From this stream the CO_2 is relatively easily removed. The oxygen required for the combustion is extracted *in situ*, from air.
- **Post-combustion:** CO_2 is removed from the exhaust gas through absorption by selective solvents.
- **Pre-combustion:** the fuel is pre-treated and converted into a mix of CO_2 and hydrogen, from which CO_2 is separated. The hydrogen is then burned to produce electricity or fuel.

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[5] Note that 'permanently' is used here to indicate the projected long timescales. The 2005 IPCC Special Report on CCS concluded that the fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99 percent over 100 years and is likely to exceed 99 percent over 1000 years.

For large-scale CO_2 transportation, pipelines are the primary option, although shipping is also a possibility.

Storage is possible, amongst other options, in various types of geological formations. The primary options are depleted oil and gas fields and natural underground formations containing salty water, known as deep saline aquifers.

Compared to a “normal” power plant, CCS adds four additional costs. Firstly, capture equipment needs to be installed. Secondly, the capture process needs to be powered, leading to additional fuel costs. Thirdly, a transport system needs to be built. And finally, the CO_2 must be stored. All of this requires both additional capital investment and additional operational cost.

The required investment per project is significant. The cost will be discussed in more detail in the following chapter, but to give an idea: a non-CCS 900 MW coal power plant built around 2020 would require around € 1.5 billion in capital investment. Fitting the plant with CCS would raise that amount by roughly 50 percent. Investments in transport, storage and operational costs are smaller.

3.2 CCS abatement potential

Given the current energy mix, energy demand growth in emerging markets and issues of energy security and prices, experts believe that despite increasing use of renewables, fossil fuels will continue to comprise a significant part of the energy mix until 2030[6], both globally and for Europe (currently some 30% of European electricity is generated from coal). In fact, with the predicted increase in electricity demand, fossil fuel-based electricity generation is expected to double globally by this date. [Exhibit 2]

The single largest fossil fuel in the energy mix is coal, at 40 percent of the global energy mix in 2005, forecast to increase to 45 percent by 2030[7].

Today CCS is the only technology known to be able to capture emissions from existing CO_2 emitters – not only from fossil fuel power plants, which account for almost half of all emissions in Europe [Exhibit 3], but also from other industrial processes such as steel, cement and refining. For many or even most of these processes, at current technological knowledge, CO_2 cannot be avoided as a by-product.

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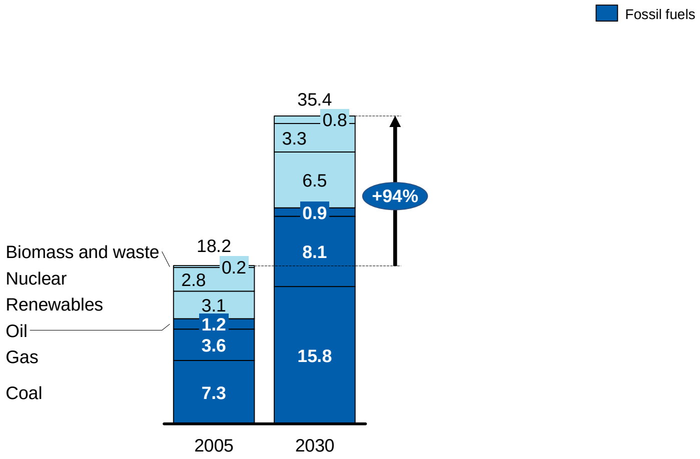
[6] “World Energy Outlook,” IEA, 2007

[7] ibid

Exhibit 2

IEA business-as-usual forecast of Worldwide electricity generation

TWh x 1000



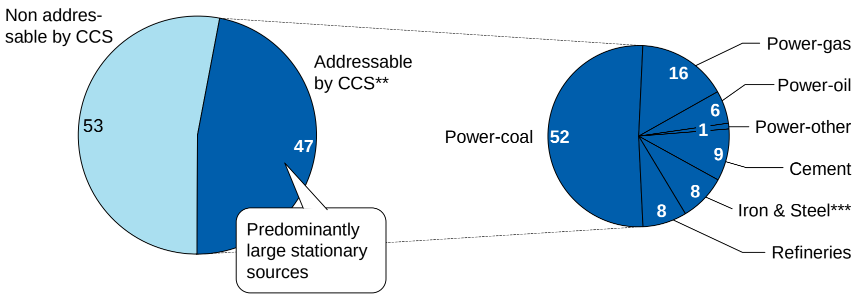
Source: World energy outlook, IEA 2007

Exhibit 3

European CO_2 emissions from fuel combustion and industrial processes

Total emissions*
100% = 4.2 $GtCO_2$, 2007

CCS addressable emissions
100% = 2 $GtCO_2$, 2007



* IEA estimates of CO2 emissions from fuel combustion and industrial processes in 2007. Does not include miscellaneous small CO2 emitters and non-CO2 emissions such as methane (e.g. forestry, farming, etc.)

** Not including biomass, oil sands, paper mills, ammonia, ethanol, ethylene, hydrogen, and other industries

*** Includes metal ores processing

Source: EEA GHG Emission Trends and Projections 2007; IEA World Energy Outlook 2007; Team analysis

CCS, then, is an important potential CO_2 abatement method. Various recent reports estimate that CCS could potentially abate between 1.4 and 4 Gt globally by 2030 (e.g. Stern 1.4 Gt[8], IEA 4 Gt[9], and McKinsey/Vattenfall 3.5 Gt[10]). McKinsey and Vattenfall's global cost curve work estimates that up to 3.5 Gt per year of abatement could be achieved from CCS globally[11] 0.4 Gt of it in Europe, representing 20 percent of European abatement opportunities beyond '"business-as-usual"[12].

CCS requires long lead times before it can be deployed at full scale. It also requires large investments in single projects.

The corresponding CO_2 abatement of each single plant is large: one CCS power plant could provide roughly 1.5 million European households with low carbon electricity. By comparison, providing the same number of households with wind power would require roughly 1400 typical full scale (2.3 MW) wind turbines.

CCS has an added attraction: it reduces emissions from reliable "base-load" power (power that can run 24 hours a day, 365 days a year). Today, nuclear and coal typically fuel base-load plants in Europe, and eliminating coal from the power mix, as might be called for without CCS, would have significant implications for the power system[13]. This would potentially put European energy security at risk: while well-supplied with coal, Europe is short of oil and gas.

3.3 The current state of CCS

While many of the component technologies of CCS are relatively mature, to date there are no fully integrated, commercial-scale CCS projects in operation. [Exhibit 4] In particular:

a. Capture technologies are based on those that have been applied in the chemical and refining industries for decades, but the integration of this technology in the particular context of power production still needs to be demonstrated[14].
b. Transportation of CO_2 over long distances through pipelines has proven successful for more than 30 years in the central US, which has more than 5,000 km of such pipelines[15] for Enhanced Oil Recovery – a technology by which CO_2 is injected into oil fields to increase oil production.

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[8] Stern Review

[9] "World Energy Outlook," IEA, 2007

[10] McKinsey/Vattenfall GHG abatement cost curve v1.0

[11] ibid

[12] ibid

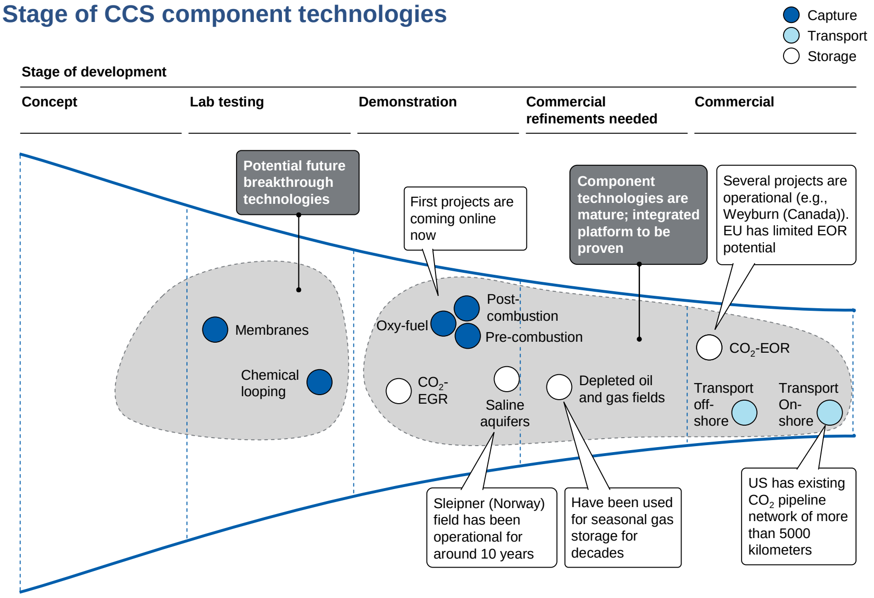
[13] Unless a workable renewables solution, with effective electricity storage, capable of base-load generation proves feasible

[14] ZEP Technology Matrix, 2008 (draft version 5)

[15] Intergovernmental Panel on Climate Change

Exhibit 4

Stage of CCS component technologies



Source: Interviews; Team analysis

c. CO_2 storage projects have been operational worldwide for at least ten years, e.g. in Sleipner (Norway), Weyburn (Canada), and Salah (Algeria). The industry can also build on the knowledge obtained through the geological storage of natural gas, which has been practiced for decades.

Despite their relative maturity, some uncertainties concerning these technologies still exist, for instance questions about the storage potential of deep saline aquifers.

Recently (in September 2008), Vattenfall's 30 MW Schwarze Pumpe oxy-fuel pilot capture project in Germany was opened. Several other CCS projects have been announced recently, for example in Germany (RWE's Hürth project), the US (AEP Alstom Mountaineer), Australia (Callide Oxy-fuel) and China (GreenGen). To date, however, there are no fully commercial-scale, integrated operations. Establishing a first set of such "demonstration" projects is generally considered the next necessary step in CCS development. The purpose of such projects would be to prove that the technology works at scale and in integrated value chains; to get a more accurate picture of the true economics of CCS; to validate storage potential and permanence; to prove transport safety; and to address public awareness and perception issues.

4. Cost for CCS reference case

There is a high degree of uncertainty in estimating the costs for CCS because of significant variations between projects' technical characteristics, scale and application. There is also uncertainty over how costs will develop with time, given both the wide possible range of learning rates and scale benefits, and the variability of input costs such as steel, engineering and fuel development.

Our objective in this chapter, then, is not to predict overall CCS costs, but rather, through the use of consistent reference cases, to explain how costs are likely to develop over time. The focus in this chapter is on one main application: new build coal power plants. Specifically, the analysis presented here focuses on new hard coal and lignite power plants, to provide one consistent case that can be assessed over time. These plants also represent the class of fossil fuel power installations with the highest amount of specific emissions of CO_2 per MWh produced; they are therefore likely to be a major application of CCS technology.

Approach to determining the cost of CCS

The "cost of CCS" is defined as the additional full cost, i.e. including initial investments and ongoing operational expenditures, of a CCS power plant compared to the cost of a state-of-the-art non-CCS plant, with the same net electricity output and using the same fuel. The cost includes all the components of the value chain: CO_2 capture at the power plant, its transport and permanent storage.

The cost of CCS is expressed in real terms (that is, adjusted for predicted inflation), in Euros per tonne of net CO_2 emission reduction, to allow comparison with other abatement technologies. [Exhibit 5]

The "capture cost" also includes the initial compression of CO_2 to a level that would not require additional compression or pumping if the storage site were closer than 300 km; transport cost would include any boosting requirements beyond this distance. For storage, only geological storage options have been considered, such as depleted oil and gas fields and deep saline aquifers.

CCS costs have been synthesized into "reference cases" which indicate the likely cost level of CCS at different stages of development – from initial demonstration projects, to early

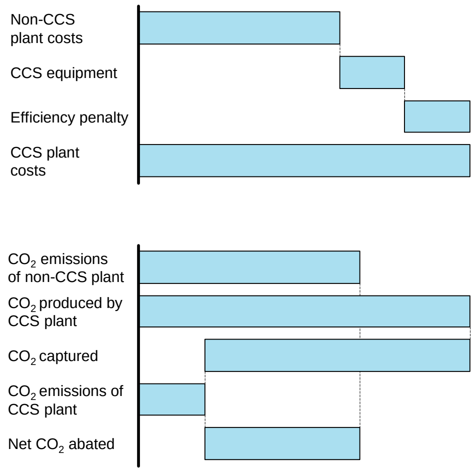
Exhibit 5

Approach followed in the CCS analysis

CONCEPTUAL

Additional CCS cost defined as additional full cost vs. state of the art non CCS-plant

CCS cost expressed as cost per tonne of net CO_2 abated



Source: Team analysis

commercial and, eventually, mature commercial projects. While the analysis is based on a detailed bottom up review of the main technologies currently under development (in particular for capture, post-combustion, pre-combustion and oxy-fuel), the results reported do not refer to any specific process or power plant. [Exhibit 6 + 7]

Exhibit 6

Specifics of the reference case

Reference case consists of combination of different fuel types and technologies for a new build coal plant

New build coal power plant*

CCS technologies
- Post-combustion
- Pre-combustion
- Oxy-fuel

Fuel types
- Hard coal
- Lignite

Reference case costs consist of a range of technology-fuel combinations

CONCEPTUAL

- Hard coal post-combustion
- Hard coal pre-combustion
- Hard coal oxy-fuel
- Lignite post-combustion
- Lignite pre-combustion
- Lignite oxy-fuel

* Other applications such as retrofit and industrial are treated as variations of the reference case
Source: Team analysis

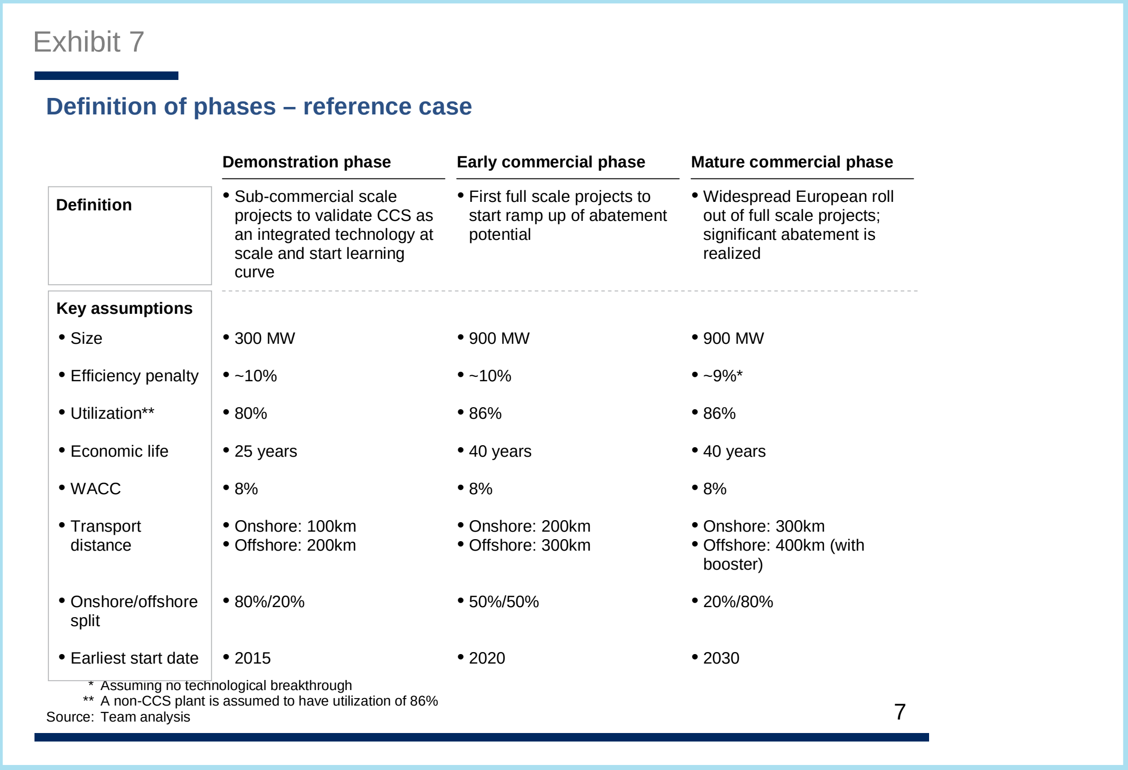


Exhibit 7

Definition of phases – reference case

	Demonstration phase	Early commercial phase	Mature commercial phase
Definition	Sub-commercial scale projects to validate CCS as an integrated technology at scale and start learning curve	First full scale projects to start ramp up of abatement potential	Widespread European roll out of full scale projects; significant abatement is realized
Key assumptions			
Size	300 MW	900 MW	900 MW
Efficiency penalty	~10%	~10%	~9%*
Utilization**	80%	86%	86%
Economic life	25 years	40 years	40 years
WACC	8%	8%	8%
Transport distance	Onshore: 100km Offshore: 200km	Onshore: 200km Offshore: 300km	Onshore: 300km Offshore: 400km (with booster)
Onshore/offshore split	80%/20%	50%/50%	20%/80%
Earliest start date	2015	2020	2030

* Assuming no technological breakthrough

** A non-CCS plant is assumed to have utilization of 86%

Source: Team analysis

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4.1 Main findings

a. Cost of early commercial CCS projects: The early full commercial scale CCS projects, potentially to be built shortly after 2020, are estimated to cost € 35-50 per tonne CO_2 abated.

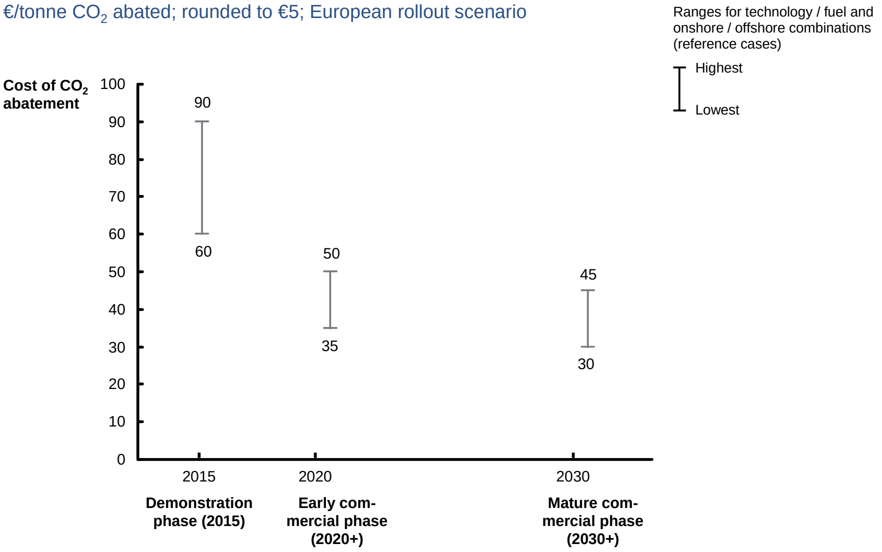
b. Cost of initial demonstration projects: Given their smaller scale, and focus on proving technologies rather than “optimal commercial” operations, these projects, to be deployed around 2012-15, would typically cost between € 60-90 per tonne CO_2 abated. Note that these cost ranges indicate that individual project costs are likely to vary significantly. Costs for some projects – such as those with large transport distances – may even fall outside this range.

c. Possible development of CCS cost beyond the early commercial stage: The later CCS cost would depend on several factors including the learning effect on development of the technology, its economies of scale, the availability of favourable storage locations and the actual roll-out realized. A total CCS cost between € 30-45 per tonne CO_2 abated for new power installations (typically higher for non-power and retrofit applications) could be reached, assuming a roll-out in Europe of 80-120 projects by 2030. In the case of a broader global roll-out, reaching 500-550 projects by 2030, the costs could be roughly € 5 per tonne CO_2 lower. Finally, additional cost reductions of roughly € 5 per tonne CO_2 could be expected from technological breakthroughs in the capture phase, with the introduction of new processes currently being researched. [Exhibit 8]

Exhibit 8

CCS overall cost journey – reference case

€/tonne CO_2 abated; rounded to €5; European rollout scenario



Note: Cost for other CCS options (e.g., coal retrofit, industry) will vary
Source: Team analysis

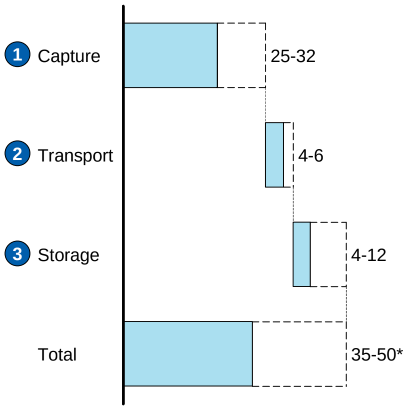
4.2 Cost of early commercial CCS projects

The total CCS cost for early commercial CCS projects is estimated at € 35-50 per tonne CO_2 abated, of which around € 30 per tonne CO_2 is for the capture phase, around € 5 per tonne CO_2 is for transport and around € 10 per tonne CO_2 is for permanent geological storage. [Exhibit 9]

Exhibit 9

Total cost of early commercial projects – reference case

€/tonne CO_2 abated; ranges include on- and offshore



Assumption

- CO_2 capture rate of 90-92%
- CCS efficiency penalty of 7-12% points
- Same utilization as non-CCS plant (86%)
- CO_2 compression at capture site

- Transport through onshore/offshore pipeline network of 200/300 km in supercritical state with no intermediate booster station
- Use of carbon steel (assumed sufficiently dry CO_2)

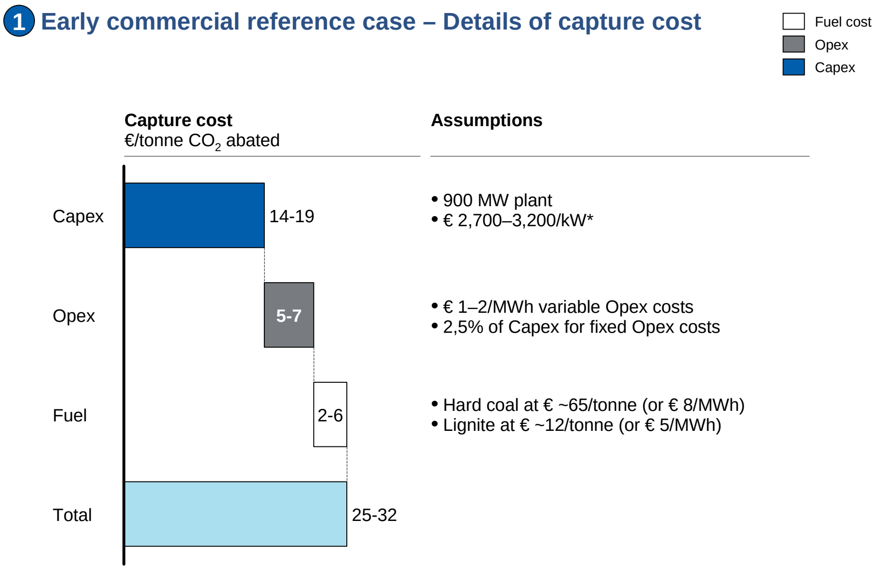
- Injection depth of 1,500 m in supercritical state
- Use of carbon steel (assumed sufficiently dry CO_2)
- Vertical well for onshore/ directional for offshore

* Ranges are rounded to 5 on totals
Source: Team analysis

The CO_2 capture phase represents the main cost block, representing roughly two-thirds of total costs. The reference case assumed for capture is a new, 900 MW net output plant, fuelled by hard coal or lignite, with an expected lifetime of 40 years, and the same utilization rate of a non-CCS plant, at 86 percent. The technology considered is an ultra-supercritical 700°C technology for boilers, coupled with drying in the case of lignite, bringing an efficiency level of 50 percent and 52 percent for hard coal and lignite respectively. While this technology is not currently available, it should be when early commercial CCS projects are built – around 2020 – and is therefore used as a reference.

The main cost drivers for the CO_2 capture are the addition of capture-specific equipment and the efficiency penalty caused by the energy absorbed in the capture process. The additional capture-specific equipment – for example, the air separation unit for the oxy-fuel technology or the CO_2 scrubber for post-combustion – increases the initial capital expenditure (capex) and Operation and Maintenance (O&M) running costs. The absolute efficiency penalty, estimated at around 10 percent for the reference case (meaning plant efficiency reduces from around 50 percent to around 40 percent), drives an increase in fuel consumption and requires an over-sizing of the plant to ensure the same net electricity output. Overall, additional capex would contribute more than half of the CO_2 capture cost, at € 14-19 per tonne CO_2, while fixed and variable operational expenditure (opex) and fuel cost would represent the remaining part at € 5-7 per tonne CO_2 and 2-6 per tonne CO_2 respectively. [Exhibit 10]

Exhibit 10



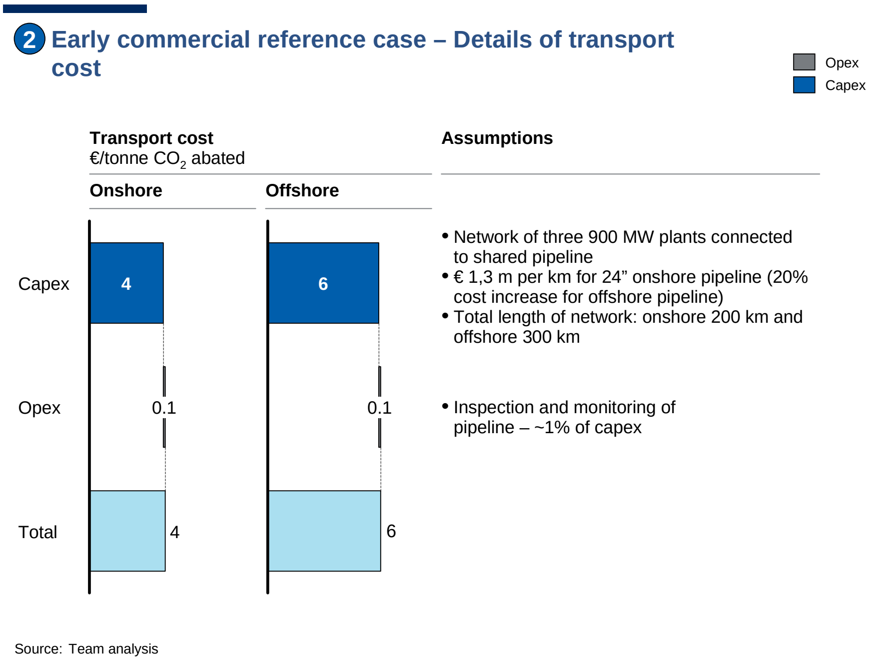
* Assuming industrialized CCS equipment production process

Source: Team analysis

At the current level of development, our analysis indicates that the choice of a specific technology (e.g. pre-combustion, post-combustion, oxy-fuel) does not significantly affect the total cost of capture for a “reference” large-scale plant, even though the relative shares of capex, opex and fuel costs within the total may vary markedly. It is expected that after the first demonstration phase it would be possible to assess in much greater detail the technical and economic performance differences among the processes, allowing a prioritization depending on the specific application.

The transport cost reference case assumes between 20 and 25 CCS projects in Europe, which is sufficient for the formation of small local transport networks and would achieve some economies of scale. Transport would be through pipelines, and the two main possibilities, onshore and offshore storage, have been considered. Each alternative has a significant impact on transport cost: with a total distance assumed for transport of 200 km for onshore and 300 km for offshore respectively, of which 100-200 km would be a “backbone” line sufficient to support three plants. The total cost is around € 4 per tonne CO_2 for onshore, and € 6 per tonne CO_2 for offshore. More than 95 percent of this cost is represented by the initial capex. [Exhibit 11]

Exhibit 11



② Early commercial reference case – Details of transport cost

Assumptions

- Network of three 900 MW plants connected to shared pipeline
- € 1,3 m per km for 24” onshore pipeline (20% cost increase for offshore pipeline)
- Total length of network: onshore 200 km and offshore 300 km
- Inspection and monitoring of pipeline – ~1% of capex

Source: Team analysis

For storage, four specific cases have been considered, to account for onshore and offshore storage and the possibility of using depleted oil and gas fields (DOGF) and deep saline aquifers. The main assumption allows for one storage site per capture facility, which is driven by the likely size of storage locations.

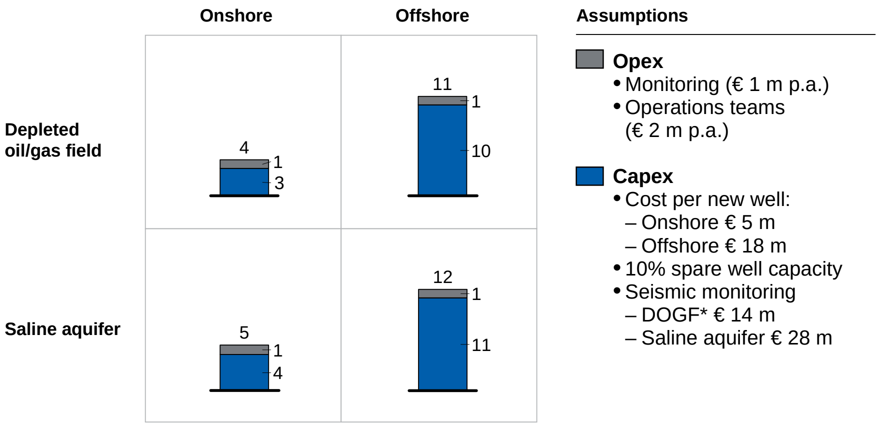
The total storage cost has been calculated taking into account the initial exploration, site assessment phase and site preparation (e.g. drilling). It also reflects its operation over a period of 40 years and the likely costs associated with site closure and monitoring for a further 40 years, a period considered sufficient to confirm permanent storage.

Total storage cost is highly dependent on onshore versus offshore locations, due to an overall increase of equipment, exploration and site set-up/closure costs in the offshore case. Deep saline aquifers are, initially, likely to be more expensive than DOGF due to higher exploration and site mapping costs. Overall, the total onshore storage cost is estimated at € 4 per tonne CO_2 for DOGF and € 5 per tonne CO_2 for deep saline aquifers. But the cost increases significantly to € 11-12 per tonne CO_2 in the offshore case. Some 80-90 percent of that total cost is represented by capex (storage equipment, e.g. wells, pumps, platforms). Opex costs are assumed to be relatively low due to highly automated operations and the absence of pressure-boosting expenses (included within the capture and transport phases). [Exhibit 12]

Exhibit 12

③ Early commercial reference case – Details of storage cost

Storage cost, €/tonne CO_2 abated



Assumptions

Opex
- Monitoring (€ 1 m p.a.)
- Operations teams (€ 2 m p.a.)

Capex
- Cost per new well:
  - – Onshore € 5 m
  - – Offshore € 18 m
- 10% spare well capacity
- Seismic monitoring
  - – DOGF* € 14 m
  - – Saline aquifer € 28 m

* Depleted oil and gas fields

Source: Team analysis

4.3 Cost of initial demonstration projects (2015)

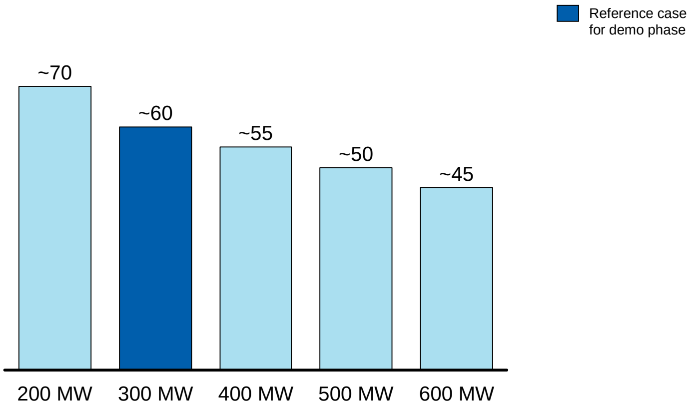
No large-scale, integrated CCS project is currently operational. The prevailing assumption is that initial demonstration projects need to be built in a first phase, in which different CCS technologies along the entire value chain are tested at scale.

The first demonstration projects would be operational in Europe around 2012-15, at the earliest. The reference case assumed for demonstration projects is a 300 MW plant. This is smaller than a commercial hard coal or lignite power plant, in order to limit cost and initial investment, but large enough to test CCS technology at a scale which would allow easy transition to larger plants. [Exhibit 13]

Exhibit 13

Demonstration projects – cost effects in capture due to scale

€/tonne CO_2 abated for capture; all assumptions except plant scale identical to the demo phase reference case



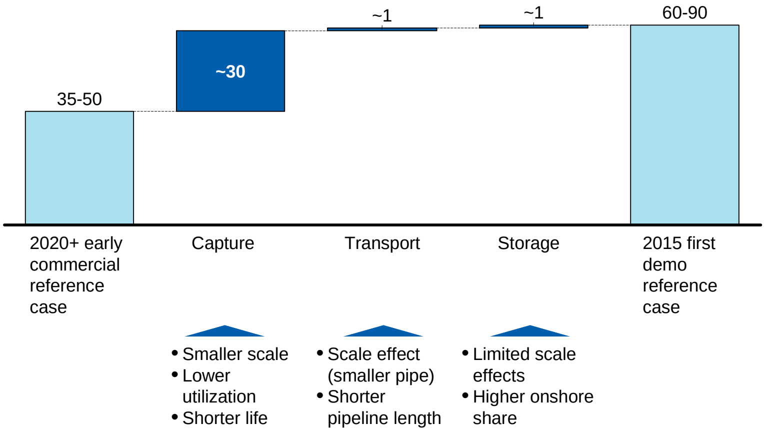
Note: Averages rounded to 5
Source: Team analysis

The cost of these integrated capture-transport-storage projects will be significantly higher than that of the early commercial projects, and is estimated at € 60-90 per tonne CO_2 [Exhibit 14], with a significant spread likely between individual projects, due to their specific characteristics.

Exhibit 14

Cost delta between demonstration and early commercial reference case

€/tonne CO_2 abated



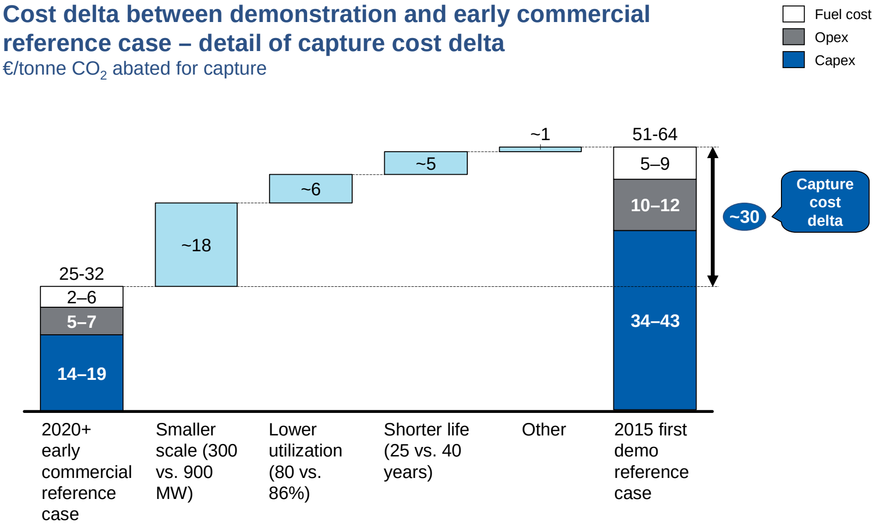
Source: Team analysis

In particular, capture costs are estimated to be roughly double those for the early commercial plants, at around € 50-65 per tonne CO_2, mainly due to their smaller scale (300 vs. 900 MW), lower utilization rate (80 percent versus 86 percent) and shorter overall life (25 versus 40 years) [Exhibit 15]. In general, the demonstration projects are first of their kind and incur costs for the learning experiences they are designed to deliver.

Exhibit 15

Cost delta between demonstration and early commercial reference case – detail of capture cost delta

€/tonne CO_2 abated for capture



Note: Numbers in ranges may not add up due to interdependence of factors (e.g. lowest Opex may only be possible in plant with higher Capex)
Source: Team analysis

Transport costs are projected to be comparable to the early commercial case, at around € 5 per tonne. This would be driven by two opposing factors: on the one hand the ability to “cherry pick” projects with favourable storage locations in order to minimize transport distance, (assumed at 100 km in the reference case used), but on the other the lack of network and scale benefits, due to the limited number and likely dispersed locations of the projects. Long distance transport to the storage location could increase the cost of transport significantly, to around € 10-15 per tonne for distances of 200-300 km.

Finally, the cost of storage cost is projected to be comparable to the early commercial case. However, it will vary widely, assuming that all the main alternative types of geological storage, including offshore locations, are explored.

While relatively costly, the demonstration phase is a fundamental step to reach the commercial stage for CCS. In order to reduce the cost from the demonstration phase to the level described for the early commercial stage, we estimate a need to reach an installed capacity of 21-23 GW, which corresponds to between 23 and 27 plants. If demonstration projects were operational by

2015, the early commercial phase could, at the earliest, be reached at the beginning of the 2020s.

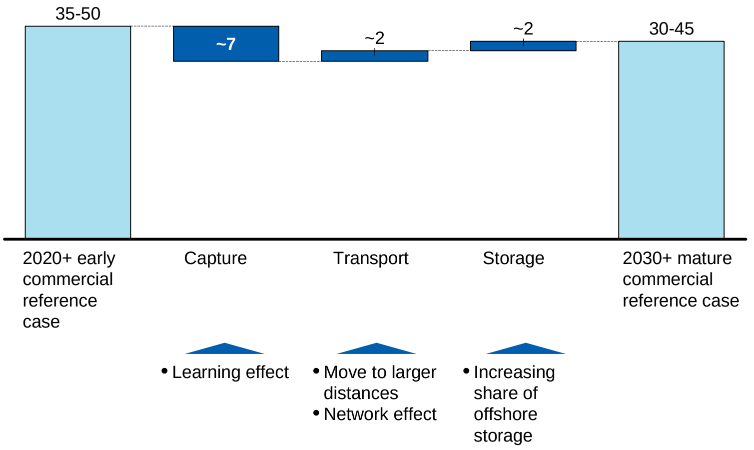
4.4 Possible development of CCS cost beyond the early commercial stage (2030+)

Beyond early commercial development, the cost of CCS is expected to evolve differently at each stage of the value chain and according to different driving factors. [Exhibit 16]

Exhibit 16

Cost delta between early and mature commercial reference case

€/tonne CO_2 abated



Note: Numbers may not add due to rounding

Source: Team analysis

In the capture phase, learning effects beyond the first 20 to 30 full commercial-scale projects could potentially produce a capex cost reduction of around 12 percent for each doubling of capacity installed, and an absolute 1 percent reduction of the efficiency penalty. The learning rate assumed is similar to that seen for potentially similar industries, such as Liquefied Natural Gas (LNG), at 13 percent, and capture systems for sulphur dioxide (SO_2) and nitrogen oxide (NOx), at 12 percent. However, the rate is much lower than that of solar photovoltaic (PV), at 18-23 percent, due to the relative maturity of capture sub-components (e.g. the scrubbing process used in the chemical industry, and air separation units operational at technical gas plants, both of which are by now well developed.) [Exhibit 17]

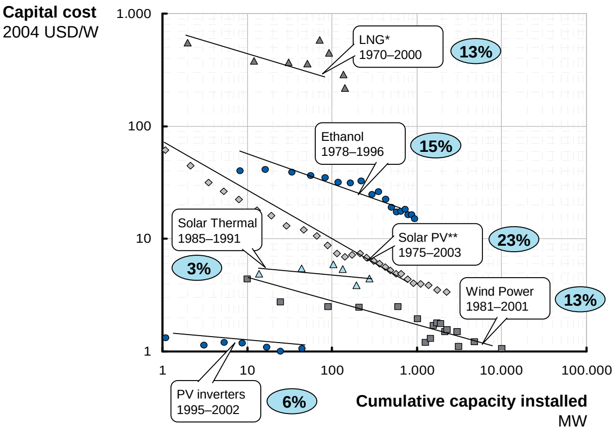
Exhibit 17

CCS learning rate compared with other industries

Percentage cost decrease per doubled capacity

⬭ Implied learning rate per doubled capacity

Learning rate experience from renewables and LNG as capacity is installed



- **CCS learning rate is assumed to be 12%**
- **Assumption is based on comparison with learning rates of**
  - **LNG and renewables (see left)**
  - **SO_2 and NO_x capture systems (12%); comparable capture technology**

* LNG capital cost measured in USD/t and capacity measured in bcm
** Other sources indicate learning rates as low as 18% for solar PV
Source: Worldwatch Institute; IEA; BTM consult; ABS; NREL; IIIEE; ABI; Drewry 2007; UC Berkeley ERG; Navigant consulting; Team analysis

The cost of transport would benefit from scale and network effects once CCS is more broadly rolled out, which would act to offset the likely increase in average transport distances. Given the maturity of gas transport technology, no substantial learning effect is expected.

Storage cost development would be driven mainly by the mix of onshore and offshore storage over time. Since the storage process is, in general, based on established oil and gas drilling technologies and practices, learning effects are expected to be relatively limited.

The overall impact of these factors on CCS cost would depend on the roll-out scenario assumed after the early commercial phase. If no roll-out occurs, the costs of CCS will likely remain as they were in the early commercial phase. For a European scenario that assumes 80 to 120 CCS projects in 2030, the total CO_2 abatement cost for the CCS mature commercial reference case could be around € 30-45 per tonne. Alternatively, For a Global scenario with 500 to 550 CCS projects in 2030, this would be reduced by around € 5 per tonne CO_2.

Finally, the introduction of new “breakthrough” technologies, currently in the early development phase, such as chemical looping or membranes, could potentially lead to a step-like reduction in the cost of CO_2 capture. The total CCS cost could then be reduced further by around € 5 per tonne CO_2.

The estimate of the long-term CCS cost is “structurally” more uncertain, as it is highly dependent on assumptions such as learning rates on currently non-operational processes, possible new technologies, storage location and availability, and roll-out hypotheses.

4.5 Implications

Based on this analysis:

- Significant cost improvements can be expected in CO_2 capture beyond the demonstration phase provided an “industrial scale” roll-out takes place.
- The relative similarity of the expected economic performance at scale of the three main capture technologies, coupled with the margin of uncertainty, make it too early to pick the best option(s). This implies that a potential CCS demonstration programme should be designed to cover all three main capture technologies, and the various storage options, in order to determine which are the best.
- Significant variation will occur between individual projects’ costs depending on factors such as distance to and type of storage. Since this could potentially drive an increase in overall CCS cost, further studies are needed to locate and qualify “economic” storage in favourable locations.
- Costs will come down faster with a broader roll-out, so global introduction of CCS would increase the overall cost efficiency.

5. Sensitivities and variations in CCS costs

The previous chapter laid out the costs of the reference cases for CCS, along with the drivers of those costs. This chapter explains the sensitivities in the costs, and reconciles the reference cases' cost numbers with some previous reports, to demonstrate how assumption differences contribute to cost estimates. In addition, the chapter discusses some of the major cost factors that will drive variations between projects and applications for CCS.

5.1 Reference Case sensitivities

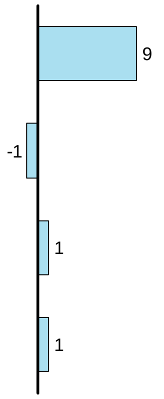
To provide transparency on the main assumptions and uncertainties that drive cost differences within the reference cases, sensitivity analyses have been run, calculating the change in total costs if the main cost drivers are changed and comparing this with the reference cases.

Overall, the review of external factors [Exhibit 18] indicates that the actual Weighted Average Cost of Capital (WACC) employed by a company investing in CCS can significantly affect the total CCS cost. On the other hand, even relatively large changes in coal, steel and engineering services prices would have a more limited effect. That said, any or all of these factors could affect one particular link in the CCS chain more than another. For example, steel prices will have a strong impact on transport costs.

Exhibit 18

Sensitivity analysis – External factors

Parameter	**Reference case value**	**Sensitivity value**	**Rationale for change**	**Impact on total cost of change** €/tonne CO_2 abated, 2020
WACC Percent	8	10	• 10% WACC reflects higher risk for CCS than standard utilities' projects	9
Coal price €/tonne	65	50	• Return to pre-2005 price average	-1
Steel price €/tonne	800	1050	• Continuation of price increase over last 5 years	1
Engineering costs Index	140	220	• Continuation of price increase over last 5 years	1



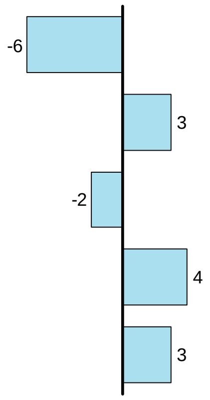
Note: Sensitivities performed for following examples: early commercial hard coal reference plant (capture), offshore network for single early commercial project (transport), offshore depleted oil gas field (storage)
Source: Turner building cost index; Chemical plant engineering cost index; BAFA; SBB; Team analysis

A sensitivity analysis of internal factors [Exhibit 19] indicates that the main driver of overall CCS cost is the plant capex. The relative impact of capex, in turn, is driven by the plant size; the capex per unit impact decreases with increasing installed capacity, due to scale economies on some components.

Exhibit 19

Sensitivity analysis – Internal factors

Parameter	Reference case value	Sensitivity value	Rationale for change	Impact on total cost of change €/tonne CO_2 abated, 2020**
CCS – Capex €/kW	1,000	750	• 25% reduction of additional Capex vs. non-CCS plant because of breakthrough technology	-6
Fixed Opex Percentage of Capex	2.5	4.0	• Opex above industry norm initially before learning CCS operations	3
Efficiency penalty Percent	7.0	3.5	• Breakthrough technology reduces efficiency loss vs. non-CCS	-2
Utilization Percent	86	81	• Market conditions reduce utilization by 5% points	4
Learning rate Percent*, 2020-2030	12	6	• Most conservative expert group estimate	3



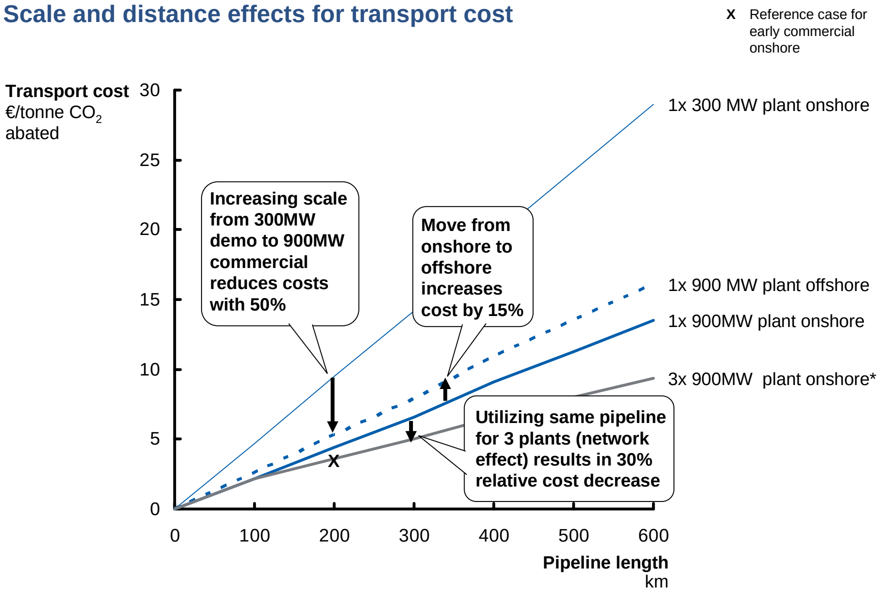
Note: Sensitivities performed for following examples: early commercial hard coal reference plant (capture), offshore network for single early commercial plant (transport), offshore depleted oil gas field (storage)
* Per doubling of installed plant capacity for EU rollout (increase from 22.5 to 81 GW)
** 2030 for learning rate sensitivity
Source: Team analysis

For transport cost, distance is the main factor [Exhibit 20]. Cost of material and construction are highly proportional to distance. For example, while the transport cost would be around € 4 per tonne in the reference case of 200 km onshore in the case of a single pipeline, this would increase to around € 9 per tonne for a 400 km pipeline with one intermediate pressure booster. Overall, the impact of transport cost uncertainties on the total CCS cost is relatively limited, due to the low share of transport cost in the total. So a 100 percent transport cost increase, for instance, from € 5 to 10 per tonne would in fact represent only a ~10 percent increase in the total CCS cost.

Storage costs are, as mentioned in the previous chapter, especially sensitive to whether storage is onshore or offshore. A second driver of cost difference is linked to the specific characteristics of the storage site: deep saline aquifers are estimated to carry storage costs on average 10-15 percent higher than those of depleted oil and gas fields. This is due to the lack of extensive geological data on deep saline aquifers, which in turn creates the need for additional preliminary exploration and mapping, and thus higher initial capex.

Exhibit 20

Scale and distance effects for transport cost



* A network of 3 plants of 900 MW connected to shared large pipeline
Source: Team analysis

An important driver of storage cost is the actual size of the storage site. Since a relevant part of the cost for storage is linked to site exploration and characterization, the larger the site, the more these costs would be distributed over larger CO_2 quantities, driving down the storage cost per tonne CO_2. The effect could be significant: storage cost for a large field that can service two commercial-scale plants simultaneously, could be roughly one third lower than for a one-on-one situation. With smaller fields, by contrast, where two distinct fields are required to store the emissions of one single plant, storage costs could be about 60-70 percent higher than in the reference case.

A final consideration related to the cost of storage is the theoretical possibility of implementing CO_2 Enhanced Oil Recovery (EOR) or Enhanced Gas Recovery (EGR) at the storage site. In these methods, CO_2 is injected into an oil or gas field to increase the amount of oil or gas that can be produced. The value of the CO_2 is estimated by the US Department of Energy at $ 25-35 per tonne CO_2. This means that EOR or EGR could potentially reduce the overall costs of CCS significantly. However, the applicability of EOR or EGR is highly dependent on the characteristics of the specific site, and currently most experts agree that the economic potential of these methods seems to be relatively limited in Europe.

Overall, the cost of storage, while not among the larger components in the CCS value chain, is the component with the highest relative variability due to the range of possible characteristics of storage locations and the potential for EOR/EGR. It thus will be a critical element to optimize, together with the capture plant capex.

5.2 Cost variations between CCS applications

CCS has four main categories of applications: new power plants (coal, gas and biofuel), existing power plants, new CO_2-intensive industrial operations (such as refining and the production of steel and cement), and existing industrial operations. In this report we have focused our detailed analysis on new coal power plants.

In this section, however, we discuss the other categories, albeit with a lower degree of quantitative analysis. The main area of cost difference would be in the capture phase; transport and storage costs would not change.

Retrofitting of coal power plants

In general, retrofitting an existing power plant would lead to a higher cost for CCS. The costs are highly dependent on the specific site characteristics, including plant specifications, remaining economic life and overall site layout. For this reason no generalization or “reference case” would be meaningful.

There are at least four main factors likely to drive the cost increase for retrofits. First is the higher capex of the capture plant. The existing plant configuration and space constraints could make adaption to CCS more difficult than in a newly built situation. Second is the installation’s shorter lifespan. The emission source is already operating, so for example where a new plant CCS system may run 40 years, the capture part of a 20-year-old power plant is likely to have only a 20 year life, reducing the “efficiency” of the initial capex. Third, there is a higher efficiency penalty, leading to higher fuel cost when compared to a fully integrated new-built CCS plant. Finally, there is the “opportunity cost” of lost generating time, because the plant would be taken out of operation for a period to install the retrofitted capture equipment.

As has been said, the actual impact of the factors driving retrofitting cost will be site and situation specific. It is estimated that retrofitting CCS is unlikely for plants older than ten to twelve years, as the total CCS cost would be at least 30 percent higher than that of new power plants (for same scale plants), and possibly much more, depending on the specific case.

There are two exceptions when the retrofit cost penalty could be significantly lower. The first is for very young (less than five to seven years) and very efficient coal power plants. If the plant was built as “capture ready”, and the retrofit planned to minimize downtime, the additional costs could be 10 percent or even lower. The potential for this therefore depends on the extent to which consideration is given to building plants that are “capture ready” (including designing the layout to facilitate later positioning of capture equipment).

The second exception is when the target for retrofitting would be old “blocks” within a power plant that are already due for extensive revamping. In this case, the impact of all the factors mentioned above would be limited, as the renovations could offer more freedom for the installation of the new CCS equipment. In this case the residual life would be comparable with a “new” plant and the interruption of operations would already be included in the revamping plan.

Finally, it is worth noting that retrofitting could be an attractive option for building a CCS demonstration project, because the capex required would be lower (and thus the risk smaller), and the construction time might be shorter. The shorter lifespan of a retrofitted CCS plant would most likely not be a problem, since the plant would in any case be expected to have a shorter life. And the impact of the possibly higher efficiency penalty would be reduced by the smaller size of the plant, the shorter life and the lower utilization.

Other types of fossil fuel power plants (new and existing plants)

CCS can be installed on all types of fossil fuel power plants, the main types being coal, gas and biomass[16]. In this report we have focused our analysis on coal, since this fuel has the highest relative net carbon emissions to energy output.

In comparing the applicability of CCS to gas and biomass power plants, scale and process characteristics appear as the main drivers for cost differences. Approximate assessment suggests that in the case of biomass power plants, the higher cost of CCS per tonne CO_2 abated could be linked mainly to the relatively small scale of these plants (currently around 100 MW) compared to large coal plants. A higher energy penalty and the typically lower efficiency of these plants compared to coal plants would also add to the higher cost.

In the case of gas power plants, scale is less of a problem, as they could be large (from 450 to 650 MW). The main driver of higher cost is the characteristics of the flue gas, which is produced in much higher volumes and with 25-30 percent less CO_2 concentration compared to a coal plant. Thus much of the CCS equipment would have to be significantly larger, with higher relative additional cost. Finally, the fuel is between two and four times more expensive (in terms of heat produced for one Euro of fuel cost) compared to coal, so a similar efficiency penalty to run the capture process would translate into costs that were two to four times higher.

In the case of retrofitting, the same qualitative considerations relevant for coal power plants (such as remaining economic life) would be applicable to other types of fossil fuel plants.

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[16] Oil-fired plants made up only about 4 percent of European electricity generation in 2005 and are forecasted to decline relative to other fuels.

Industrial applications (new and existing plants)

Sites such as refineries, steel and cement plants are also high emitters of CO_2, accounting in total for around 25 percent of stationary source emissions in the EU and making them a potential target for CCS. Large-scale steel plants using integrated iron ore-blast furnaces, for example, could produce 5-10 Mt of CO_2 per year – more than a 1000 MW coal plant would.

In general, the cost of CCS for non-power applications has not been studied in the same depth as it has for the power sector. Since the specific industrial applications are very different in terms of process characteristics, scale, CO_2 concentration and gas stream characteristics (e.g. pressure, composition), the available cost studies show a very broad range. The resulting CCS cost will depend on the specifics of the situation, although in some cases – processes where a very pure stream of CO_2 is produced, for instance – the cost is likely to be lower than in the new build coal reference case.

In general, the need for a retrofit would increase the CCS cost, much as we have seen for power plants. On the other hand, the application of CCS to processes in which the concentration of CO_2 in the flue gas is very high or in which the CO_2 is already separated as part of the production process (e.g. hydrogen production in refineries), could potentially lead to a lower capture cost.

Finally, it should be noted that, particularly for global commodities such as steel, the considerations above do not take into account the potential effect on the industry’s cost competitiveness when adopting CCS. This could represent an obstacle to the actual application of CCS to industrial processes.

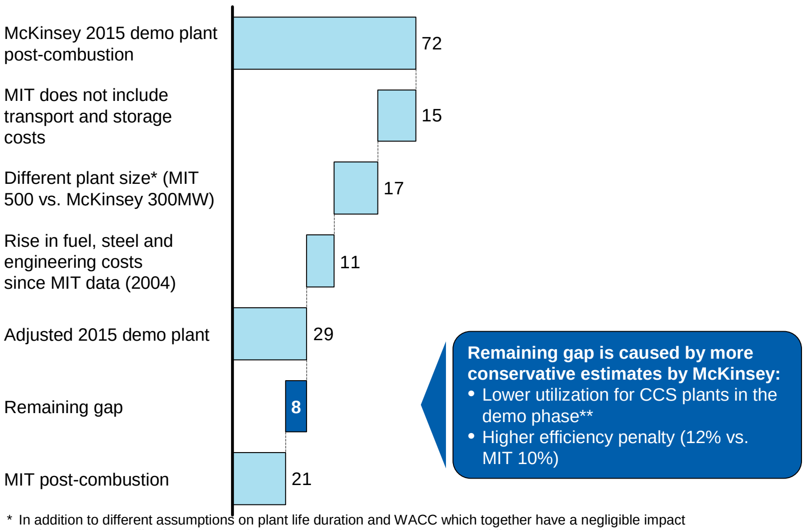
5.3 Reconciliations with other cost reports

When this study began, publicly available cost estimates for CCS appeared to vary considerably, and it was often difficult to discern the reasons for these differences without substantial analytical effort. The cost numbers in this report have therefore been compared to those of three other recent studies (MIT, IEA and IPCC) in an attempt to reconcile the differences (see [Exhibit 21] for comparison with the MIT study). This exercise has shown that the numbers in this report are in line with those from the other reports when converted to a “like for like” basis. The exercise has also shown that the assumptions in this report are where they differ from those in the other reports, overall more conservative.

Exhibit 21

Analysis of difference in CCS cost between MIT report and this report

Costs, €/tonne CO_2 abated



Remaining gap is caused by more conservative estimates by McKinsey:

- Lower utilization for CCS plants in the demo phase**
- Higher efficiency penalty (12% vs. MIT 10%)

* In addition to different assumptions on plant life duration and WACC which together have a negligible impact

** Estimate of 80% utilization for CCS plants compared to 86% for non-CCS, while MIT has 85% for CCS and non-CCS

Source: MIT; team analysis

Four factors typically explain the differences: first, some reports talk only about capture costs where others (this report included) address the full value chain; second, the characteristics of the reference plants differ (e.g., installed capacity, plant lifetime); third, the significant escalation in capex, fuel and steel costs in the last two years has driven up overall costs compared to earlier estimates; fourth, some reports have different assumptions for key variables such as the CCS efficiency penalty or storage characteristics (onshore or offshore) of Europe.

Estimates from these other sources, regardless of individual differences, do support the logic and size of cost improvements over time. Although individual numbers vary, several sources estimate – as found in this report – that the cost of CCS will drop by around 50 percent between

2010 and 2030 (e.g. IEA: from $40-90 now to $35-60 in 2030 per tonne CO_2[17]; IPCC 20-30 percent cost reduction in next decade[18]).

5.4 Implications

- The main cost uncertainties for CCS are the assumed weighted average cost of capital (WACC), the capture capex and choice of storage location.
- The storage cost could vary significantly depending on the actual characteristics of the available local storage, and is thus likely to drive cost differences among CCS applications even after the technology has matured.
- While retrofitting existing plants is in general estimated to increase CCS cost, planning retrofitting to coincide with major revamping could significantly limit the cost penalty (although this could lead to delays in the CCS roll-out).
- For forms of CCS other than the new build coal power plant reference cases, the main cost differences are in the capture phase. Cost uncertainties are high given the lack of maturity of such applications and the fact that costs will be highly dependent on specific site characteristics.

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[17] IEA Technology perspectives 2008

[18] IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage

6. Scaling-up CCS in Europe

Limited prior work exists on the development of CCS beyond the demonstration stage and it is not the objective of this report to make predictions or forecasts of the future. However, understanding the drivers for how CCS could be scaled up can be helpful for both industry players and other decision makers.

There are three main drivers that could impact the way that commercial scale-up of CCS occurs in Europe, and we explore each of these in detail in this chapter:

- **Capture:** The selection approach for, and location of, emission sources that will use CO_2 capture technology.
- **Storage:** The availability and location of sites developed for CO_2 storage, and how this affects the design of the transportation network.
- **The speed of deployment:** The speed with which new CCS projects commence, and the time to complete them.

6.1 Capture: evolution of clusters?

The mature state of CCS in 2030 on the capture side could evolve in several different ways. One possible archetype is multiple “clusters” of emission sources located relatively close to each other (e.g. in highly industrialised areas) [Exhibit 22]. The rationale for such clusters developing is threefold. Firstly, clustering capture points could improve the economics by decreasing the transport cost, as fewer, larger-scale pipelines would be needed to connect capture points to storage locations. For example, combining transport for two nearby emitters into a single 36-inch pipeline versus two separate 24-inch pipelines reduces estimated transport costs by 30 percent. Secondly, adding capture points to a region with existing public acceptance of CCS and permitting practices could improve feasibility and speed. Thirdly, the largest emitters are often effectively in “clusters” of heavily industrialised areas; local governments wanting to encourage industry development, or industry consortia pooling together to underwrite investment, could help make these the logical places to start.

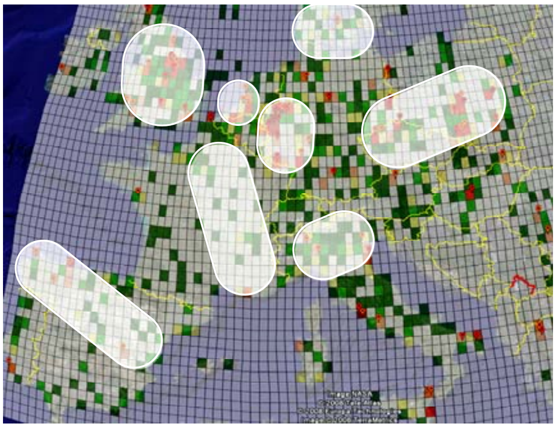
For example, the Ruhr area represents 10% of the German territory, but encompasses 75% of German emissions from large stationary sources (of more than 3 million tonnes CO_2 per year).

For illustrative purposes, we have developed an example of how the actual high CO_2 emissions sources could be grouped into eight major capture clusters that could address ~120 large emission points, mostly with emissions of more than 3 million tonnes CO_2 per year, representing a total abatement potential of about 0.4 Gt CO_2 per year in 2030.

Actual capture cluster development therefore would likely be based on large stationary emitters such as power plants (with new or relatively recent power plants having the best economics) or the largest industrial applications (such as steelworks). Based on such a “core”, other power and industry emitters in the vicinity might then retrofit capture processes, establishing a larger local “cluster”.

Exhibit 22

Possible scenario: capture clusters emerge around major industrial areas in Europe



Rationale for capture clusters:
- Economics: fewer pipes lead to lower transport cost
- Feasibility: public acceptance, permitting and local coordination of infrastructure are simpler for a region where CCS is already in place

* For heavy industry plants (e.g. cement, steel, refineries) a few smaller plants are included as well
Source: IEA GHG Emissions database; Google earth; NASA; Tele Atlas; Europe Technologies & TerraMetrics; Team analysis

6.2 Regional storage availability is key, driving the resulting transport network

The regional distribution and cost of storage in Europe would play an important role in any possible roll-out of CCS.

Three forms of CO_2 storage are often cited: geological storage, ocean storage and mineral carbonation. Most experts agree that geological storage is the only feasible option in the short term, and that within geological storage, oil and gas fields and deep saline aquifers have the most potential.

The current knowledge regarding the availability of geological CO_2 storage in Europe is still limited, especially in terms of the regional distribution of suitable aquifer storage. Currently, a pan-European project called “GeoCapacity” is underway, which will provide a first comprehensive database of European CO_2 storage availability. At the time of writing, however, this database was not yet available. Estimates here have been based on existing, fairly fragmented country reports and expert interviews.

Depleted oil and gas fields

Depleted oil and gas fields are well understood. Of total oil and gas field capacity in Europe, roughly one third is estimated to be economically useable for CO_2 storage. Non-depleted fields cannot be used[19] and many depleted fields are too small to be economically practical. Consequently, the amount of economical depleted oil and gas fields (DOGF) in Europe is estimated to have a capacity of 10 to 15 billion tonnes of abated CO_2, which is enough for the lifetime of about 50 to 60 projects. However, most of these fields are located in offshore northern Europe and are about twice as costly to access and operate as onshore fields (as described in chapter 4).

Deep saline aquifers

To date much less work has been done to map and define deep saline aquifers, as well as to understand how much CO_2 storage is possible in such geological settings. Most sources indicate that the storage available should be sufficient for European needs overall. Estimates range from 30 billion tonnes to more than 500 billion tonnes.

Preliminary analysis suggests that, despite significant uncertainty regarding the total available capacity and its distribution in Europe, it is likely that total storage capacity could be sufficient to support a full scale CCS roll-out [Exhibit 23]. The cost would depend on the regional distribution and accessibility of the storage sites. Significant uncertainty exists concerning the distribution of actual storage. [Exhibit 24]

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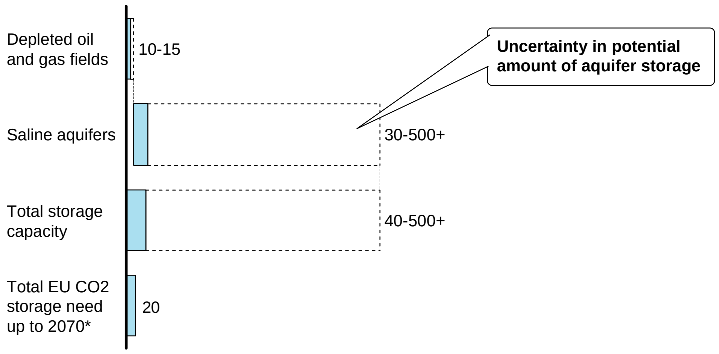
[19] Non-depleted gas fields cannot be used for CO_2 storage because of gas mixing, while non depleted oil fields can only be used for Enhanced Oil Recovery. But because a large part of CO_2 resurfaces with EOR, it is unsuitable if the goal is CO_2 storage and not increased oil recovery.

Exhibit 23

Preliminary assessment of feasible European CO_2 storage availability based on extrapolation of available information

$GtCO_2$,2030

INDICATIVE; PRELIMINARY



Uncertainty in potential amount of aquifer storage

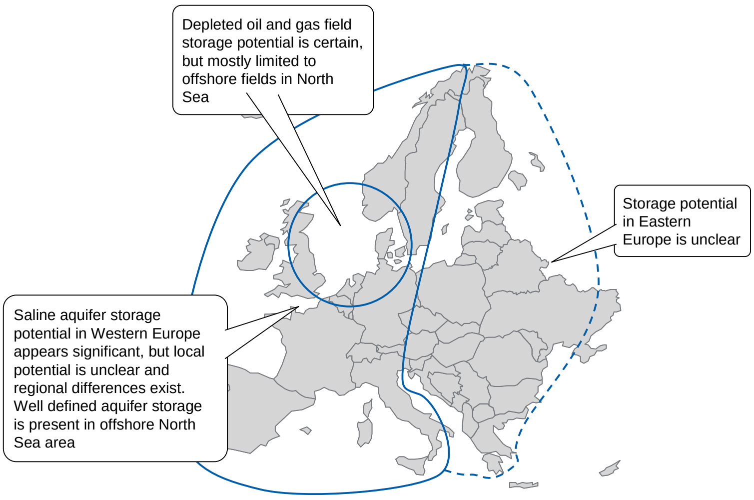
* Storage needed to accommodate all emissions of a roll-out to 0.4 Gt in 2030 and constant at 0.4 Gt from 2030 to 2070

Source: GESTCO; Joule II; Expert interviews; Team analysis

Exhibit 24

European CO_2 storage availability

CONCEPTUAL



Depleted oil and gas field storage potential is certain, but mostly limited to offshore fields in North Sea

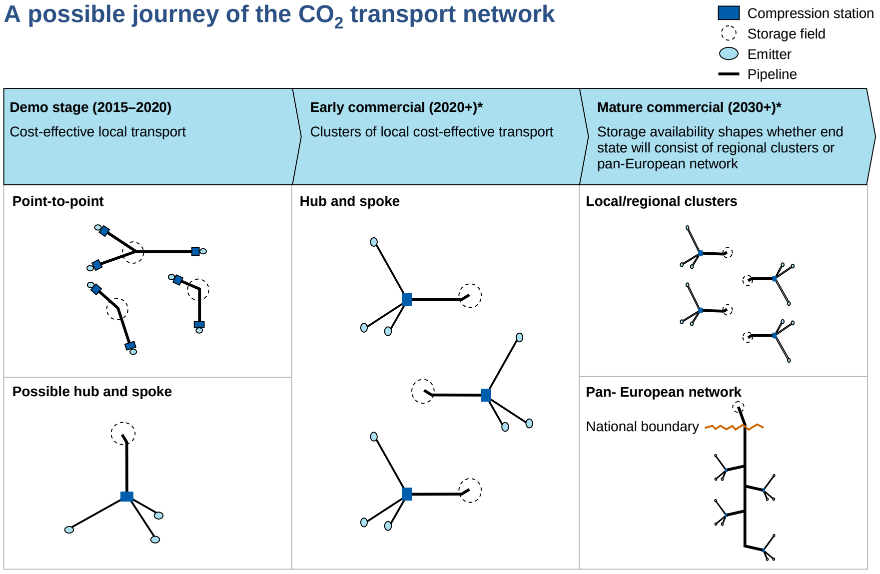
Storage potential in Eastern Europe is unclear

Saline aquifer storage potential in Western Europe appears significant, but local potential is unclear and regional differences exist. Well defined aquifer storage is present in offshore North Sea area

Source: GESTCO; Joule II; Expert interviews; Team analysis

The actual geographical distribution of storage would have a strong impact on the scale-up of CCS in Europe, including the transport network. Depending on the regional availability of storage, the mature state of CCS in Europe could develop in at least two different ways. [Exhibit 25]

A possible journey of the CO_2 transport network



* Some point-to-point networks are likely to continue to exist in the early and mature commercial stage
Source: Team analysis

Exhibit 25

- Regional capture-storage clusters: If widely distributed local storage is proven, the CCS roll-out is likely to remain largely local, with regional capture-storage clusters. These clusters would have the potential to abate 0.4 Gt of CO_2 per year in 2030 with 80 to 120 CCS sites. [Exhibit 26]

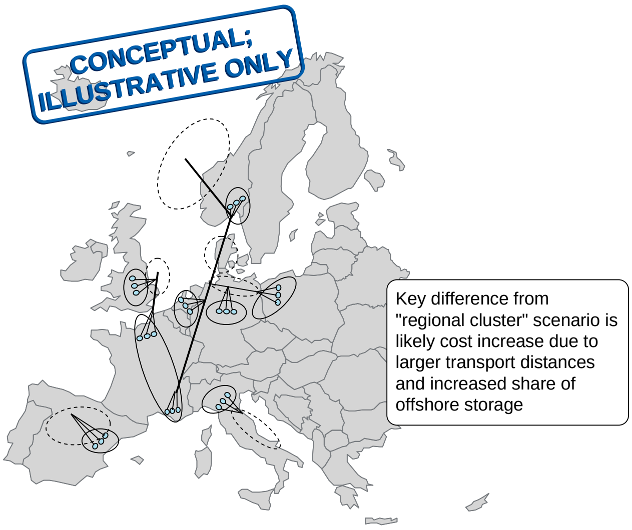
Exhibit 26

- Pan-European network: If Europe does not have enough widespread, accessible local storage, or public discussions were to lead to a mainly offshore solution, the necessary transport network would have to increase significantly in size. In that case, a pan-European transport network could be developed to connect regional capture clusters with large international storage locations, such as offshore deep saline aquifers in the North Sea area. The longer transport distance and shift to predominantly offshore storage could double transport and storage costs to about €18 per tonne CO_2 for offshore storage versus about €9 per tonne CO_2 for onshore storage in 2030 [Exhibit 27]. This could also lead to different clustering solutions, for instance with more penetration of CCS in northern Europe, or in coastal regions. However, there would be significant regulatory and logistical challenges in implementing such a network.

Large scale roll-out: what could it conceptually look like?

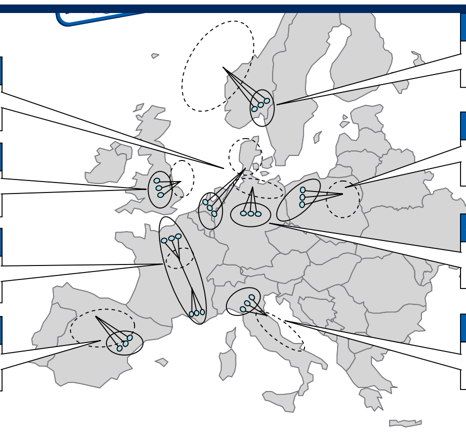
Pan-European transport network case

○ Capture cluster
◌ Storage cluster
— Pipeline



Key difference from "regional cluster" scenario is likely cost increase due to larger transport distances and increased share of offshore storage

Source: IEA GHG Emissions database v2006; pathfinder; ECOFYS; Gestco summary report; Team analysis



Cluster	Abatement	Capture sites
Rotterdam cluster	30-40MtCO$_2$/y	10-15
Western cluster	50-60MtCO$_2$/y	10-15
Paris cluster	30-40MtCO$_2$/y	10-15
Iberic cluster	50-60MtCO$_2$/y	15-20
Nordic cluster	15-20MtCO$_2$/y	10-15
Eastern European cluster	60-70MtCO$_2$/y	10-15
German cluster	90-110MtCO$_2$/y	25-30
North Italian cluster	50-60MtCO$_2$/y	15-20

Source: IEA GHG Emissions database v2006; pathfinder; ECOFYS; Gestco summary report; Team analysis

Exhibit 27

6.3 Speed of development and the broader roll-out of CCS

In moving from a handful of demonstration projects to a widespread CCS network, the main challenge is the time required to complete individual projects. The lead time for the construction and permitting of a typical new coal plant in Europe is around six years[20], due to the complexities of planning, approvals and building infrastructure. CCS adds the need for construction and permitting of CCS storage and transport infrastructure. Since any final investment decision is unlikely before all permits (capture, transport and storage) are in place, construction of a new CCS coal project is estimated to have a lead-time of six to ten years.

This lead-time impacts both key factors that determine the roll-out speed of CCS, namely the year in which the roll-out beyond the demonstration phase is begun and the roll-out rate per year. The year in which roll-out begins is practically determined by the decision as to how many years of operating experience by the demonstration projects are required before the first commercial projects are begun. The roll-out rate is determined by how many installations can be fitted with CCS each year. The lowest cost option and the logical starting point is to new build coal power plants. According to Prospex and Platts Powervision, roughly five new coal plants are planned per year in the period 2015- 2030. If the actual rate is lower, roll-out would need to focus on retrofitting and industrial applications. Retrofitting of recently built plants could be employed at relatively limited additional (10%) cost. An additional option, at relatively limited additional cost, is to retrofit when blocks of an existing plant are revamped. Beyond that gas-fired or biomass power plants could also be considered.

Based on these considerations, three scenarios regarding the roll-out have been laid out. [Exhibit 28]

Exhibit 28

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[20] IEA, web site, 2007; expert interviews

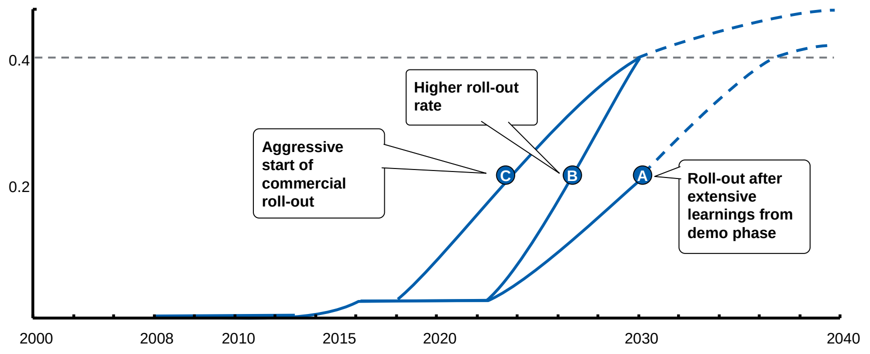
In scenario A, it is assumed that the first full commercial-scale projects will be operational around 2023. After that, additional CCS capacity equivalent to five 1000 MW power plants would be rolled out each year. A possible way to achieve this is for new build coal plants to make up 70% of the CCS build-up (three to four 900 MW projects per year), and for retrofits and industrial projects to make up the rest (each at 15% of build-up). This would result in CCS abatement of 0.2 Gt CO_2 in 2030.

To enable the achievement of CCS's abatement potential of 0.4 Gt CO_2 per year in 2030, two more aggressive scenarios have been defined. In scenarios A and B, the roll-out begins around 2023, but for scenario B the roll-out rate is faster, at a yearly capacity addition equivalent to ten to eleven 1000 MW plants, which would require more extensive retrofits and industrial applications. In scenario C, a more aggressive start of the roll-out is assumed, starting around 2018, with the roll-out rate similar to scenario A, at a yearly capacity addition equivalent to about six 1000 MW plants.

Scenarios for journey to CCS mature state

EU27, $GtCO_2$ abated per year by CCS

ILLUSTRATIVE



Source: Team analysis

The difference between the scenarios is twofold: costs and emissions. In scenario C the least CO_2 is emitted and in scenario A the most. With regard to cost, scenario A is the least costly, since in scenario B greater numbers of the more expensive retrofits are used, and in scenario C additional incentives might be needed for the early commercial projects to offset their increased risk and lower learning impacts.

Potentially, a barrier to achieve the roll-out rate in any scenario, but in particular in scenario B, is resource constraints from equipment suppliers, engineering providers or skilled labour to operate these complex projects, or other vendors that limit the rate at which new projects could be developed. This includes the industrial development needed to support "ramp up" – building manufacturing capacity, preparing supply chains and training personnel.

6.4 Implications

- For Europe to reach the 2030 CCS abatement potential of around 0.4 Gt CO_2 per year would require approximately 80 to 120 large-scale projects.

- To achieve such a level of penetration by 2030 will require an aggressive roll-out – either through an "accelerated" approach where commercial roll-out begins shortly after the learning phase of demonstration projects; or through an aggressive ramp-up during the 2020s, including retrofitting power and fitting industrial applications with CCS. In each case, early thinking is needed on the business models to be applied across the value chain; this is true particularly for the development of pipeline networks and storage projects, as well as to ensure that the resources required are in place for the roll-out.

- Storage remains a key area where uncertainty needs to be resolved – particularly the availability of suitable aquifer storage – to understand the possibility and cost of developing CCS clusters in specific regions within Europe.

7. Key barriers and uncertainties

As described above, the possible cost evolution of CCS depends on several factors, such as the roll-out rate and the local availability of storage. Based on interviews with industry players, NGOs, academics and other key stakeholders, four key potential barriers to the development of CCS were identified: public safety and support questions; lack of a specific legal framework; funding for demonstration projects; and development of commercial and risk allocation models.

The objective of this section is to provide a brief overview of these issues. We explicitly avoid drawing specific policy recommendations.

7.1 Public safety and support

There are currently public concerns about the environmental integrity of CCS[21]. These turn partly on the question of whether the CO_2 captured and stored will remain isolated from the atmosphere in the long term; and partly on whether the capture, transport and storage elements present health or ecosystem risks.

There exists additional uncertainty around the public support for CCS. An MIT study in April 2007 showed that levels of public awareness of CCS in the US were low, and that acceptance of CCS was below that of nuclear power. The same study, however, also showed a possible way of resolving some of the scepticism. It found that effective public information campaigns could significantly increase CCS acceptance[22].

7.2 Lack of a specific legal framework

Our interviews identified four main regulatory concerns, focused around storage, and, to a lesser extent, transport.

1. Legality of storage. There has been concern over existing legislation that could classify CO_2 as waste, thus increasing the hurdles for transport and storage. Related to this is the issue of purity: it has been unclear how pure CO_2 streams would have to be in order not to be considered as waste. A high purity limit could greatly increase CCS costs.

2. Storage liability. Uncertainty over long-term liability for leakage has also been a major issue. Industry and investors worry about indefinite exposure to litigation for leakage.

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[21] http://ec.europa.eu/environment/climat/ccs/what_en.htm

[22] MIT Carbon sequestration initiative

Meanwhile, as storage duration (thousands of years) is far longer than the typical lifetime of a company, the state would always be implicitly responsible for leakage in the long run.

3. Storage monitoring responsibility. There is uncertainty over who would be responsible for monitoring storage sites, how long monitoring would be needed and what that monitoring would require over time.

4. Transport. Transport for CCS is currently governed by existing natural gas transport regulation and thus the legal framework exists. However, obtaining permits for transport is time intensive in many countries, particularly where new pipeline routes are required. For projects involving cross border transportation, the necessary processes can be even more protracted.

The first three of these issues are being addressed in the EU Directive on geological storage of carbon dioxide, which is being discussed in the European Parliament this year. The challenge is of course both on the EU and national levels. Any legislative framework defined at the European level will then need to be translated into national laws – a process which will take time and which includes the potential for local variations.

Obtaining permits for transport is likely to remain a major challenge for the implementation of CCS, particularly where cross-border pipelines are required.

7.3 Funding for demonstration projects

There is uncertainty about the funding of demonstration projects. Our analysis shows that the typical cost of a demonstration project is likely to be in the range € 60-90 per tonne CO_2 abated. It is difficult to forecast the carbon price in the long term, but recent analyst estimates[23] for Phase II of the European Union Emission Trading System (EU ETS) range from € 30 to 48 per tonne CO_2, and at this stage similar levels are expected beyond Phase II (up to 2030). In this range, the carbon price is insufficient for demonstration projects to be "stand-alone" commercially viable.

Much of the current funding discussion for CCS revolves around how much additional investment is likely to be required to help manage the risks and commercial needs of these demonstration projects, and around where such funds will come from.

Assuming that CCS demonstration projects would cost between € 60 and 90 per tonne CO_2, and projecting a median carbon price of € 35 per tonne CO_2, there is an "economic gap" of € 25-55 per tonne CO_2 for each project. This corresponds to about € 500-1100 million, expressed as

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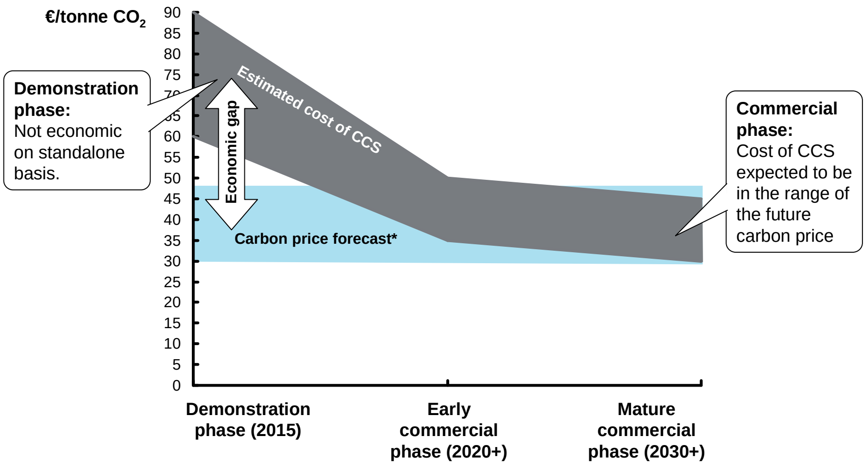
[23] Deutsche Bank May 2008, Point Carbon June 2008, Fortis Jan 2008, UBS Nov 07

a Net Present Value (NPV) over the full life of a 300 MW size project. The range depends on variations in specific project variables such as capture technology and capex, transport distance and storage solutions. [Exhibit 29]

Exhibit 29

Forecast of development of CCS costs and carbon price



Demonstration phase: Not economic on standalone basis.

Commercial phase: Cost of CCS expected to be in the range of the future carbon price

* Carbon price for 2015 from 2008-15 estimates from Deutsche Bank, New Carbon Finance, Soc Gen, UBS, Point Carbon, assumed constant afterwards

Source: Reuters; Team analysis

While a broad range of possible mechanisms for funding exist, the current CCS debate in Europe focuses on two that are linked to the Emissions Trading Scheme, and where legislative agreement could be finalized by early 2009 in the revised Emissions Trading Directive.

In addition, there is debate surrounding amendments to the draft EU Directive on geological storage that might contain some form of mandatory requirements for CCS, including potential “capture-ready” requirements (requiring all new coal fired power plants to be able to retrofit CCS in the future).

Finding a joint solution between industry players and European regulators to bridge this economic gap will be critical to the success of a possible demonstration programme.

7.4 Development of commercial and risk allocation models

CCS projects are likely to include several participating organisations. The generic business models and commercial structures for the different organisations need to be developed. Risk allocation mechanisms also need to be designed. These include ownership and operation of sites, ownership of CO_2, access to transportation capacity, and access to storage services.

Appendix

Bibliography

Bellona. 2008. “How to combat global warming”

Deutsche Bank. June 2008. “Target 2008 EUAs at EUR40/Tonne”

Encap. 2008. “Power systems evaluation and benchmarking – public version”

Greenpeace. 2008. “False Hope”

International Emissions Trading Association. 2008. “Options for financing CCS”

International Energy Agency. 2004. “Prospects for CO_2 capture and storage”. OECD/IEA

International Energy Agency. 2007. “World Energy Outlook 2007.” OECD/IEA.

International Energy Agency. 2007. “CO_2 capture ready plants”

International Energy Agency. 2005. “Legal aspects of storing CO_2“

International Energy Agency. 2008. “Geological storage of Carbon Dioxide – Storing safely underground”

International Energy Agency. 2008. “Energy technology perspectives”

International Risk Governance Council. 2008. “Regulation of carbon capture and storage”

Massachusetts Institute of Technology. 2007. “The future of coal”

Platts. July 2008. “Powervision”

Prospex. 2007. “European Coal Trading 2007”

Stern, Nicholas. 2006. “The economics of climate change”

United Nations Intergovernmental Panel on Climate Change. 2006. “Special Report on Carbon Capture and Storage”

Vattenfall, McKinsey. 2006. “Global mapping of greenhouse gas abatement opportunities up to 2030”

European Technology Platform for Zero Emission Fossil Fuel Power Plants (ETP-ZEP). July 2008. “CO_2 capture and storage matrix of technologies (V5)”

Glossary

Abatement. The process of putting an end to, or reducing, an amount (for instance, of Greenhouse Gasses).

Capex. Capital expenditures, expenditures incurred when a business spends money either to buy fixed assets or to add to the value of an existing fixed asset.

CCS. CO_2 capture and storage, the processes by which carbon dioxide is captured from the combustion of fossil fuels, prepared for transportation, moved and delivered to a storage site, and permanently stored to prevent its release into the atmosphere.

CO_2. Carbon dioxide, a Greenhouse Gas.

CO_2e. Carbon dioxide equivalent, a standardized measure of greenhouse gas emissions developed to account accurately for the different global warming potentials of the various gases.

DOGF. Depleted oil and gas fields.

EOR/EGR. Enhanced oil/gas recovery, the process of improving productivity of oil/gas wells by injecting CO_2 into them.

EUA. European allowance. Allowance to emit carbon under the European emissions trading scheme

GHG. Greenhouse gases, the major ones being: carbon dioxide, methane, nitrous oxide, chlorofluorcarbons, hydrofluorcarbons, perfluorcarbons, sulphur hexafluoride.

Gt. Gigatonne = 1 billion metric tonnes.

IEA. The International Energy Agency, a Paris-based intergovernmental organization founded by the Organisation for Economic Co-operation and Development (OECD) in 1974.

IPCC. The Intergovernmental Panel on Climate Change, a scientific body tasked to evaluate the risk of climate change caused by human activity. The panel was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), two organizations of the United Nations.

LNG. Liquefied Natural Gas, natural gas that has been converted to liquid form for ease of storage or transport.

Mt. Megatonne = 1 million metric tonnes.

NOx. Nitrogen oxide.

Opex. Operational expenditure, expenditures incurred for the on-going running of a product, business, or system.

Retrofit. An upgrade or modification of existing equipment.

Saline aquifer. Geological underground formation containing highly mineralized brines (salty water). This water is currently considered unsuitable for irrigation or drinking.

SO_2. Sulphur dioxide

Stern. The Stern Review on the Economics of Climate Change is a 700-page report released on October 30, 2006 by economist Lord Stern of Brentford for the British government, which discusses the effect of climate change and global warming on the world economy.

WACC. Weighted Averaged Cost of Capital, the rate that a company is expected to pay to finance its assets (post tax). WACC is the minimum return that a company must earn to satisfy its creditors, owners, and other providers of capital.

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