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Carbon Capture and Storage: Selected Economic and Institutional Aspects

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Summary

Carbon Capture and Storage (CCS) is the process whereby the combustion of fossil fuels is modified so as to capture the bulk of the CO2 that would otherwise be emitted, compress it, transport it, and then store it permanently in geological formations underground (or under the seabed). CCS has been identified by policy-makers at the European and global levels as an important option to help achieve a low-carbon future without creating substantial economic or environmental dislocations.

CCS is foreseen as an option for reducing emissions in coal-fired power generation, gas-fired power generation and biomass-fired power generation; in energy-intensive industries such as cement production, iron and steel, pulp, and chemicals and petrochemicals; and in fossil fuel production and transformation.

The most viable option for CCS deployment in the medium-run is in coal-fired power generation. The vast majority of current pilot projects are in that category. While hard coal may be the more frequent choice, lignite-fired CCS plants may play an important role as well, e.g. in Germany where lignite deposits are large.

The three main technological options for the capture stage are post-combustion capture, pre-combustion capture, and oxy-firing (oxy-fuel). In the medium-run it is not clear which of these three main options will prevail, so that research and development and pilot work is ongoing with all three options.

CCS is a developing technology and would not be commercially viable initially. It is generally predicted that CCS technologies would evolve progressively, gaining from the experience of practical full-scale applications called demonstration projects, so as to be fully commercially viable under reasonable assumptions about CO2 prices from 2020. In terms of the costs of the capture, transport and storage components of CCS, this report reviews the estimates presented in the 2008 McKinsey report and compares them to recent estimates from other sources. The mid-term cost estimates from the McKinsey report are found to be credible, if not prudent.

In order to ensure that the CCS demonstration projects occur, the European Union has decided to commit 300 million allowances from the new entrants reserve for supporting up to 12 demonstration projects, as well as innovative renewables projects.

The longer-run commercial viability of CCS crucially depends on the price of CO2 allowances. The EU's New Energy Policy, i.e. the 20-20-20 targets, and foreseeable future commitments, should lead to scarcity in allowances so that a robust price signal should emerge. This emerging set-up of economic incentives will probably be conducive to a *successful commercial deployment of coal-fired power plants equipped with CCS, starting some time around or a bit after 2020.*

However there is a risk that commercial deployment will be delayed if allowance prices remain comparatively low for a longer period, and/or if unexpectedly higher costs emerge during the demonstration phase. CCS projects will also effectively compete with other low- or zero-carbon solutions, including renewables and nuclear power.

In parallel, and assuming that commercial deployment is successful, investments will have to be made with respect to CO2 pipeline infrastructure. The economic geography of coal-fired (and gas-fired) generation should change as a result of CCS, as distance to CO2 storage sites will become a location factor. Government intervention may then be desirable, at least in terms of investment coordination, in order to support the creation of shared trunk lines.

CCS deployment would be particularly useful in the case of China, given her large and growing coal-fired capacity, and should therefore be encouraged. So far, however, there has been considerable resistance on the part of some developing countries to the inclusion of CCS in the UN's Clean Development Mechanism (CDM).

CCS is a potentially important plank of national energy policy for the countries of North-West Europe. To a lesser extent, Italy, the Czech Republic, Poland and Spain may also develop an increasing interest in the technology. For certain other member states, especially those that have both very low coal reserves and a lack of suitable storage sites, CCS cannot come across as particularly important, while renewables and/or nuclear power should. This should however not lead to insurmountable policy differences between member states.

CCS is gathering momentum and benefits from wide (and deserved) support. While many uncertainties remain, CCS is too promising an option not to be attempted on a commercial scale in the near future. Legal and institutional frameworks that are still lacking should therefore be dealt with so as to enable market forces to move forward.

Keywords: *carbon capture and storage, CCS, energy policy, environmental policy, CO2 pipelines*

JEL classification: *L52, Q42, Q48, Q58*

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I Introduction

According to the most recent assessments of global energy and environment trends, notably the IEA's flagship World Energy Outlook 2008, the world's energy system is at a crucial crossroads. Current trends in both energy consumption and greenhouse gas (GHG) emissions are unsustainable, economically, environmentally and socially. In particular, the world's energy system requires substantial *decarbonization* in order to prevent the onset of dangerous climate change. However the European Union and its member states are well positioned to take a leading role in developing and promoting the development of a new, more efficient and less emissions-intensive energy system.

The decarbonization of Europe's energy system, i.e. the substantial reduction of yearly GHG emissions, is an enormous challenge. Fossil fuels, though supply-constrained, remain cost-competitive, flexible, and technologically feasible. Nuclear power is a key option to plug in some of the gaps and will be part of the solution for many member states. But according to IEA (2008a) the bulk of emissions reductions will have to come from the following three key changes, listed in decreasing order of magnitude:

(i) energy efficiency improvements,

(ii) greater use of renewables, and

(iii) carbon capture and storage (CCS).

CCS is the process whereby the combustion of fossil fuels is modified so as to capture the bulk of the CO2 that would otherwise be emitted, compress it, transport it, and then store it permanently. CCS is foreseen as an option for reducing emissions in coal-fired power generation, gas-fired power generation and biomass-fired power generation; in energy-intensive industries such as cement production, iron and steel, pulp, and chemicals and petrochemicals; and in fossil fuel production and transformation. In the present report only power generation is discussed.

CCS is often described as a 'bridging technology' which could give the global energy system an important breathing space roughly over the period 2020-2050. That period is necessary to ensure that the ultimately unavoidable transition to a completely different energy system (i.e. one based primarily on renewable energy sources) can be achieved without serious global dislocations, whether environmental or economic. There are two

[*] The author wishes to thank Ms. Irina Gaubinger, temporary research assistant at wiiw, for extensive support particularly with respect to interviews of Austrian and international experts and stakeholders.

other significant arguments in favour of CCS, both expressed notably by Energy Commissioner Piebalgs[1]. The first has to do with European energy security, the second has to do with global linkages in climate change policy.

The energy security argument is that the geographical distribution of global coal reserves is somewhat more favourable – from an EU perspective – than those of natural gas. The EU has relatively small reserves of coal on its own territory and import dependence is already significant[2]. However according to BP (2008) the EU has another 50 years' worth of own reserves given current production levels, whereas the corresponding time-to-depletion for natural gas is just 15 years. A partial shift in favour of coal would therefore enable the EU to be less strongly dependent on fossil fuel imports. The problem with that shift in the energy mix is that coal is more CO2-intensive than natural gas per unit of generated power, making GHG emissions targets more difficult to attain. That problem is solved thanks to CCS. Again, CCS serves as a (partial) bridging solution, roughly over the same period as at the global level.

The climate policy linkages argument is an extension of the general energy and climate policy argument. As evidenced by all available long-term scenarios of global energy demand, both China and India are expected to massively increase their energy consumption levels and, as part of this, their power generation levels. Both countries already use coal to a large extent and are expected to continue to rely heavily on coal. China's GHG emissions have already overtaken those of the USA, and will continue to grow massively up to 2050, as will those of India. Whatever success the EU has in reducing emissions, those gains will be dwarfed by the increase in emissions from China and India, making dangerous climate change inevitable. However if CCS were available, both countries could be convinced to opt for coal with CCS. Prima facie one would expect that neither China nor India would have much of an incentive, let alone political will, to develop CCS as a first-mover. The EU on the other hand can and should create a first-mover advantage for itself by developing CCS and encouraging its implementation in China, India and other developing countries.

The report is structured as follows. Section II contains an overview of the main technological components of CCS. Section III addresses the main economic features of CCS and the connecting arguments in favour of public policy intervention. Section IV reviews the most important financing mechanisms relevant for CCS from a European perspective. Section V takes a step back and assesses the global picture in terms of coal reserves, global emissions and power generation investments, and gives an overview of

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1 Remarks given at the European Forum Alpbach conference "Europe – A global player in energy?", Vienna, 24 November 2008.

2 According to Eurostat energy data, net imports accounted for approximately 41% of gross inland consumption (all solid fossil fuels together) for the EU-27.

the main CCS projects and the main corporate actors at the global level. Section VI summarizes the positions and policy stances of major groups of stakeholders. Section VII concludes.

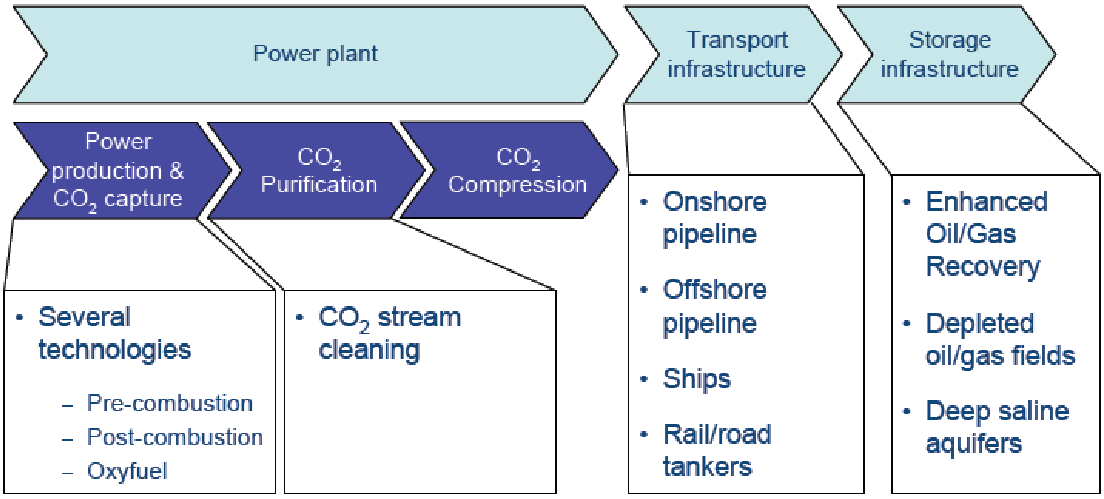
II Overview of CCS technologies

II.1 CCS Value Chain

The value chain of CCS in power generation is illustrated in Figure II.1. A power plant using fossil fuels, typically coal or gas, is fitted or retro-fitted with capture technology. Power is generated, and CO2 is captured. It is then purified ("cleaned") and compressed on-site to make it ready for transportation. Transportation may be achieved by pipeline (onshore and/or offshore), by ship, by road or by rail. On destination it may be stored in depleted oil or gas fields, or in deep saline aquifers. Alternatively it can be used for Enhanced Oil Recovery or Enhanced Gas Recovery.

Figure II.1

CCS Value Chain



Source: ZEP (2008a).

In this report the expression *pilot project* is used to describe currently functioning *elements* of the CCS chain (e.g. capture units, storage sites). The expression *pilot plant* is used to describe an *integrated* plant that is typically smaller than the expected commercial plant, but which integrates CO2 capture with transport and storage. The role of the pilot plant is to demonstrate the technical validity of the integrated process and use the observed results to better design a larger version. The next stage is to build a demonstration plant. A *demonstration plant* is a full-scale integrated plant. Its purpose is to verify and optimize the various technical settings, and to demonstrate the commercial viability of its operation. The final stage is the deployment of commercial plants which are competitive without external financial support, provided certain assumptions are met (e.g. on carbon prices).

In general, one may state that the components and sub-components of the CCS value chain have all been tested in some form. Some of the sub-components are very well understood and can be considered to be mature, e.g. because they are already in commercial use but for purposes other than CCS. Other components and sub-components work well but (so far) only at the level of small-scale pilot projects or pilot plants. Ongoing research and development work, and further testing and piloting, should lead to improved performance and efficiency. There is general agreement, most of all, that what is missing is more certainty about how well a full-scale integrated CCS project (from power plant to storage) would perform, technically and economically. In other terms, questions remain essentially with respect to scale and process integration. As a result, it is recognized by all stake-holders that the key in the near future is to reach the demonstration project stage. The current consensus at the level of EU governments and institutions is that the progression towards the demonstration project stage needs to be both enabled (e.g. appropriate legislative frameworks) and encouraged (e.g. financial assistance). Those elements are discussed in Chapter III. In the remaining sections of the current chapter the main components of the CCS value chain are presented and briefly discussed.

II.2 Carbon capture technologies

The three broad technological options for carbon capture in power generation are post-combustion, pre-combustion, and oxy-firing (also called oxy-fuel or oxy-fuelling). All three options are in principle possible with coal, natural gas, biomass or other fossil fuels.

Post-combustion capture occurs after the fossil fuel has been combusted. In most cases it consists in chemically absorbing the CO2 contained in the flue gas (exhaust gas from combustion), a process usually referred to as *CO2 scrubbing*.

Oxy-firing is similar to post-combustion capture, except that the combustion occurs with pure oxygen (previously separated from air), rather than with air, and results in exhaust gas that has very high CO2 concentration, often referred to as a CO2 stream.

Pre-combustion follows a completely different principle. Here, fossil fuels are broken down into *syngas*, i.e. carbon monoxide (CO) and hydrogen gas. Further processing with steam yields CO2 and hydrogen gas. Hydrogen is then used for power generation separately.

The basic chemical principles underlying each three option separately for both coal and natural gas are shown in Figure II.2.

Figure II.2

Chemical principles of carbon capture

		Combustion reaction	Principle
Post-combustion	Coal	C + Air => CO_2	Exhaust gas CO_2 cleaning
	Gas	CH4 + Air => CO_2 + H2O	
Pre-combustion	Coal	C + O2 => CO CO + H2O => CO_2 + H2	C-free syngas burning
	Gas	CH4 + H2O => CO_2 + H2	
Oxy-firing	Coal	C + O2 => CO_2	High concentration CO_2 stream production
	Gas	CH4 + O2 => CO_2 + H2O	

Source: ZEP (2008a).

The types of power plants for which each capture technology is most relevant are shown in Figure II.3.

Figure II.3

CO2 capture technologies and power plant definitions

CO_2 capture technologies		CO_2 capture principle	Combustion principle	Power plant definition
Oxyfiring	Coal	High concentration CO_2 stream production	O2 combustion of coal/gas	Oxy-firing plant (Boiler-based)
Post-combustion	Coal	Exhaust gas CO_2 scrubbing	Air combustion of coal/gas	Pulverised Coal (PC) or Circulating Fluidised Bed (CFB)
	Gas			Natural Gas Combined Cycle (NGCC)
Pre-combustion	Coal	Inlet gas CO_2 cleaning	Air combustion of H2	Integrated Gasification Combined Cycle (IGCC)
	Gas			Integrated Reforming Combined Cycle (IRCC)

Source: ZEP (2008a).

Statements about the general suitability of any one of the three broad capture options over the other two cannot be made (at least at present), as each one has advantages and disadvantages depending on the type of plant they should be integrated into as well as other factors. At present, research and development efforts, as well as design work for both pilot and demonstration plants, is ongoing with all three options.

In the case of *post-combustion*, a number of CO2 capture technologies are already in commercial use. Most existing capture systems are based on chemical absorption using amine solvents, in combination with heat-induced CO2 recovery so as to re-use the solvent for further capture. It is worth mentioning, as in IEA (2008b), that post-combustion capture was in commercial use in the United States in the 1980s and was commercially viable. The CO2 was then used for enhanced oil recovery. However when the price of oil collapsed in the 1990s the installations were closed. From a technical viewpoint there is therefore no problem with post-combustion capture *per se*, and IEA (2008b), as well as two scientists we interviewed directly, describe it as the *potentially* best option for conventional coal- and gas-fired power plants of current vintage. However, research and testing on more efficient scrubbing (or other) methods is ongoing. IEA (2008b) is somewhat optimistic about potential efficiency gains, while ZEP (2008a) characterizes both the capture stage and the overall process integration as not immediately ready for a *demonstration* plant. However, ZEP (2008a) predicts that by 2012 these obstacles will have been mostly overcome (see ZEP (2008a), page 53). Finally, one should note that post-combustion, along with oxy-firing, is a likely candidate for retrofitting of existing plants, though this would only be viable on relatively recent plants with comparatively high thermal efficiency.

Pre-combustion capture is seen primarily as the best option in combination with Integrated Gasification Combined Cycle (IGCC) plants. IGCC plants transform coal into syngas, which is then combusted. The advantage of IGCC plants is that they allow for lower sulphur and nitrogen oxide emissions as compared to conventional coal-fired power plants. IGCC with CCS therefore seems an attractive proposition. According to IEA (2008b) all the necessary components for pre-combustion have already been tested at the pilot level. ZEP (2008a) also reports that all key components are ready for a large-scale demonstration project. Both sources however indicate that questions remain about overall process integration. In general, however, pre-combustion is reported to be at a somewhat more mature stage than either post-combustion or oxy-firing.

Oxy-firing is at a comparatively less mature stage than pre-combustion, although substantial progress is expected by 2012, see ZEP (2008a) page 49. Also, IEA (2008b) suggests that oxy-firing could, among other uses, be an interesting retrofit option for certain coal-fired plants, i.e. recently built ones with comparatively high thermal efficiency. Moreover, one advantage of oxy-firing over post-combustion is that it can also substantially reduce sulphur and nitrogen oxide emissions, i.e. as compared to a conventional coal-fired plant fitted with post-combustion capture.

II.3 CO2 transport

Transport of CO2 is possible by onshore or offshore pipeline, by ship, or by road- or rail-bound tankers. Similarly to the transportation of other gaseous substances, CO2 transport would be most cost effective using pipelines in most cases. At present there is no dedicated CO2 pipeline system in Europe, however long-standing practical experience exists in North America, where a network of CO2 pipelines was constructed starting in the 1970s in order to supply CO2 for enhanced oil recovery. One issue is corrosion of the pipeline material due to impurity of the gas stream, though this is an issue which seems to have been clearly identified and understood. In a more general sense, pipeline technologies for gaseous substances are very well understood in Europe (e.g. natural gas pipelines). Technical feasibility is therefore not a problem[3].

II.4 CO2 storage and the issue of seepage

The question of storage is somewhat more controversial than either capture or transport of CO2. The first concern, quite naturally, is that stored CO2 could seep out into the atmosphere, thus partly negating the environmental gains of the entire process. Moreover, as storage is supposed to be long-lasting, the type of time-frame one should consider with respect to risks (and rates) of seepage goes beyond the type of time-frame that private companies (and even states) are usually able or willing to take into consideration.

The risk of seepage (sometimes also called *CO2 leakage*, not to be confused with *carbon leakage*) is in fact generally considered to be very low, much too low to put into question the benefits of CCS. Before CO2 is stored underground, it is first compressed and liquefied. It is then injected into porous rock formations deep underground. The CO2 fills the pores in the rock formation. It would then tend to rise. However, a well-chosen storage site would be a layer of porous rock which is capped by non-porous rock which will not let any CO2 through it. Such formations exist in nature, and the best example is a natural gas field. A natural gas field has exactly the kind of structure described – a porous rock capped by non-porous rock – which is why the natural gas accumulated there and stayed there. This is why expected seepage rates from well-chosen sites are estimated to be very low. This is also why the argument that there is a lack of experience with underground gas storage is true but partly misleading. Underground gas fields are examples of natural underground gas storage with very low rates of seepage, and their properties can be analysed by geologists. In other terms, there is rather more knowledge about how compressed gases behave in rock formations than the general critique suggests. As concerns derived estimates of what seepage rates one may experience with CO2 storage, the reference publication is IPCC (2005) which estimates that, for well-chosen geological formations, there is a probability of only 1% that seepage would exceed a rate of 1% *over a period of*

[3] One scientist interviewed during the preparation of this report expressed surprise that the issue was raised at all.

100 years. Naturally, the authors specify (page 246) that the sites should be "well selected, designed, operated and appropriately monitored".

The most pessimistic average seepage rate that can currently be found in any kind of literature is *1% per year* which is assumed (though without any connection to scientific literature) in a kind of worst-case scenario in Greenpeace (2008). Naturally such a high average rate would make CCS quite unattractive. However that scenario is not realistic. As experience with storage and monitoring of storage grows in the future, if seepage rates over the world's storage sites averaged 1% per year, storage would be limited to the few sites that have the lowest seepage rates, and CCS in general would be partly abandoned as a solution. Greenpeace (2008) implicitly assumes that one would inject 100 years' worth of CO2 into the ground (presumably that would take at least 100 years to happen), and then seepage would start, at a rate of 1% per year, so that by that time (in around 2120) one would have the same yearly emissions' level as today coming only from seepage. That is not a particularly realistic scenario.

The risk of seepage naturally attracts scrutiny, leading to efforts to improve knowledge and modelling of long-term storage site integrity. It is difficult, however, to make more informed statements than what is already discussed above. The older IPCC (2005) estimates, themselves based on extensive research, have not been strongly overturned by more recent research efforts. However as practical experience with CO2 injection increases the available data for further empirical research and improved modelling techniques should improve considerably. More comprehensive assessments of actual seepage risks (e.g. by site, by type of site, by type of injection method) could however be encouraged.

Another issue which should be briefly mentioned concerns the risk of a more comprehensive site failure, resulting in a sudden and substantial release of CO2. The latter constitutes a local health hazard, as even a relatively low local concentration of CO2 can lead to loss of consciousness and, ultimately, to death from asphyxia. Unsurprisingly, research and analysis is also available on that topic, see e.g. Aines et al. (2009). The latter identify well failure as the most dangerous possibility if it occurs. While the likelihood of a well failure is not high, if it does occur the upward release of CO2 would be substantial and concentrated. The immediate area around the well-head would then become hazardous. Aines et al. (2009) find, using very prudent assumptions, that life hazard drops rapidly as one moves away from the well-head. Worst-case scenarios, assuming no wind turbulence which would spread the CO2 around across a very large volume of air, foresee that danger would exist up to several hundred meters from the well-head, thus warranting a number of safety procedures if the well-head is in the immediate vicinity of a residential area. At somewhat greater distances, however, the authors conclude that the risks are negligible.

III Economic aspects of CCS

III.1 Efficiency penalties and costs of capture

The economics of CCS would be easy if CCS were costless, but it is not. Not only does fitting or retro-fitting CCS incur additional capital expenditures, it also substantially raises operating costs by reducing the thermal efficiency of a plant by several percentage points. Table III.1 shows some estimates from the literature for both gas-fired and coal-fired plants, for each of the three main capture options. The resulting cost per tonne of CO2 that is avoided is indicated as well.

Table III.1

Thermal efficiency and cost of CO2 avoided with and without CCS

Technology	***Thermal efficiency (% LHV)***	***Cost of CO2 avoided ($ / t CO2)***
Gas-fired		
No capture	55.6	-
Post-combustion	47.4	58
Pre-combustion	41.5	112
Oxy-firing	44.7	102
Coal-fired		
No capture	44.0	-
Post-combustion	34.8	34
Pre-combustion	31.5	23
Oxy-firing	35.4	36

Source: Gibbins and Chalmers (2008), IEA GGP (2006).

The estimates presented in Table III.1 were first published in 2006 and therefore refer to estimates made sometime in 2005 or 2006, with cost estimates in 2005 prices and exchange rates. The costs shown account only for capture, not for transport and storage. However, the results suggest that the efficiency penalty (efficiency loss) due to CCS can be quite considerable, at least 8 percentage points for a gas-fired plant, and at least 8.5 percentage points for a coal-fired plant. Correspondingly, a plant with CCS consumes a larger amount of fuel per kWh than a plant without CCS. Ultimately these costs are reflected in the cost of CO2 avoided and, naturally, the average market price of carbon allowances must be higher than the cost of CO2 avoided for the plant to be commercially viable. As can be seen, for prices of carbon below 50 dollars (at 2005 prices) CCS can only be applied to coal. Indeed, current expectations and interest in CCS on the part of industry in Europe and elsewhere is focused almost exclusively on coal (see Section V.3). Most existing pilot projects are likewise based on coal, and it is highly likely that the first commercial projects will also be coal-fired. In terms of energy markets three effects may be briefly pointed out. Electricity prices will typically be higher than without CCS (though slightly lower or similar to those from wind-power), demand for coal should rise quite substantially, and demand for natural gas (if CCS is broadly deployed) may fall.

One key question is how the cost of CO2 avoided might evolve, and indeed, what it will actually be in the case of a full-scale integrated plant. The most influential recent publication which sheds light on this issue is McKinsey (2008), a widely quoted assessment of the main economic aspects of CCS. As presented in McKinsey (2008: 17), the total cost of CO2 avoided could be between 60 and 90 euros in 2015, between 35 and 50 euros in 2020, and between 30 and 45 euros in 2030. Contrary to the estimates shown in Table III.1, the McKinsey estimates include transport and storage costs.

How do the McKinsey (2008) estimates compare with recent scientific literature? And how relevant are the estimates in practice? Bukhteeva et al. (2009) arrive at a total cost of CO2 avoided, all costs included, of AUD 75.1 per tonne (at 2008 prices), i.e. EUR 43.1 at 2008 prices, with a specific scenario of post-combustion capture (using the KS1 solvent) in Australia. Their estimate for the capture stage alone is EUR 32.8 (cost of separation plus cost of additional fuel due to the efficiency penalty). The corresponding range in McKinsey (2008) is EUR 25 – 32 for a more efficient (ultra-supercritical) plant. The estimates are therefore quite similar.

As will be presented in detail in Section V.1, the European Union is relatively abundant in lignite (brown coal) but poorly endowed in hard coal. In the case of Germany in particular, roughly 27%-30% of electricity generation comes from brown coal. It is also not a coincidence that one of the leading CCS pilot plants, the Schwarze Pumpe project operated by Vattenfall, is lignite-fired. It is therefore useful to consider the cost of capture per tonne of CO2 in the case of lignite. Ideally, one should have access to estimates of these costs for each main vintage of power plant, for both lignite-fired and hard-coal fired plants. Such a comprehensive review is difficult to find. However a few general considerations can be made which can guide the analysis. Older vintages, essentially subcritical plants, have lower efficiencies to begin with, and this typically leads to higher costs of capture than with more recent build. Future build on the other hand, where CCS is integrated in the design phase to begin with, should present the lowest cost of capture. It follows that estimates for existing subcritical plants, i.e. as part of retro-fitting scenarios, particularly for comparatively less efficient installations, are the most useful benchmark as they should constitute the upper-bound of what may be achievable overall.

A good partial answer to these questions can be found in Ho et al. (2009) which provides estimates of the cost of CO2 capture for existing lignite-fired power plants in Australia. The authors start by noting that a large stock of Australia’s power generation comes from lignite-fired subcritical plants that have rather low thermal efficiency. The authors construct cost estimates for retro-fitted post-combustion capture based on chemical scrubbing. They provide estimates for three different types of solvents: MEA, KS1 and a potassium carbonate solution. They find that the latter would offer the best performance. Provided retro-fitting includes waste heat integration as well, they arrive at an estimate of USD 30 per tonne of CO2 avoided at 2008 prices, as compared to USD 73 per tonne using MEA without waste heat integration, USD 55 with MEA and with waste heat integration, and USD 46 with KS1 and with heat integration. Coming back to McKinsey (2008: 17), the capture stage of the process is assumed to be in a range of EUR 25 – 32 in the early period of commercial deployment (2020-2030). However those estimates refer to future build: an ultra-supercritical plant operating at 700 C (which would include a drying bloc if lignite is used). Assuming the estimates of Ho et al. (2009) are accurate and that the solvent they describe can be produced and used for the costs they assume to be possible, then the conclusion is that the estimates of McKinsey (2008) are entirely reasonable. If a cost of USD 30 per tonne of CO2 avoided is possible for an existing subcritical plant, it would stand to reason that future build should be more favourable still – otherwise the optimal solution for investors would be to stick to subcritical plants, which are less efficient by definition.

III.2 Economic aspects of CO2 transport

The first economic question with respect to transport of CO2 concerns the magnitude of its costs, e.g. on a simple point-to-point basis from capture plant to CO2 storage site. A pipeline will be a cost-effective solution provided the present value of the flow of gas more than offsets the present value of the costs related to the initial capital expenditure and of the costs related to pipeline operation and maintenance. If the value of the flow of gas is relatively high, the latter depending on the flow volume, the duration of the flow (assuming the flow is continuous), and its unit value, then it is typically the case that a pipeline is substantially more cost-effective than other forms of transportation, e.g. by road or rail, as is for instance the case with natural gas transportation.

This general framework holds true for transportation of CO2 as well. An integrated CCS facility, assuming a given price of CO2, reduces its operating costs by reducing the number of CO2 allowances it must purchase. This is equivalent to being a producer of CO2 who makes a profit by selling CO2. If the price of CO2 is sufficiently high, pipeline transportation will be the profit-maximizing solution. Coming back to the case of CCS, pipeline transportation will be the lowest-cost transportation option, as well as being affordable, provided the price of CO2 is above a certain threshold. McKinsey (2008: 17) suggests a range of EUR 4 – 6 per tonne of CO2 as an estimate of the cost of transporting CO2 by pipeline. The underlying assumptions is that the distance would be moderate (200 – 300 km), using a pipeline with no intermediate booster stations. A more recent and more detailed exercise is Bukhteeva et al. (2009) which simulates CO2 transportation costs in a region of Australia. Contrary to the assumptions in McKinsey (2008), Bukhteeva et al. (2009) analyse the case of a simple but relatively long pipeline network, of a total length of

895 km and incorporating 8 booster stations. The results from their central estimate is that the costs of transportation would amount to 1.5 + 3.3 + 7.6 = 12.4 Australian dollars (at 2008 prices) for the sum of transport-relevant costs, respectively transmission, compression and pipeline. Converting this into euros, using the average AUD / EUR rate for 2008, yields 12.4 / 1.7416 = 7.1 euros at 2008 prices and exchange rates. This is slightly higher than the McKinsey estimates, though this should not come as a surprise given that the pipeline network in question is considerably longer than what is assumed by McKinsey. The results are however informative and give a better feeling for the levels of costs one should expect. Given the generally much shorter distances in the European Union, 7.1 euros per tonne of CO2 transported can be seen as a pessimistic (or very cautious) upper-bound. As with capture, the estimates presented in McKinsey (2008) for the early commercial phase seem reasonable and in line with recent academic research.

The broader strategic question with respect to CO2 transport infrastructure development is the issue of the economic geography of existing and future thermal power plants with respect to potential storage sites. Without CCS the decision as to where to locate a coal-fired plant depends primarily on the proximity to a source of coal (reduces the cost of the coal delivered), on the proximity to a source of water (needed for cooling purposes) and on connections with the electric grid. Additionally, proximity to other facilities or dwellings opens up the possibility of supplying process steam and/or long-distance or district heating. That balance of costs is modified by the introduction of the additional cost factor of transporting CO2 to a storage site. The costs of transport may therefore be a problem for existing plants that should be retro-fitted and that are not close to any suitable storage facility. For new build what will happen is that plant location will be the result of the five transport cost factors mentioned above, rather than just four of them as previously. Government policy-makers should expect a new type of geographic distribution if CCS is widely deployed, and plan accordingly.

Some decision support tools for plant location and the layout of transport infrastructure already exist. One notable example is the *SimCCS* model which is illustrated in Bielicki (2009) with examples of cost-minimizing locational choices for plants and reservoirs in the case of California. Further development of such tools should prove useful for the private sector as well as for public authorities in the European Union as well.

With respect to the financing of the transport infrastructure, in particular the need for CO2 pipelines, there is a need for high (and risky) up-front capital expenditures. The latter could in some circumstances lead to a market failure (i.e. coordination failure between private companies as to how to share capital costs and risks). This may justify some government intervention. Under the reasonable assumption that CCS deployment would start slowly and then potentially accelerate, private companies that are first-movers might be tempted to opt for point-to-point CO2 pipelines, i.e. connecting the capture-equipped power plant directly to the storage site. However a more cost-effective option from the point of view of overall (e.g. national) economic return may be to build a network of pipelines including a trunk (backbone) line, with connectors between the various CCS power plants (current and future) and the backbone line. In order for this outcome to occur it is likely that government intervention would be helpful, at the minimum in order to help coordinate private investment, and at the maximum by full government financing for the infrastructure. One recent paper which compares financing scenarios with a numerical simulation of pipeline infrastructure investment is Chrysostomidis et al. (2009). Their results are based on the simulation of financing options for one specific scenario, namely the phasing-in of operation of 10 new IGCC plants with CCS over a 7 year period and their connection with an identified and suitable storage site. Their specific scenario leads to the conclusion that full state investment and ownership of a backbone pipeline would be the first-best solution. A public-private partnership (PPP) with state guarantees for the issuing of project-related bonds by the private partners is found to be the second-best solution. Various forms of purely private investment are found to be less efficient. Naturally those results should be taken for what they are: a simulation of only one scenario which may or may not be realistic for any given country or group of countries. In general terms, however, the broader point which should be taken is that a PPP or even full state funding can be preferable to entirely private funding in certain cases. The main policy instruments short of full state ownership which may be relevant, i.e. public-private partnerships and risk-sharing facilities (e.g. risk-sharing loans), are briefly discussed from the institutional perspective in Sections IV.4 and IV.5.

III.3 Economic aspects of CO2 storage

Chronologically speaking, the costs of a storage site can be split into three main parts. The initial phase, which is devoted to site exploration, assessment and preparation, and which requires capital expenditure and other sunk costs. The operational phase, which may last a few decades, during which CO2 is injected into the site, and which requires continuous monitoring and operation costs. And finally the closure phase, which McKinsey (2008) suggests could last as long as the operational phase (e.g. 40 years), during which the site is continuously monitored so as to ascertain the permanency and the integrity of the site. The bulk of the cost is due to capital expenditure, e.g. wells, pumps, platforms.

Altogether, McKinsey (2008: 17) provides a range of EUR 4 – 12 per tonne of CO2 stored. That range is relatively wide, and is partly due to differences between costs for onshore sites as compared to offshore sites. Bukhteeva et al. (2009), on the other hand, assume much lower costs of AUD 5.5 in total (EUR 3.2), including, apparently, some form of insurance costs. More detailed research, incorporating model simulation over a large selection of known storage sites, is presented in McCoy and Rubin (2009). The authors focus on the case of saline aquifers and construct simulations of costs based on the geological parameters drawn from four case studies of known sites. After conducting a sensitivity analysis they find a relatively large range of costs in terms of the minimum and maximum values: USD 0.38 per tonne and USD 8.86 per tonne. However they also find a 90% confidence interval of [0.53; 2.15] US dollars per tonne, i.e. the probability that the cost would exceed USD 2.15 is 5%. A more general assessment of possible costs of storage can be found in Wildenborg et al. (2009) who developed, as part of the EU-funded CASTOR project, a detailed long-term scenario (up to 2050) for large-scale deployment of complete CCS chains across the European Union. The authors estimated storage injection costs to be in a range of EUR 1 – 5 per tonne.

As many authors have pointed out, the modelling of storage costs has received somewhat less attention as compared to the costs of capture or transport. While this is bound to change relatively quickly, the temporary conclusion is that many estimates are at the low end of the range suggested by McKinsey (2008). The latter may therefore be interpreted as a prudent estimate for the time being.

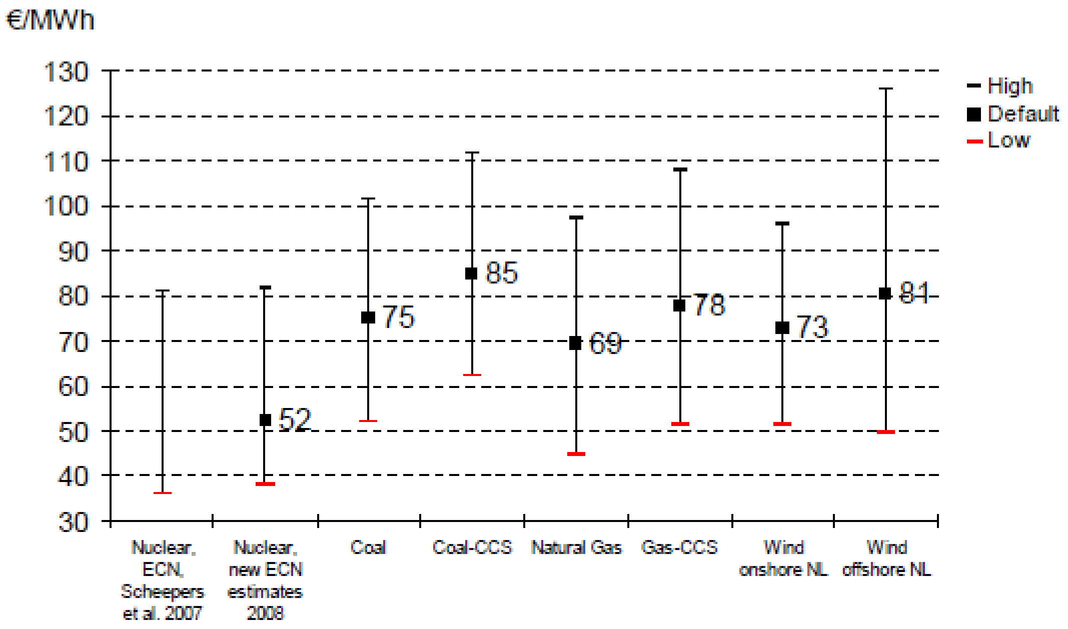
III.4 CCS versus renewable energy in power generation

The classical approach towards assessing the relative merits of renewable energy sources for power generation, as compared to each other and as compared to conventional, nuclear and CCS, is to look at total costs per kWh under various scenarios about global energy prices, local (EU) prices for CO2, and assumptions about future capital expenditure and operation and maintenance costs. Unfortunately, estimated cost ranges for key types of renewable energy as well as for the main CCS options are wide and overlap to a large extent as soon as one considers long-range projections from the literature. Figure III.1 will suffice to illustrate the problem, although a number of other insights can be drawn from it as well. Leaving hydro-electricity aside (which is generally cheaper than most forms of energy if topography is favourable), the most promising form of renewable energy is onshore wind power, closely followed by offshore wind power. Solar power is forecast to remain substantially more expensive than other solutions for some time. Nuclear power, on the other hand, is generally found to be very promising in medium-term assessments. In the case of the UK, for example, estimates presented in UK House of Lords (2008: 28) suggest that nuclear power (assuming a CO2 price of GBP 20 per tonne) would be the best option under existing technologies, slightly ahead of both conventional gas and conventional coal, and also substantially ahead of both onshore and offshore wind.

Beyond plant-specific cost estimates, three additional issues need to be taken into consideration: the cost of modifying the electricity grid in order to accommodate new sources of power in new locations (e.g. offshore wind installations); the cost due to the inherent intermittency of some forms of renewable energy, particularly wind and solar; and the effective cost premium related to uncertainties with respect to fossil fuel supplies and prices. The latter two each deserve a short comment.

Figure III.1

High- and low-bound estimates for cost of electricity generation in 2020 by type



Source: Seebregts and Groenenberg (2009).

Intermittency is the extent to which power supply from a specific installation is unstable through time. Both wind and solar energy are examples of sources with high intermittency, yielding variable and unpredictable power output as wind currents and sun-light fluctuate. As a result, wind and solar are referred to as intermittent power sources, whereas coal (with or without CCS), nuclear, hydro-electric and geothermal facilities are referred to as base-load power sources[4]. The intermittency of wind and solar generates costs due to the uncertain profile of the power they generate. Two main corrective measures are used to counter this problem. First, build excess capacity to begin with, and second, ensure that there is sufficient back-up in terms of base-load capacity from conventional and nuclear power generation. As these measures imply, a country's power generation cannot rely wholly on wind and solar. This by itself means that a combination of hydro-electric, nuclear and fossil-fuel-fired generation is desirable, up to a point. It also means that additional costs must be borne, beyond installation-specific costs per kWh, if a national electricity grid is to be able to cope with a higher share of intermittent sources of power.

4 Gas-fired power generation can be used for base-load generation, but is more responsive and is hence used partly for peak generation as well.

The other element which is often missing from cost comparisons is the effective cost premium that results from uncertainties (economic, commercial and political) with respect to fossil fuel supplies and prices. While security of supply (or energy security) arguments are often used, assigning a cost premium due to uncertain future prices of fossil fuels and to risks to the physical supply of fuels is a complex issue and will not be further discussed in this report. It is however worth mentioning the issue here alongside the other core ingredients which should be looked at in the context of a review or assessment of any country's national energy policy.

In the broader analysis what justifies public intervention from the economic point of view is that there are market failures, typically due to externalities. Climate change as caused by anthropogenic GHG emissions is one such externality. Reducing emissions is therefore a public good, and governments should take the lead. The ideal policy instrument, if available, would be to directly control the total level of emissions. This is not quite possible due to the decentralized nature of a large share of emissions. The best practical solution is what has been committed to, i.e. a cap-and-trade system that applies to all large emitters, with caps imposed by government, and taxation (ideally of carbon, but taxing energy products such as fuel for transportation through excise taxes is nearly equivalent) for small emitters, i.e. private transportation and the residential sector.

In the case of power generation we are entirely within the scope of the EU's Emissions Trading System (EU ETS). Finding the right policy should then be simple. Governments would develop an understanding of the cost to society of emitting additional CO2 (in terms of damage to the earth's climate). Capping emissions too drastically would lead to economic losses (as well as, ultimately, losses in tax revenues) while being too lax with allocations would lead to low CO2 prices and to very little change in yearly emissions.

The balance between various forms of power generation, if left to the market, will respond to the price signals that are there. If coal becomes more expensive then, ceteris paribus, less coal will be consumed. However EU governments have made additional commitments, in the form of nominal targets, with respect to renewable energy as well. Somewhat similarly to the case of CCS, it is typically assumed that there is a potential for technological improvement, but that that potential cannot be exploited to the full unless additional inducements are given.

The more general argument, and certainly the most important one, is that while additional inducements should be distributed in the best possible way (i.e. where they can do the most good in a longer-term perspective in terms of enabling solutions that would otherwise have taken 'too long' to develop), the core issue remains the proper functioning of the EU ETS and the necessity for a clear and unwavering commitment to ever-larger emission cuts. If the price signal is there and if it is strong, investments will be made in those technologies that become the most cost-effective. In that context it therefore seems odd to commit to a quantitative target for renewables in power generation. It would be just as inefficient to commit to a quantitative target for CCS or for nuclear power. That said, as CCS does benefit from exceptional and (hopefully) temporary assistance, it is reasonable (as has already been done) to ensure that promising renewables technologies get an extra push as well. If the latter occurs, the risk that CCS could crowd out investments in renewables seems low. First of all CCS isn't quite ready yet. Second, some forms of renewables will become cost-effective for similar CO2 prices as those required to make CCS cost-effective. Investment in renewables should therefore be expected to occur alongside CCS, rather than necessarily in opposition to it. Member states anyway already clearly display their national preferences which are strongly related to their national endowments. North-West European countries are the source of most of the action in terms of existing CCS projects (see Section V.3) either because they have more coal, or because they have more storage potential, or both.

III.5 The effects of CCS on electricity markets

Given recent political commitments by EU member state governments, the EU ETS will be subject to an ever-decreasing cap for total emissions over the coming decades. The price of a European Union carbon allowance (EUA) should therefore be supported by a strong upward trend over the next few decades (though shorter-run fluctuations could be substantial). For purposes of long-term planning – whether for governments or private corporations – the general trend should however be decisive.

In the absence of CCS – or indeed of any other new technology at the commercial level – electricity prices should likewise follow a general upward trend. Rising EUA prices would make all fossil fuel generation more costly. In addition, it is generally assumed that the prices of all fossil fuels will be on an upward trend over the coming two decades due to ongoing growth in global demand outstripping (on average) growth in global supply. If no large changes occur with respect to the cost of electricity from renewables and nuclear power, the energy mix will shift in favour of the latter, but the average wholesale price of electricity would nevertheless be raised, while fossil fuels would not be entirely phased out. With CCS, the efficiency penalties – and hence higher demand for coal – would naturally push up the price of coal. The latter effect, combined with the need to recoup higher initial capital costs, would lead to higher costs of electricity generation. While CCS would partly offset rising costs thanks to avoided emissions, most simulations conclude that wholesale electricity prices would rise in the presence of CCS as well.

For the case of North-Western Europe (Germany, France, the UK, the Netherlands and Belgium), scenario simulations presented in Seebregts and Groenenberg (2009) outline the pattern described above. The deployment of CCS would contribute to a rise in electricity prices, but electricity prices should rise anyway due to the cost-increasing effect of the EU ETS on conventional fossil fuel generation. In addition, the authors find that an increased deployment of renewables would push up electricity prices as well compared to current prices, directly, because those technologies (e.g. wind) are assumed to be more costly to begin with, but also indirectly, due to the increase of intermittent power generation. The authors conclude that CCS deployment should not be opposed due to its potential effects on electricity prices.

IV Financing mechanisms for CCS

IV.1 CCS and the EU's Emissions Trading Scheme (EU ETS)

Without additional support measures, the EU ETS would provide the main incentive for CCS through the price of emission allowances. Companies would gain more from re-selling their unused allocation of allowances, and/or from buying less allowances to begin with at auction, than they would lose due to the capital costs of CCS and its corresponding premium on operating costs. Implicitly, therefore, the laissez-faire policy would be to ensure that the carbon market operates properly, create scarcity in allowances from above according to emissions commitments, and let the private sector make its own decisions.

Until recently the structure of the EU carbon market presented a number of distortions that made this market-based allocation impossible. Some of these distortions have been addressed. Others remain. I briefly review some of the arguments in the debate.

One argument which is often mentioned is that there is (as yet) no global carbon market. On the other hand, almost all power generation facilities that produce electricity and heat for EU consumers must be located on EU territory for reasons of economic geography. As such they constitute stationary targets for environmental policies. Instead, higher costs due to environmental policies will affect value added margins and end-user prices in a combination which will depend on the extent of competition on the electricity market. As an aside, a separate analysis of the role and impact of electricity trade with non-EU countries could be interesting, e.g. Finland and the Baltic States with Russia and Belarus, or the eastern regions of Central European countries with Belarus and Ukraine.

One important problem so far with the EU ETS, as pointed out in de Coninck and Groenenberg (2007), is that it has been based on short trading periods without clear long-term commitments to emissions reduction targets. As such the EU ETS cannot offer a price signal which reflects a long-term commitment to emissions reductions which would justify adopting new technologies with long lead times and high entry costs. At present companies are incentivized to choose the best *short-term* technological solution, i.e. based on minor improvements of existing technologies or on substitutions between existing technologies that are readily available[5]. This is set to change to an important degree, although a number of important questions remain open.

In December 2008 the European Parliament (see EP, 2008) adopted the commitments made by the European Council with respect to the Energy Policy for Europe that had been proposed by the Commission in January 2007. A key part of the policy is the 20-20-20 initiative, i.e. to achieve by 2020 a 20% reduction in GHG emissions, a 20% improvement in energy efficiency, and to raise the share of renewables in gross inland consumption of energy to 20%.

A more ambitious commitment of a 30% reduction in GHG emissions was also agreed upon, but made dependent on commitments from non-EU states at the December 2009 Conference of the Parties in Copenhagen (COP15). A general commitment was also made for a 50% reduction by 2050, but the wording of the approved text (unless this author misunderstood) seems open to interpretation, as the formulation is that by 2050 emissions 'should be reduced by at least 50% below their 1990 levels' (see EP (2008), page 80). Of course, the fact that EU industry must expect at least a 20% reduction to be enforced through the EU ETS (and other means) is a strong signal, but a ten percentage point difference over a time period of 8 years (Phase III of the EU ETS spans the period 2013-2020) would make a very substantial difference to carbon prices, while the commitment for 2050, and hence its possible effect on carbon prices, seems open to future amendments. Concerning power generation, EP (2008) specifies that 'full auctioning should be the rule from 2013 onwards' and that 'no free allocation should be given for carbon capture and storage'. Deviations from full auctioning will however be granted under certain conditions for existing installations, though this will be entirely phased out by 2020.

This forthcoming set-up of incentives raises the prospects for the future commercial deployment of CCS. Allowance prices should be expected to rise substantially from 2013 onwards and the power generation industry should then face a strong price signal and should be able to assume that the EU and its member states are committed to additional reductions beyond 2020 as well. For example, Societe Generale, a French bank, was predicting[6] in late 2008 that the European Union carbon allowance (EUA) price in the 2013-2020 trading period (Phase III of the EU ETS) would fluctuate between 45 and 79 euros if the 20% commitment is upheld, and could rise to up to 94 euros if the 30% commitment is upheld.

However forecasting future carbon prices is difficult. The price will react strongly, in due course, to the increased deployment of renewables, to improvements in energy efficiency,

5 One symptom of this has been the 'dash for gas' over the last few years, though regulation of sulphur emissions also played a role.

6 See 'European carbon prices to quadruple by 2020-SocGen', Reuters UK, 10 October 2008.

and to the number and size of commercial CCS installations that come online. General economic developments and global energy prices may also impact EUA prices quite substantially, as can be seen at present. It is therefore difficult to predict the price path of allowances and how many CCS projects will come online. In addition, EUA futures contracts will certainly be used to hedge against EUA price fluctuations as well as for forecasting purposes, but may also provide distorted signals, particularly if they become the source of substantial speculative activity. One issue which would deserve separate analysis would therefore be EUA and EUA futures price formation patterns, including the risk of speculative bubbles, see e.g. Hintermann (2008). That said, if the EU ETS imposes, as is foreseen, a more-or-less linear reduction, year after year, in the total number of allowances this should offer a 'permanent' price support for several decades.

The elements mentioned above concern the period after 2013 (and implicitly also after 2020). At present the EUA price is low, and CCS has yet to reach the demonstration phase before commercial deployment can be considered. In order to bridge the gap the Commission suggested taking allowances from the new entrants reserve[7] and using these as a means of payment to private companies that commit to building CCS demonstration plants provided certain conditions are met. After some negotiation with the Member States it was decided that a total of 300 million allowances would be given to support up to 12 CCS demonstration projects as well as demonstration projects using innovative renewable technologies. The closing date for this process is 2015. The selected projects should be on EU territory, geographically balanced within the EU, and reflect several different technological options. Also, no single project may receive more than 45 million allowances. The selected operators will receive the market value of the allowances as disbursed by the relevant Member State(s). Member States may offer additional co-financing. It is not yet clear what date(s) will be used for the market valuation of the allowances, nor what share of the 300 million allowances will go to CCS projects, nor how exactly the projects will be selected. However the decision to allocate these allowances for CCS was strongly backed by the Commission and is naturally generating considerable interest in the private sector and may prove decisive for the concrete realization of CCS demonstration plants.

Another source of financing – not related to the EU ETS – concerns the EU recovery programme. As a response to the economic crisis of 2008-2009, the European Council approved recovery plan projects in the field of energy. EUR 1.05 billion were envisaged for CCS projects and EUR 0.565 were envisaged for offshore wind projects. A call for proposals was published by DG TREN, and closed on 15 July 2009.

[7] The new entrants reserve is a share of allowances, amounting to 5% of the Phase III total, which is set aside for auctioning for new installations that enter the Phase III after it begins operation.

IV.2 CCS and the Clean Development Mechanism (CDM)

One key goal EU member states have been pursuing with the encouragement of the Commission and of the IEA has been to have CCS included within the UNFCCC's Clean Development Mechanism (CDM). In other terms, the idea would be that Annex B countries (which includes all the advanced economies and all EU member states) would finance CCS projects in non-Annex B countries (i.e. low- and middle-income countries) and have the corresponding emissions reductions (called Certified Emission Reductions – CER) credited as national reductions in return. This solution, evidently attractive for Annex I countries, and prima facie not necessarily unattractive for non-Annex I countries, has nevertheless encountered some opposition from certain developing countries, notably Brazil, Venezuela, Grenada and Jamaica. India has also expressed scepticism, though less forcefully than the former group of countries.

At the COP14 conference in Poznan in December 2008 the working group responsible for the discussion on including CCS in CDM concluded in a brief written statement[8] that no consensus had been found between participating states. This was interpreted[9] as meaning that the inclusion of CCS in CDM would be most likely off the table for the COP15 conference in Copenhagen in December 2009. At COP15 the positions expressed were very similar to those that had been expressed at COP14 and no progress was made.

Written submissions provided in advance of COP14 came from Brazil, New Zealand, Norway, Saudi Arabia and Slovenia. The latter made its submission in its (then) role of Presidency of the European Union (representing the Community and all member states). The EU submission was furthermore endorsed by Bosnia and Herzegovina, Croatia, the former Yugoslav Republic of Macedonia, Serbia, Turkey and Ukraine. Brazil was the only country to oppose the inclusion of CCS in CDM in the advance written submissions. At the conference Venezuela and Jamaica announced positions similar to the Brazilian one. The main concerns expressed were about seepage of CO2 from chosen underground or underwater sites, and about related legal responsibilities and accountability, particularly in the long-run. The question one may ask is the extent to which the positions of Brazil, Jamaica and Venezuela on authorizing CCS projects *within the CDM* are justified from a general economic and political viewpoint.

At COP14 some of the other delegations reminded the audience that a positive decision would not create an obligation for any developing country to accept a CCS project. In its tone, the Brazilian declaration sounded like a defence of developing countries in general, as if developing countries could be put in a weak bargaining position that would draw them into accepting projects that are not in their own interest. However one well-informed expert

8 FCCC/SBSTA/2008/L.21.

9 See e.g. Carbon Capture Journal (CCJ), "Setback for CCS inclusion in CDM", Online News Item, 10 December 2008.

who was interviewed for this project suggested that Brazil took this position due to a fear that CDM projects using technologies other than CCS (from which Brazil has benefited a great deal in recent years) may be crowded out by CCS projects in China and other coal-intensive non-Annex I countries. Be that as it may, Brazilian government officials have indicated very openly[10] their view that CCS in the CDM might prevent development of renewable energy and would create a positive incentive for increased fossil fuel extraction (enhanced oil and gas recovery using CO2). While Brazil's own major oil company, Petrobras, is involved in a number of CCS pilot projects in Brazil, it seems clear that Brazil's position has to do with strategic choices in terms of energy policy, i.e. with a focus on renewables, notably biofuels, in which the country is a world leader. Turning very briefly to other notable positions in the CCS in CDM debate, one may note that oil exporting countries (with the notable exception of Venezuela) have usually had favourable positions, that micro-states have generally been opposed (e.g. Tuvalu, Micronesia) and that, additionally, India has also been sceptical. China on the other hand has expressed great interest in CCS and no opposition to including it in the CDM.

At COP15 the main positions were confirmed. Brazil again took the lead of the 'no camp', supported by Grenada, Jamaica and Paraguay. Brazil seemed confident in the knowledge that the decision was once again being postponed. Grenada was more combative, not only by opposing CCS in the CDM, but also by stating that the debate was taking up too much time to begin with. Grenada also stated that CCS technologies should simply be transferred. Jamaica stated its support for the position of Grenada, while Paraguay described CCS as a 'revolutionary and unknown' technology, and that anyway the real goal should be to move away from fossil fuels altogether.

Saudi Arabia, Kuwait and Qatar expressed strong support for CCS in the CDM, and wanted no more delays. Some irritation was also palpable with respect to arguments used by the 'no camp' concerning alleged lack of knowledge about CCS technology and its risks. Kuwait stated its view that there is 'nothing wrong' with CCS. Qatar stated that it could not understand why some countries objected to CCS in the CDM. Kuwait and Saudi Arabia also complained that they never get CDM projects, and that CCS is their main (or perhaps only) chance in that respect.

The European Union (represented by Sweden) as well as Japan, Australia and Norway reiterated their support for CCS in the CDM in very clear terms.

At a more subtle level, the debate has now moved on to the issue of 'environmental integrity' of CCS projects, which is where Brazil wanted it. While smaller countries from the Western Hemisphere can oppose CCS in the CDM with quite light-headed arguments (and while Middle Eastern countries can impatiently demand a green light immediately), the real debate

[10] See Miguez (2007).

is between Brazil and the countries of the OECD, including the European Union. The latter accept the general validity of the argument of integrity (but feel that sufficient guarantees can be put in place, thus not justifying Brazil's position). Again, while long-term liability for seepage is a genuine question, the core disagreement seems to be based on differing national interests, rather than on what constitutes the best solution to combat climate change. A broader political deal may therefore be necessary to convince Brazil to change its position. If that occurs, it is likely that smaller states from the Western Hemisphere would quietly drop or water down their positions as well. If no solution can be found, however, then it is possible that OECD countries would start to think about circumventing or replacing the CDM with a new mechanism in which individual states have less power.

IV.3 CCS and Joint Implementation (JI)

Joint Implementation is similar to CDM except that it is designed for projects between Annex B countries. As in CDM, a country may credit emissions reductions (called in this case Emissions Reduction Units – ERU) by financing a project in another country. The main recipients of JI projects have been Annex B transition countries, notably Romania and Poland. The debate on including CCS under JI has been considerably less prominent than the one for CDM. In most contributions where JI is mentioned, both JI and CDM are discussed simultaneously, with an implicitly or explicitly (much) greater interest in CDM as both industry and Annex B countries recognized the very significant potential for CCS in China.

IV.4 CCS and Public-Private Partnerships (PPPs)[11]

There are various categories of public-private partnerships. First of all, they can be distinguished into Institutional and Contractual PPPs[12]. While the former involve the joint foundation of an institutional entity by public and private parties or the transfer of an existing institution from the public to the private operator, the latter are characterized by a contractual agreement between the public and the private sector, whereby the private operator commits to provide services for some kind of financial remuneration.

Table IV.1 shows a selection of different types of PPPs sorted by increasing risk transfer from the public to the private sector. The choice of the most suitable option depends on the specific circumstances and requirements of the respective project and can be tailored accordingly. PPPs are characterized by complex legal and financial arrangements and – on the European level – are mainly employed in sectors like transport, energy, infrastructure, public safety, waste management, and water distribution.

[11] This section, as well as section IV.5, was contributed by Ms. Irina Gaubinger.

[12] Renda and Schrefler (2005), p. 3.

Table IV.1

Modalities of PPPs by type

Type	**Modalities**
Service contracts	The private party procures, operates and maintains an asset for a short period of time. The public sector bears financial and management risk
Operation and Management contracts	The private sector operates and manages a public owned asset. Revenues for the private party are linked to performance targets. The public sector bears financial and investment risks
Leasing-type contracts ▪ *Buy-build-operate (BBO)* ▪ *Lease-develop-operate (LDO)* ▪ *Wrap-around addition (WAA)*	The private sector buys or leases an existing asset from the government, renovates, modernizes, and/or expands it, and then operates the asset, again with no obligation to transfer ownership back to the government
Build-operate-transfer (BOT) ▪ *Build-own-operate-transfer (BOOT)* ▪ *Build-rent-own-transfer (BROT)* ▪ *Build-lease-operate-transfer (BLOT)* ▪ *Build-transfer-operate (BTO)*	The private sector designs and builds an asset, operates it, and then transfers it to the government when the operating contract ends, or at some other pre-specified time. The private partner may subsequently rent or lease the asset from the government
Design-build-finance-operate (DBFO) ▪ *Build-own-operate (BOO)* ▪ *Build-develop-operate (BDO)* ▪ *Design-construct-manage-finance (DCMF)*	The private sector designs, builds, owns, develops, operates and manages an asset with no obligation to transfer ownership to the government. These are variants of design-build-finance-operate (DBFO) schemes

Source: Renda and Schrefler (2005), p. 5.

For CCS-related activities, PPPs could play a role in the provision of CO2 transport infrastructure or with regard to a CCS demonstration project. Concerning the former, the main argument for a PPP is that it is the type of arrangement that is best suited for overcoming the large-scale commitment coordination problems that typically arise for important cross-border infrastructure projects, in this case the construction of a cross-border network of CO2 pipelines.

Regarding the design of PPPs both parties, public and private, have a role as private companies naturally are prepared to design the infrastructure needed on an individual basis (i.e. the pipeline from the plant to the storage site) and public intervention could focus on (1) drafting a 'backbone' connection additional to the individual infrastructures; (2) securing / planning access for other (current or future) users; (3) coordinating expressions of interest and contributions from other potential users.

The arguments for a public share in the financing of PPPs refer to the notion of 'common interest' on the European level and could be considered in a similar context on the national level. E.g. if a project aims at promoting effective operations, the development of the internal (energy) market, the rational use of energy resources, the development of lessfavoured regions, the security of energy supply, and sustainable development in general (articles 2, 3, 4 and 6 in Decision 1364/2006/EC), community aid might be granted. Which part of CCS activities can be considered to be ‘of common interest’, however, would need to be evaluated. The case of the Trans-European Energy Networks might provide guidance, e.g. as to upper limits on public finance participation (< 10% of total investment costs) as well as Community guidelines on state aid for environmental protection (maximum of 40% of eligible costs to be financed by national aid with regard to cogeneration or renewable energy projects)[13].

The operation of the network would optimally be carried out by a private party, either from the capture or storage side or by an independent third operator. As for ownership of the pipeline network, there are various alternatives, e.g.

- the public sector owns the infrastructure throughout the project,
- the private sector owns the infrastructure throughout the project,
- the private sector owns the infrastructure for a specific contracting period after which ownership is transferred to the public sector,
- the public sector sells the infrastructure to the private sector at a specific date during the project.

As can be seen, there is scope for a splitting of tasks between private and public parties in the areas of design, financing and ownership, while operating the network would remain in private hands. Concerning the public finance component, the main public partner would be a Member State. In addition Community aid, or institutions such as the EIB, could contribute, e.g. funding of R&D, soft loans, subsidized loan guarantees, direct grants or participation in risk-capital[14].

IV.5 CCS and institutional risk-sharing loans

European financial institutions like the European Investment Bank (EIB), the European Bank for Reconstruction and Development (EBRD) or the European Investment Fund could also play an important role in financing CCS-related activities by providing risk-sharing facilities. This section takes a look at some of the EIB’s activities.

The EIB, in cooperation with the European Commission, set up a Risk Sharing Finance Facility (RSFF)[15] for investments in Research, Development and Innovation. Community funds available under the Seventh Framework Programme (FP7) are leveraged through EIB financing. The Bank and the EC share the credit risk which enables the EIB to provide

13 Official Journal of the European Communities (2001/C 37/03).

14 de Coninck and Groenenberg (2007), p. 26.

15 http://www.eib.org/products/loans/special/rsff/ (accessed on 13 March 2009).

favourable loans or guarantees which normally would not be financed due to their low investment grade risk profile. Eligible projects are in the areas of basic or fundamental research, applied or industrial research, experimental or pre-competitive development, definition stage or feasibility studies as well as pilots and demonstration activities. Support can be granted with regard to investments in equipment, R&D operating costs, salaries of participants or other types of costs. Given the official standing of the EIB and the relatively long-term nature of its assistance, participation in the RSFF also facilitates access to additional funding, e.g. from commercial banks, an often difficult hurdle with new technologies. Generally speaking, the EIB has helped finance a large number of innovative projects in many areas relating to new energy and environmental technologies. This role, as well as the role of other public sector funding institutions, should perhaps be encouraged in the near future given the current global financial climate.

V Global aspects of CCS deployment

V.1 Global reserves, production and consumption of coal

Coal is a relatively abundant fossil fuel which comes in various forms in terms of texture and energy content. As with other fossil fuels, the concept of proven reserves is the most useful (and the most prudent) from an economic viewpoint. Proven reserves are those resources which can be extracted with very high likelihood under current conditions in terms of available technologies and market conditions, notably energy prices. As with crude oil, proven reserves data fluctuate somewhat depending on: new discoveries and revisions (upward or downward) for existing fields or seams, extraction technology, and fuel prices. The likelihood of new discoveries is itself influenced by fuel prices, as more costly types of exploration work (e.g. more thorough, and/or in more difficult locations) will be undertaken if fuel prices rise or are expected to rise.

Proven reserves of coal by country are presented in Tables V.1 and V.2. Table V.1 contains the data presented in BP's *Statistical Review of World Energy 2009*, itself based on World Energy Council data. The latter split coal into two categories: bituminous coal (including anthracite), with relatively harder texture and higher energy content, and sub-bituminous coal (including lignite), with softer texture and somewhat lower energy content.

Table V.2 contains data from Germany's Federal Institute for Geosciences and Natural Resources (BGR). The BGR data follows a different classification and splits coal between 'soft brown coals' (*Weichbraunkohlen*), which overlaps almost exactly with lignite, and 'hard coals' (*Hartkohlen*), which covers all other types of coal, i.e. the harder end of the spectrum from among sub-bituminous coals (hard brown coal), and all bituminous coals, up to and including anthracite.

Table V.1

Proven reserves of coal by country according to BP / WEC

Country	**Anthr. and bitumin.**		**Sub-bituminous**		**Total**	
	Tonnes, bn	% of total	Tonnes, bn	% of total	Tonnes, bn	% of total
United States	109.0	26.5%	129.4	31.2%	238.3	28.9%
Russia	49.1	11.9%	107.9	26.0%	157.0	19.0%
China	62.2	15.1%	52.3	12.6%	114.5	13.9%
Australia	36.8	8.9%	39.4	9.5%	76.2	9.2%
India	54.0	13.1%	4.6	1.1%	58.6	7.1%
Ukraine	15.4	3.7%	18.5	4.5%	33.9	4.1%
Kazakhstan	28.2	6.8%	3.1	0.8%	31.3	3.8%
South Africa	30.4	7.4%	-	0.0%	30.4	3.7%
European Union	8.4	2.0%	21.1	5.1%	29.6	3.6%
Rest of the world	17.9	4.4%	38.3	9.2%	56.2	6.8%
Total World	**411.3**	**100.0%**	**414.7**	**100.0%**	**826.0**	**100.0%**

Source: BP (2009), based on WEC (2009).

There are quite substantial differences between the BP / WEC data and the BGR data. The latter is based on a recent data collection effort, while the former is based on an interim (and incomplete) update of older estimates[16]. While both sources are presented for purposes of comparison and analysis, the BGR data is quite naturally the preferred source at this moment in time.

Table V.2

Proven reserves of coal by country according to BGR

Country	**Soft brown coal**		**Hard coal**		**Total**	
	Tonnes, bn	% of total	Tonnes, bn	% of total	Tonnes, bn	% of total
United States	31.0	11.5%	231.9	31.8%	263.0	26.3%
China	11.0	4.1%	180.6	24.8%	191.6	19.2%
Russia (1)	91.6	34.1%	69.9	9.6%	161.6	16.2%
India	4.3	1.6%	76.4	10.5%	80.7	8.1%
Australia	37.3	13.9%	39.6	5.4%	76.9	7.7%
European Union	53.4	19.9%	18.2	2.5%	71.6	7.2%
Ukraine (1)	2.3	0.9%	32.0	4.4%	34.4	3.4%
South Africa	0.0	0.0%	31.0	4.3%	31.0	3.1%
Kazakhstan (2)	3.1	0.0%	18.9	2.6%	22.1	2.2%
Rest of the world	37.9	14.1%	30.8	4.2%	68.7	6.9%
Total World	**268.9**	**100.0%**	**729.5**	**100.0%**	**998.4**	**100.0%**

Notes: 1) Russia and Ukraine: soft brown coal data are over-estimates as they include hard brown coal, whereas the hard coal data are under-estimates as they exclude it. - 2) Kazakhstan estimate for soft brown coal taken from WEC lignite estimates.

Source: BGR (2009). Estimates as of end of 2007.

[16] See WEC (2009: 1). A full update will be published in the course of 2010.

According to the BGR data, the countries with the largest reserves are the United States, China, Russia, India and Australia. As is clear from those figures, proven reserves of coal are highly concentrated geographically. South Africa holds 95% of Africa's proven reserves of hard coal (there is virtually no lignite on the African continent). The United States has 94% of all proven reserves of hard coal in the Americas.

The BGR estimates are mostly higher – in some cases substantially – as compared to BP/WEC estimates. This reflects the effect of recently higher energy prices and greater concerns with respect to security of supply, both of which raise the potential profitability (and political desirability) of coal extraction, and hence proven reserves estimates. One of the most spectacular changes with the BGR estimates is for soft brown coal in Germany. The new estimate, see BGR (2009: 91), is 40.82 billion tonnes, as compared to 6.56 billion tonnes (of lignite) as reported in WEC (2009: 5). This remarkable revision means that the European Union has – pending possible revisions in other countries – the second largest reserves of soft brown coal in the world. The picture is however essentially unchanged for hard coal: the European Union holds a very modest 2.5% of global reserves.

The other substantial change reported in BGR (2009) as compared to BP/WEC concerns China. There is, first of all, a relatively strong downward revision for soft brown coal, from 18.6 billion tonnes (lignite) as reported by WEC to 11.0 billion tonnes as reported by BGR. But most importantly there is almost a doubling of proven reserves for hard coal, from around 96 billion tonnes in WEC (2009: 5) to 180.6 billion tonnes in BGR (2009: 83). Sizeable upward revisions are also found for the United States, India and a few other countries. South Africa's reserves, on the other hand, were recently revised downwards, though this is captured in both WEC (2009) and BGR (2009). A closing comment on the issue of proven reserves of coal is of course that more work is needed on reserves estimates. It seems possible that some countries have – for a number of reasons – been more active than others (or more active sooner) in re-assessing their potential. Additional revisions could therefore come to light over the next several months. The World Energy Council's fully updated survey, expected by September 2010 at the latest, may prove to be a useful data source in this respect.

How long will these reserves last at the production levels that are predicted from available scenarios? I present a simplified estimate in Table V.3. The estimate is constructed taking the reserves presented above and subtracting the projected production levels for the period 2006-2030 presented in the IEA's World Energy Outlook 2008. Importantly, the estimate does not take CCS into consideration for the moment.

The key result is that coal reserves would still be vast in 2030, even taking into account the IEA's projection that yearly global coal production might increase by 59% between 2006 and 2030. Indeed, the estimate suggests that the world would still have another 123 years of coal reserves before reaching full depletion after 2030, assuming that global production peaks in that year and remains constant thereafter. By 2030 the United States and Russia would have by far the largest reserves endowments in the world. China would slip down the ranking somewhat, though it would still have 38 years' worth of reserves at the end of the period.

Table V.3

Estimated future proven reserves of coal by country by 2030

	2008	**2015**	**2030**	***Years-to-depletion***
United States	263	257	243	*247*
Russia	162	160	155	*437*
China	192	175	129	*38*
India	81	78	71	*117*
Australia	77	75	69	*161*
European Union	72	70	67	*371*
Ukraine	34	34	33	*405*
South Africa	31	29	26	*100*
Kazakhstan	22	21	20	*207*
Rest of the world	69	65	56	*90*
Total World	998	961	865	*123*

Notes: reserves are in billions of tonnes for all types of coal. Years-to-depletion computed on the assumption that production remains constant at 2030 levels after 2030.

Source: BGR (2009); IEA (2008a); own estimations.

In the case of the European Union, the results suggest a long life-time for the Union's reserves. However the EU's coal consumption is higher than its production already today. Again referring to the IEA's World Energy Outlook 2008, the EU's demand, production, net imports and net import dependence ratio for the period 2006-2030 are shown in Table V.4.

Table V.4

Demand, production and net imports of coal, European Union, 2006-2030

	2006	**2015**	**2030**
Demand	463	460	372
Production	273	232	180
Net imports	190	228	192
Net import dependence ratio	41%	50%	52%

Units: Millions of tonnes of coal equivalent.

Source: IEA WEO 2008; own estimations.

Generally speaking, the introduction of CCS should push up demand for coal for two reasons. First, the efficiency penalty associated with the capture process should push up the amount of coal needed. Referring to the thermal efficiency ratios given in Section III.1, one should expect, very roughly, an extra 15% to 30% of coal use for the same amount of power generation without CCS. Second, CCS would make coal more important than previously anticipated in the energy mix of OECD countries.

Concerning the second point, a forthcoming study by Eurelectric foresees a trend reversal in the EU's use of coal, starting in the early 2020s (as CCS starts to operate commercially). So while coal use would continue its current slow and moderate decline up to around 2020, demand would then rise again, and be roughly 10% higher than it currently is by 2040. Linking this with the contents of Table V.3, one might estimate very roughly a consumption of around 500 million tonnes. That said, the new reserves estimate for Germany discussed earlier departs strongly from previously held assumptions. The key question is whether a much more ambitious deployment of lignite-fired CCS facilities may be feasible (or indeed desirable) in the EU, in which case Germany's lignite reserves could play an important role in Germany and in Germany's immediate geographical vicinity. The physical properties of lignite (high water content, low energy content, and ultimately low price-weight ratio) strongly reduce the scope for trading it across large distances. The EU's total trade turnover (imports plus exports) with the rest of the world was, in 2008, almost 31 billion dollars for hard coal, but only 92 million dollars for lignite. Germany's exports of lignite in the same year went almost exclusively to its immediate neighbours, chiefly Belgium, Austria, France and the Czech Republic[17].

Table V.5

Main sources of hard coal imports for the European Union

Country	**Value (USD mn)**	**Share**	**Cum. Share**
Russia	7,218	23.5%	23.5%
Australia	5,532	18.0%	41.5%
United States	5,321	17.3%	58.9%
South Africa	4,545	14.8%	73.7%
Colombia	2,817	9.2%	82.9%
Indonesia	1,805	5.9%	88.8%
Canada	1,406	4.6%	93.3%
Ukraine	671	2.2%	95.5%
Rest of the World	1,373	4.5%	100.0%
Total	**30,687**	**100.0%**	

Note: 2008 data. Product classification: HS 2002, code 2701 (includes briquettes).

Source: UN COMTRADE; own estimations.

Hard coal on the other hand is traded over much larger distances overland, as well as across oceans by tanker. The most important sources of hard coal imports into the

17 Source: United Nations COMTRADE database.

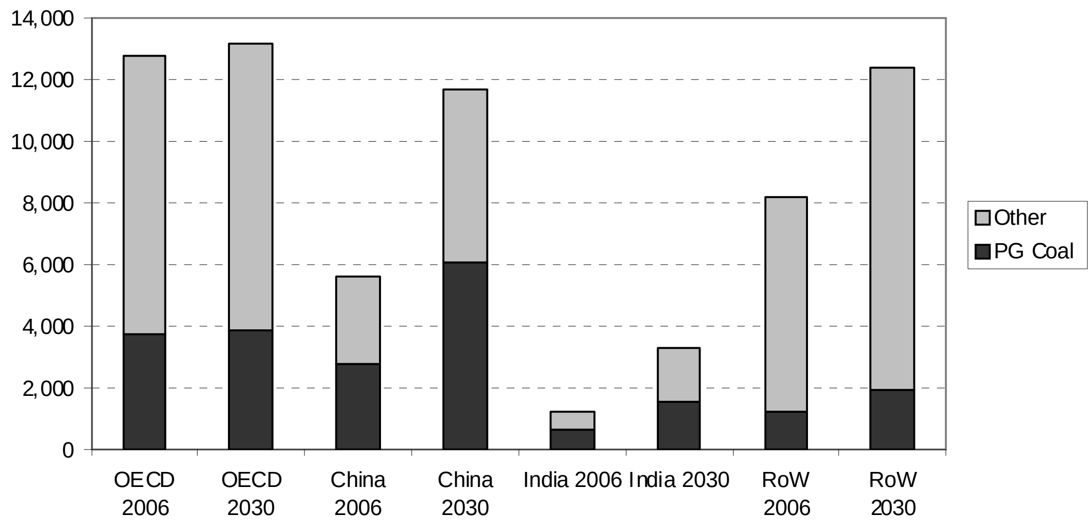
European Union are shown in Table V.5. As can be seen, geographical proximity matters only to a limited extent. While Russia is the main source, Australia, the US, South Africa and Colombia are important sources as well. Ukraine on the other hand seems below potential, given its reserves and proximity.

V.2 Global emissions and the role of CCS

As mentioned in the introduction, large non-OECD countries, in particular China, are expected to contribute massively to the increase of CO2 emissions over the next few decades, notably due to an expansion in the use of coal-fired power generation. China recently overtook the United States as the world's largest emitter of CO2. By 2030 China's emissions could be not far behind those of the OECD as a whole. Figure V.1 shows recent versus projected total CO2 emission levels for the OECD, China, India and the rest of the world for the years 2006 and 2030. The picture that is emerging by 2030 is that emissions will be split almost evenly between the OECD, China, and all other countries put together. By implication, emissions reductions achieved by OECD countries may pale in comparison with increases in emissions from China and, to a much lesser extent, India. Also, while coal-fired power generation is not the whole story, Figure V.1 does illustrate its important contribution to the projected rise in emissions from both China and India. On the other hand, coal-fired generation is projected to play a much smaller role in the rest of the world (e.g. Africa, Middle East, Latin America).

Figure V.1

CO2 emissions, total and coal-fired power generation, 2006 vs. 2030



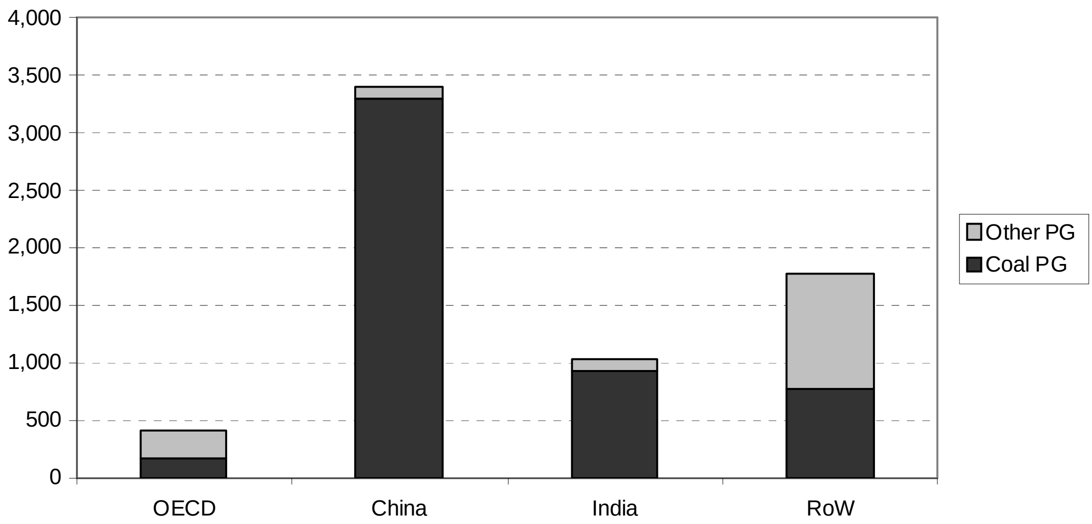
Units: Millions of tonnes of CO2.

Source: IEA (2008a) and own calculations.

If one focuses only on power generation the picture becomes starker still. The issue here is not that emissions from other sectors matter less, but rather that different policy instruments need to be deployed to deal with different sources of emissions. Transportation, which is overwhelmingly based on petroleum products, would require a completely different approach[18] while CCS is not a serious option[19]. The residential sector also requires specific solutions[20] and a role for CCS is hard to imagine. So if CCS is to be assessed within its proper context, it is chiefly power generation (and potentially heavy industry) which one should consider. Focusing then on the former, a very telling picture emerges if one looks at projected growth from 2006 to 2030 rather than at levels. This is shown in Figure V.2, which illustrates the overwhelming role of coal in China and India in contributing to increased emissions from power generation.

Figure V.2

Projected increase in CO2 emissions from power generation to 2030



Units: Millions of tonnes of CO2.

Source: IEA (2008a) and own calculations.

The general pattern with respect to increases in generation capacity, see Figure V.3, reveals that most of the action will occur outside the OECD, with China again in a leading role. While coal should represent the bulk of China's new capacity over the next two decades, the role of renewables should not be dismissed. China is projected to create more renewables capacity up to 2030 than the United States and almost as much as the European Union. As concerns coal (and bearing in mind that the projections shown

18 E.g. more mass transit, efficiency improvements, and fleet replacement in favour of hybrid, plug-in hybrid and/or all-electric vehicles (EV).

19 CCS-equipped vehicles is a very unlikely option on a commercial level. Some research is being carried out in that direction, but is so far seen more as an interesting technical challenge than anything else.

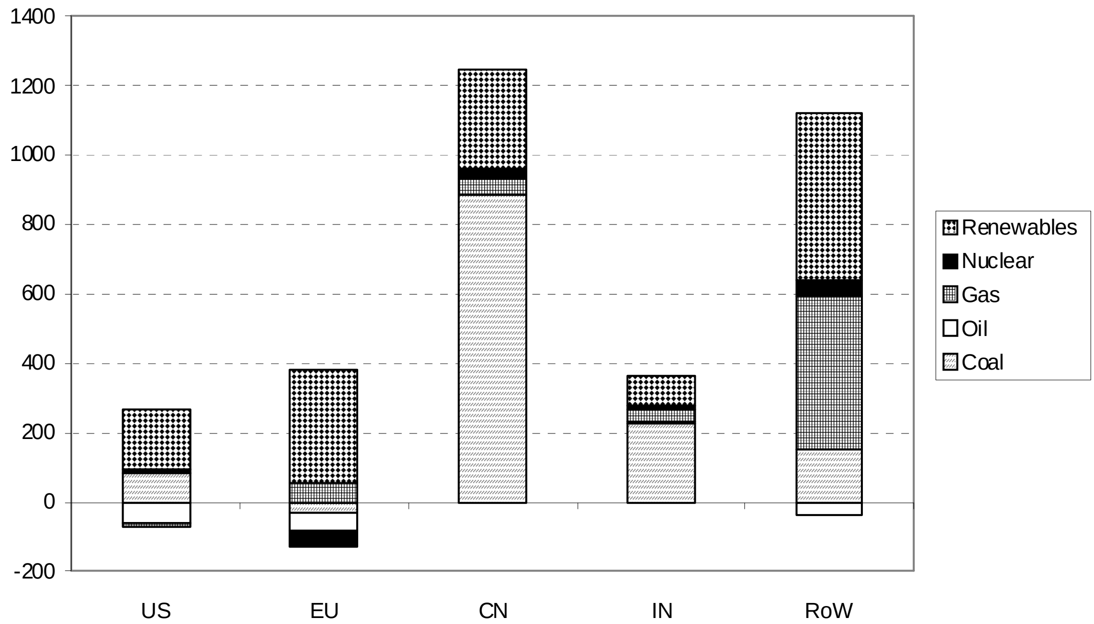
20 E.g. improved insulation and temperature regulation, and better building materials such as low-emissivity windows.

essentially exclude CCS), the data points to very substantial investment flows in coal-fired generation in China and India over the period. The data should however not be taken to imply that investments will be proportionately higher in China as compared to the EU or the US, given that only the net changes in capacity are shown. Since the data spans a period of 24 years, one needs to bear in mind the need to replace decommissioned facilities, the potentially higher cost per GW of higher technology build, and the generally (much) higher nominal construction costs in the EU and in the US as compared to China and India.

According to IEA (2008a) projections, new investments in power generation capacity over the period 2007-2030, excluding related investments in transmission and distribution, should amount to around 1400 billion dollars (at 2007 prices) in North America, 1500 billion dollars in European OECD countries, and around 1300 billion dollars in China. Those estimates are somewhat higher than earlier IEA estimates due to increases (up to mid-2008) in the prices of energy and basic materials. While those costs have now fallen again to some extent, the broader lesson is that investment flows will be large, and that total investment in China may be roughly on a par with EU or US levels, i.e. still considerable monetary volumes, but less than generation capacity projections in Gigawatts would suggest.

Figure V.3

Projected increase in power generation capacity to 2030 by type



Units: Gigawatts.

Source: IEA (2008a) and own calculations.

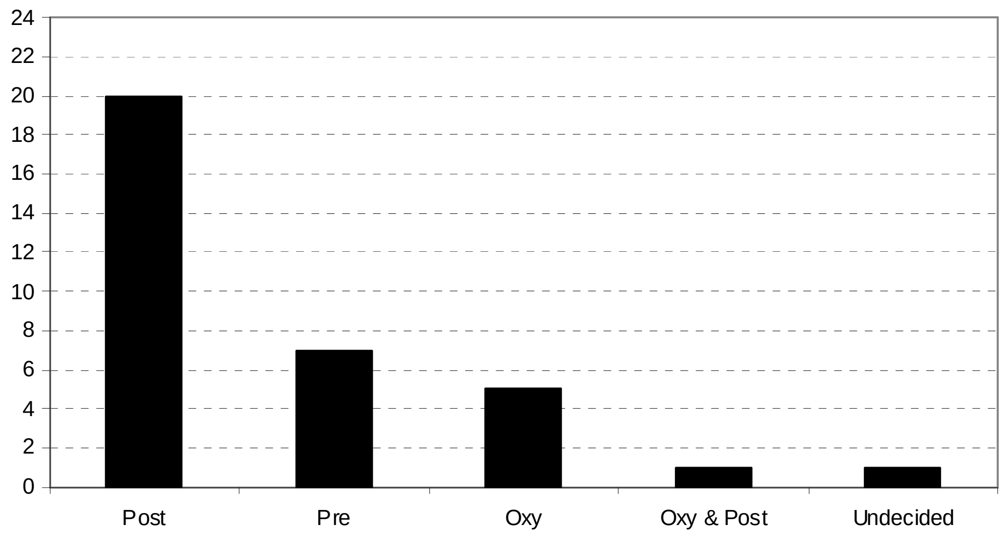
The projections mentioned in this section will naturally be subject to repeated revisions. The 2008 spike in oil prices, which had a knock-on effect on many other commodities and cost items, has now passed, and an extremely sharp global recession has followed. While there is little doubt that investment needs in power generation are vast regardless of what path commodity prices may follow in the short and medium-run, the current concern is naturally that the private sector, particularly in OECD countries, faces considerable challenges in terms of investment risk assessment and access to financing.

V.3 CCS in the world: project types and project locations

In this section a snapshot of current CCS projects worldwide is presented. The source of the data is the Carbon Capture and Sequestration Technologies Program at the Massachusetts Institute of Technology (MIT)[21]. MIT keeps up a database of CCS projects, based on publicly-available information (mainly media reports and corporate press releases), and divides projects into three main categories: currently or previously active capture projects with storage and/or EOR, announced capture projects with storage and/or EOR, and stand-alone storage projects. Focusing for now on the first category, and taking only those projects that are active and for which a timeframe for starting operation has been publicly announced, one finds a total of 34 projects as of mid-September 2009. The full list of projects is in Appendix A of this report.

Figure V.4

Active CO2 capture projects by capture principle



Source: Carbon Capture and Sequestration Technologies Program, MIT.

The main features that are in evidence from the MIT list of projects are as follows. The vast majority of projects are coal-fired (29 out of 34, or 85%), while just 2 are gas-fired and the rest are based on other fuels or on a mix of fuels. In terms of main capture method, a clear

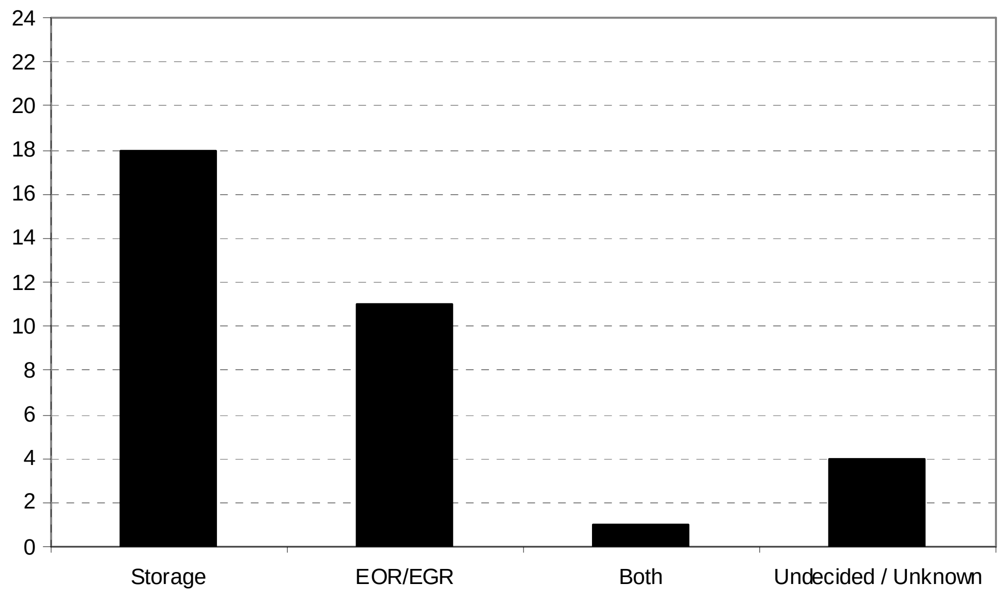
[21] The MIT data summarized in this section and in the next section was accessed in late September 2009.

majority are post-combustion projects (20 out of 34). Seven are pre-combustion, 5 are oxy-firing, 1 is a combination, and 1 is as yet undecided, see Figure V.4.

As for the final use of the captured CO2, see Figure V.5, a majority of projects are storage (sequestration) projects (20 out of 34), however a substantial number of projects (10, or 29%) are Enhanced Oil Recovery (all based on post-combustion, one in Norway, all others in North America). One project foresees both uses (Schwarze Pumpe, Germany), one other project is destined for Enhanced Gas Recovery (Janschwalde, Germany), while four others are as yet uncommitted or of unknown status.

Figure V.5

Active CO2 capture projects by final use of CO2



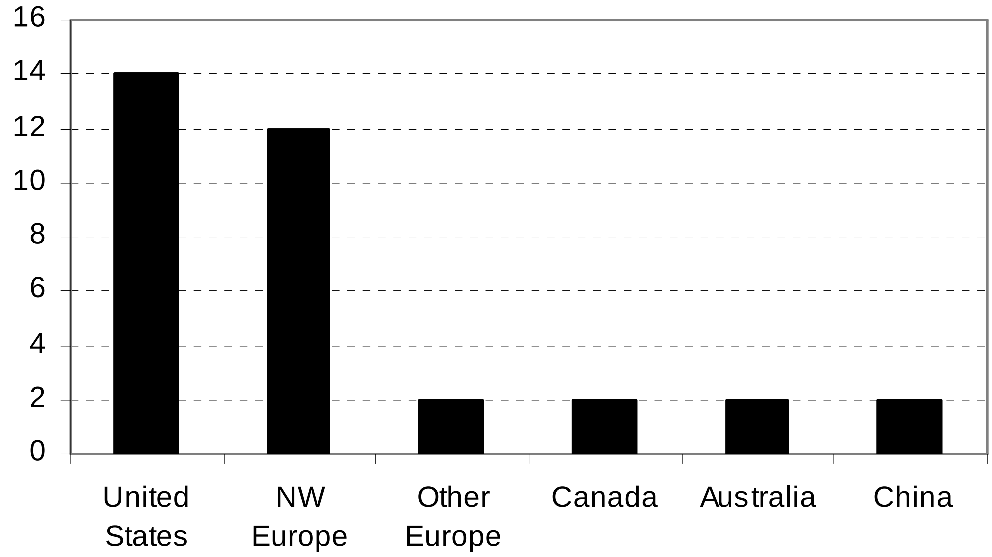
Source: Carbon Capture and Sequestration Technologies Program, MIT.

As shown in Figure V.6, the geographical location of active CCS projects is highly concentrated, with the United States and North-West Europe together accounting for over three quarters of all projects. China is – so far – the only non-OECD country with active capture projects on its territory.

It is relevant to take note of announced projects as well. While the survival rate of projects that are merely announced publicly at an early stage is not necessarily high, it is interesting to note that announced projects as recorded in the MIT database have slightly different characteristics as compared to the more mature projects discussed above. In particular, all of the announced projects that include capture are in Europe. Moreover, although many projects are from North-West Europe, other European regions are increasingly well represented. Out of a total of 11 announced capture projects, 2 are from the Czech Republic, 3 from Italy, 5 from the Netherlands and 1 from the UK.

Figure V.6

Active CO2 capture projects by country



Note: North-West Europe: UK, France, Benelux, Germany and Norway.

Source: Carbon Capture and Sequestration Technologies Program, MIT.

Table V.6

Active storage-only projects

Project	Leader	Location	CO2 Source	Size Mt/Yr	CO2 Sink	Start
Sleipner	StatoilHydro	Norway	Gas Process	1.000	Brine Res	1996
Weyburn	Pan Canadian	Canada	Coal Gasif.	1.000	EOR	2000
In Salah	BP	Algeria	Gas Process	1.200	Depleted Gas Res	2004
K12-B	GDF-Suez	Netherlands	Gas Process	0.200	Depleted Gas Res	2004
Zama	Apache	Canada	Gas Process	0.067	EOR	2006
Snohvit	StatoilHydro	Norway	LNG Process	0.700	Depleted Gas Res	2008
Otway	CO2CRC	Australia	Natural Dep.	0.100	Depleted Gas Res	2008
Ketzin	CO2Sink	Germany	H2 Prod.	0.030	Sandstone Res	2008
Decatur	MGSC	IL, USA	Ethanol Prod	0.300	Brine Res	2009
Gorgon	Chevron Texaco	Australia	Gas Process	3.300	Brine Res	2009
Cranfield	SECARB	Miss, USA	Gas Process	1.000	Brine Res	2008-9
Entrada	SWP	CO/WY USA	Gas Process	1.100	Brine Res	2008-12
Fort Nelson	PCOR	Canada	Gas Process	1.000	Brine Res	2011
TAME	MRCSP	OH, USA	Ethanol Prod.	0.280	Sandstone Res	2011
Riley Ridge	Big Sky	WI, USA	Gas Process	0.500	Sandstone Res	2015

Source: Carbon Capture and Sequestration Technologies Program, MIT.

The other aspect which is important is to note the general growth in the size of projects over time. Taking the active projects discussed[22], one can compute the average capacity of projects by start-up date. For those with start-up dates in 2008-2010 the average is 171 GW; for start-up dates in 2011-2013 the average capacity is 455 GW; and for start-up dates in 2014-2015 the average capacity is 615 GW. Finally, the average capacity for the announced projects (various dates) is 1003 GW. This general progression is naturally indispensable if CCS is to fulfil the hopes of its supporters. At present the data suggests a certain level of confidence and ambition on the part of the major actors, though much remains to be done. In any case, the next few years will be crucial.

As mentioned earlier, a number of projects deal with storage in isolation, i.e. they are not commercially or legally integrated with a power generation project, though CO2 storage may already be a regular activity (e.g. Sleipner, Weyburn). A list of active storage-only projects is presented in Table V.6.

V.4 CCS in the world: institutional and corporate actors

In this section we take a look at the main corporate actors involved in CCS projects. We start by looking at the active CO2 capture projects, as was done in the previous section.

The vast majority of CCS projects are carried out by consortia of 2 – 5 corporate actors. These consortia often benefit from additional cooperation or assistance from state-backed institutions, in some cases purpose-built umbrella groups coordinated by national governments, e.g. WESTCARB, SECARB, Big Sky or PCOR in the United States (regional partnerships initiated by the Department of Energy). Major research institutes are also sometimes involved, e.g. the French Petroleum Institute (IFP) or the National Energy Technology Laboratory (NETL) in the USA.

As concerns private sector actors, the 34 active projects from the MIT database are operated by around 70 distinct (separately incorporated) private companies. The vast majority of those companies are only involved in one project out of the 34. This reflects the relative novelty of CCS, i.e. an activity with many new entrants. However it is already possible to identify a smaller number of somewhat established corporate players. Taking, as a very simple filtering rule, only those private companies that are involved in at least two projects out of the 34 active projects, one is left with just 9 companies. In addition, if one takes into consideration the storage projects as well as the announced CCS projects (both capture and storage), and if one adds those companies that have one project in the active list and one in one of the other lists, one finds a total of 16 leading corporate players, presented in Table V.7. The selection method used here naturally has its caveats: slightly

[22] Williston and NZEC are excluded given uncertain core data. Mid-point values are taken for all projects where value ranges are given for start-up dates or for capacity.

different selection criteria would have led to the inclusion of, among others, BP and E.ON. But for what it is worth, the list does give a (partial) snapshot of the leading actors.

Table V.7

Selected leading corporate actors in CCS

Name	**Country**
Air Liquide	France
Alstom	France
American Electric Power (AEP)	USA
DONG Energy	Denmark
Enel	Italy
Fluor Corporation	USA
GDF-Suez	France
Nuon	Netherlands
Powerspan	USA
Royal Dutch Shell	UK / Netherlands
RWE	Germany
Sargas AS	Norway
Schlumberger	US / France / other
Siemens	Germany
Statoil Hydro	Norway
Vattenfall	Sweden

Source: MIT database and own filtering based on overlapping occurrences (see text).

To conclude it is important to say a word on China. One of China's two projects is a bilateral (inter-governmental) cooperation between the UK and China called NZEC which is still at a relatively early stage. The other project, called GreenGen, is China's domestic flagship project, involving a large consortium of Chinese corporations and organizations. The target date for the start-up of operation is 2010. The consortium's majority shareholder (with 51% of shares) is China Huaneng Group, a major state-owned power generation company. One may note that the GreenGen group explicitly states on its web-site[23] its intention to develop CCS with 'independent intellectual property rights'. In other terms, the Chinese authorities are hoping that Chinese companies will become competitive with respect to Western companies on a future Chinese market for CCS, if not on international CCS markets.

VI Policy stances and stakeholder opinions on CCS

VI.1 States and supra-national organizations

The development of CCS is supported by most major states. At the 2008 Hokkaido Toyako Summit the G8 endorsed the IEA's recommendation to launch 20 large-scale

[23] http://www.greengen.com.cn/en/aboutus_02.htm, accessed on 30 September 2009.

demonstration projects by 2010, with a view to starting broad (commercial) deployment by 2020. As for the International Energy Agency, it strongly supports CCS as an important abatement solution, as argued in IEA (2008b) and cited in the introduction of this report.

Taking a broader perspective, it is possible to identify the interest of countries in the technology according to their general national energy strategies, their income level and their geographical endowments. Essentially, high-income countries that are relatively abundant in coal have expressed strong interest in CCS, notably Australia, the United States and Germany. Poland's position has also become rather positive after some initial hesitations. China seems very interested as well, however Russia seems quite detached from the debate (although it endorsed the G8 declaration). Countries that have good storage potential, e.g. depleted oil and gas fields, have likewise expressed strong interest, e.g. Norway, the United Kingdom and the Netherlands. Another category of country that has, in the main, expressed positive views about CCS are the oil-producing countries of the Persian Gulf, notably Saudi Arabia and Kuwait. Venezuela on the other hand has made common cause with Brazil in opposing CCS *in the CDM*, citing similar reasons. India, as well as a number of small developing states and micro-states have also expressed opposition to CCS *in the CDM*, implicitly favouring projects and aid on renewables, waste management and efficiency instead. However some of these countries have pilot CCS projects on their territory, notably Brazil.

Within the European Union the pattern is less extreme. Member states can choose freely whether or not to develop a storage site on their territory, as well as their own prioritization between renewables, energy efficiency and CCS. This enables the somewhat more sceptical (or less interested) member states to support the regulatory and legal work for CCS at the EU level, while negotiating for good conditions for renewables and efficiency projects (according to two interview respondents this is how Austria's position has been interpreted).

At the EU level support is strong. DG Energy sees CCS as a very important component of both energy and environmental policies that helps to solve several important problems, i.e. emissions reductions in Europe and globally, and energy security concerns. (A similar position has been expressed by the US authorities, using both arguments. Also, US interest in the technology is reasonably bi-partisan.) DG Environment and DG Research have also been very supportive of CCS in many ways. As for the European Parliament, it has tended to produce quite clear majorities in favour of texts that contained measures favourable to CCS.

VI.2 Private corporations

The vast majority of Western energy companies, regardless of what part of the energy industry they are involved in, have expressed active interest in CCS and a readiness to invest as soon as the right incentives are in place. The major oil and gas companies on both sides of the Atlantic have expressed interest especially in storage projects and have formed a lobbying platform to that effect called the ‘CO2 Capture Project’. The most prominent members of that platform are BP, Chevron, ConocoPhillips, Eni, Petrobras, Shell and StatoilHydro. The platform is supported by the US government (Department of Energy), the Norwegian government (Research Council) and the European Commission.

The other consortium of private companies (and other groups) that must be mentioned is the European Platform for Zero Emission Fossil Fuel Power Plants (ZEP). ZEP is one of the several European Technology Platforms that have been set up in recent years with encouragement and support from the European Commission (DG Research).

ZEP is an impressive group as it lists among its sponsors the entire range of EU companies that would be interested in CCS. ZEP is supported by Eurelectric (the official federation of electricity producers in Europe) and VGB Powertech e.V., a very large federation of electricity and heat industry companies, in addition to two federations of suppliers of parts for thermal power plants (EUTurbines and EPPSA – the European Power Plant Suppliers Association). In addition, some of the major energy companies mentioned earlier are also sponsors of ZEP, namely BP, Shell and Statoil, in addition to Total and Schlumberger. The work ZEP does is organized in taskforces of experts mainly from private companies, from research institutes and universities and from EU governments. The lists of taskforce participants available from the ZEP web-site suggest that it is the leading CCS organization in Europe (if not in the world) given the number of experts that work for them and the diversity of institutions and companies they represent.

A few additional corporations are worth mentioning separately. Vattenfall, a Swedish energy company, is one of the technology leaders in carbon capture and has made a strong impression with the launch of an *integrated pilot plant* (reportedly the world’s first) at Schwarze Pumpe in Germany in 2008. McKinsey is also very prominent in the CCS debate. Its 2008 report on the economics of CCS had a very strong impact and has been cited very favourably by Commission officials as well as by other stakeholders (including some of the experts interviewed for this report). McKinsey and Vattenfall moreover collaborate on other influential publications concerning environmental economics.

To conclude on the corporate sector, the general picture that seems to emerge is that of a nascent technology with many potential actors. The usual caveats apply in terms of corporate lobbying of governments and of ‘optimism bias’. It is however not possible to assign the enthusiasm for CCS to a narrow interest group.

VI.3 Non-governmental organizations and civil society

With non-governmental organizations the balance of the debate is more divisive, particularly among environmental movements. None of the major environmental groups feel entirely comfortable with CCS, as it is a solution that doesn't fit with their longer-term vision of an entirely new energy system based solely on renewable sources of energy. That said, it is relevant to note the very different positions of Greenpeace and WWF. Greenpeace has decided to oppose CCS completely. Its main argument is that CCS will begin working too late, and as such constitutes an unwelcome diversion and delay from the shift in favour of renewables. WWF on the other hand considers that CCS is a 'necessary evil', because, in its view, fossil fuels cannot realistically be phased out quickly enough. WWF therefore subscribes (more-or-less) to the mainstream view that holds that CCS is the necessary bridging technology that can hold down emissions given that countries such as China will use coal to a massive degree in the next decades. However WWF strongly supports deep cuts in emissions and a strong focus on renewables and on efficiency measures wherever possible.

Nevertheless, all the major environmental groups share a concern that a loophole may be in the making in some countries due to the use of the concept of 'capture ready' coal-fired plants. The idea is that coal-fired plants commissioned today should be 'capture ready', in other words, not equipped with CCS, but built in such a way that, at some stage in the future, when prices are right, they can be retro-fitted. Environmental groups fear that this is a tactic to soothe public opinion, and that the necessary retro-fitting may never materialize, as uncertainties about the commercial viability of CCS remain. Accordingly, Friends of the Earth (while accepting CCS-fitted coal-fired plants for the future) demands from the UK government that no new coal-fired plants should be commissioned without CCS.

Another development, which so far only concerns the United States, is a more active backlash against 'clean coal' which has involved celebrity film directors (the Cohen brothers) with some backing from former Vice President Al Gore. The debate in the United States is somewhat different to the European debate, as the label 'clean coal' has been used to refer only to the partial removal of sulphur oxide and nitrogen oxide emissions. But since CCS is not yet in operation, and given other environmental concerns notably with respect to coal mining techniques, the promotion of coal under the name 'clean coal' now seems rather unfortunate. In Europe, on the other hand, while environmental groups naturally express their opinion (and at times disapproval) with respect to CCS, it is generally recognized that public awareness is low. Proponents of CCS, presumably, are concerned that this vacuum could be easily filled with negative perceptions about environmental and public health aspects of CCS. That said, the debate among environmentalists so far – even in the United States – is not fundamentally defined by hostility to CCS.

VI.4 Academics

A number of scientists from Austrian technical universities were interviewed specifically for the purposes of this report. A brief overview of the views expressed are summarized here.

None of the scientists interviewed were strongly sceptical or thought that one or more parts of the CCS value chain would not work technically. All of them however pointed out that a number of uncertainties remain both at the capture stage and at the storage stage. Transport raised fewer comments, and was generally considered to be less problematic, if at all. Several respondents expressed the hope that CCS would be applied to natural gas as well as to coal. Respondents differed in the time horizon for commercial deployment of CCS. Two respondents believed that commercial deployment could already start in 2020, one believed that 2030 was more realistic, and one other thought that the possibility of CCS not working at all at the commercial level should not be dismissed, but that this would become clear during the demonstration phase, so that by 2020 one would either start deployment or drop CCS altogether. Implicitly, most respondents assumed that CCS will be commercially deployed, given reasonable assumptions about carbon prices. Also, one respondent pointed out that the technology, notably in terms of overall thermal efficiency, has improved relatively rapidly over the last few years. While this should not be an exercise in trend prolongation, the implication was that the efficiency limits have not yet been reached.

Respondents were relatively optimistic about storage, while insisting on the importance of adequate selection and monitoring efforts. In the case of underground storage, one respondent stated that seepage from well-chosen sites could be below 0.1% in total in the absence of adverse external events. Another respondent stated that long-term seepage was difficult to assess and preferred not to give a quantitative estimate. Respondents also pointed out the local health hazards (asphyxia, death) in case of a sudden and substantial release of CO2 (e.g. pipeline breach, well failure).

VII Conclusions

It is now well understood that there is a narrowing window of opportunity to turn the global energy system around before benign climate change turns into dangerous climate change. Infrastructure investments, notably in power generation, heavy industry, transport and the residential sector, have relatively long lead-times and, crucially, long life-times once they are completed.

Carbon capture and storage has been described by the IEA as a key carbon abatement option. As is clear from scenario projections of emissions from coal-fired power generation, notably with reference to Chinese growth patterns over the next decades, it is difficult to think of a more powerful solution – partial though it might be – to help curb global emissions growth.

At the level of the European Union there are, to some degree, conflicting interests. CCS is a potentially fundamental plank of national energy policy for the countries of North-West Europe. To a lesser extent, Italy, the Czech Republic, Poland and Spain may also develop an increasing interest in the technology. For certain other member states, especially those that have both very low coal reserves and a lack of suitable storage sites, CCS cannot come across as particularly important, while renewables and/or nuclear power should. Those differences need not however lead to strong differences in opinion between member states. EUAs from the new entrants' reserve, as well as funds for economic recovery, have been allocated for both CCS and innovative renewables projects. This balanced approach is important. Just as much as the IEA (among others) identifies CCS as a key option, it also identifies renewables and efficiency improvements as the other two key challenges that countries world-wide should focus on.

The core message from the present study is that CCS is gathering momentum and benefits from wide (and deserved) support. While many uncertainties remain, CCS is too promising an option not to be attempted on a commercial scale in the near future. Legal and institutional frameworks that are still lacking should therefore be dealt with so as to enable market forces to move forward.

The most important conclusion, however, concerns fundamental economic principles. While some special support, particularly in times of economic crisis, for the nascent industries of tomorrow is interesting, justified and important, the risk of distortions to the carbon market should not be overlooked. The key to the success of the European Union's broader commitments in terms of emissions reductions lies in an undistorted EU ETS supported by solid, unflinching and of course binding emissions caps. CCS will have the successes (and the failures) that it deserves, as will renewable energy.

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Appendix A

Table A1

List of active CCS projects

Project Name	Location	Leader	Fuel	Size MW	Capture	CO2 Fate	Start-up
Schwarze Pumpe	DEU	Vattenfall	Coal	30	Oxy	Seq / EOR	2008
Pleasant Prarie	USA	AEP	Coal	5	Post	Seq	2008
AEP Alstom Mountaineer	USA	AEP	Coal	30	Post	Seq	2009
Total Lacq	FRA	Total	Oil	35	Oxy	Seq	2009
Callide-A Oxy Fuel	AUS	CS Energy	Coal	30	Oxy	Seq	2009
Williston	USA	PCOR	Coal	450	Post	EOR	2009-15
GreenGen	CHN	GreenGen	Coal	250/800**	Pre	Seq	2010
Kimberlina	USA	CES	Coal	50	Oxy	Seq	2010
Brindisi	ITA	Enel &Eni	Coal	660	Post	Seq	2010
AEP Alstom Northeastern	USA	AEP	Coal	200	Post	EOR	2011
Plant Barry	USA	MHI	Coal	25	Post	Seq	2011
Sargas Husnes	NOR	Sargas	Coal	400	Post	EOR	2011
Scottish & S. Energy Ferrybridge	GBR	SSE	Coal	500	Post	Seq	2011-2012
Naturkraft Kårstø	NOR	Naturkraft	Gas	420	Post	Undecided	2011-2012
ZeroGen	AUS	ZeroGen	Coal	100	Pre	Seq	2012
Antelope Valley	USA	Basin Electric	Coal	120	Post	EOR	2012
Appalachian Power	USA	AEP	Coal	629	Pre	Undecided	2012
Teeside	GBR	CE	Coal	800	Post	Seq	2012
WA Parish	USA	NRG Energy	Coal	60	Post	EOR	2013
Wallula Energy Resource Center	USA	Wallula Energy	Coal	600-700	Pre	Seq	2013
RWE npower Tilbury	GBR	RWE	Coal	1600	Post	Seq	2013
TCEP	USA	Summit Power	Coal	600	Pre	EOR	2014
Trailblazer	USA	Tenaska	Coal	600	Post	EOR	2014
HECA	USA	HEI	Petcoke	390	Post	EOR	2014
UK CCS project	GBR	TBD	Coal	300-400	Post	Seq	2014
Statoil Mongstad	NOR	Statoil	Gas	630 CHP	Post	Seq	2014
Bow City	CAN	BCPL	Coal	1000	Post	EOR	2014
NZEC	CHN	UK&China	Coal	Undecided	Undecided	Seq	2014
Janschwalde	DEU	Vattenfall	Coal	500	Oxy & Post	EGR	2015
RWE Goldenbergwerk	DEU	RWE	Coal	450	Pre	Seq	2015
AMPGS	USA	AMP	Coal	1000	Post	Unknown	2015
Boundary Dam	CAN	SaskPower	Coal	100	Oxy	EOR	2015
Meri Pori	FIN	Fortum	Coal	565	Post	Unknown	2015
Nuon Magnum	NLD	Nuon	Various	1200	Pre	Seq	2015

Note: Only projects with a publicly announced start-up date or timeframe were selected.

Source: Carbon Capture and Sequestration Technologies Program at the Massachusetts Institute of Technology (MIT). http://sequestration.mit.edu , status as of 16 September 2009.

Appendix B

Acknowledgements

The author wishes to thank the experts and stakeholders who agreed to be interviewed during the preparation of this report. Some respondents preferred to retain full anonymity (marked as ‘X’ below). In those cases the corresponding institutions are identified if they are large enough to have more than one potential respondents on the topic of CCS.

The views expressed by the respondents were used as background information only. Institutional views, where reported, derive from an observation of publicly available documents. Any mistakes are the responsibility of the author of this study.

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X	X
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