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SECURE

Security of Energy Considering its Uncertainty, Risk and Economic Implications

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Carbon Capture, Transport, and Sequestration (CCTS) – The Future of Coal in Europe?

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Executive Summary

1. This report summarizes the findings of Work Package 5.3 of the Secure project, with regard to the role of carbon capture, transport and storage (CCTS) for the future of European coal supply security. The executive summary puts forwards one main thesis: CCTS is the real threat to European supply security with coal. This thesis is substantiated in the subsequent report, with more technical details and some case study evidence.
2. The real issue in European supply security regarding coal is the absence of an economically and politically sustainable use of the coal for electricity, liquefaction, gasification, etc. Whereas earlier deliverables in this Work Package 5.3 “Coal Sector” have indicated that there are few risks for European energy supply with (steam) coal, there is an implicit supply security threat, i.e. that coal will no longer be an essential element of European energy supply because the CCTS roll-out will be delayed or not be carried out at all.
3. According to the IEA “Technology Roadmap” the next 10 years are a critical period for CCTS (IEA, 2009). There is a real danger that the ambitious development plans in CCTS demonstration over the next decade will not be met. This is due to a lack of determination of public authorities to overcome the significant obstacles inherent in CCTS, and the difficulties of industry to embrace a technology that might challenge the business model of coal electrification. Also, the business model of CCTS-plants (base-mid load) is incompatible with the dispatch of a largely renewable based electricity system that values flexibility more than base load.
4. The extensive database assembled in this work package indicates that real progress in CCTS has been slow over the past five years. Among the 62 CO_2 capture projects, only 7 pilot projects are operating on the pilot scale. By contrast, large-scale demonstration projects that were envisaged, e.g. in the US (SuperGen) and the UK tender have been delayed. It remains to be seen whether the European Recovery Programme will be able to kick start the development of six large capture projects.
5. While each individual element of the CCTS-chain seems to pose no major obstacles, the technical, financial, and institutional structures of the entire chain poses significant challenges. From a technical side, the choice of the capture technology and the environmental impacts thereof (e.g. amine use in post-combustion) are still open. Financially, it is impossible to provide cost estimates for the system as a whole, making a serious economic assessment of the future role of CCTS difficult. From an institutional perspective, questions of ownership, regulation, and responsibility are wide open.
6. The industrial feasibility of CO_2 capture out of a gas mixture no longer needs to be demonstrated as it is state of the technology in the ammonia industry, hydrogen production or natural gas processing. However, up scaling of the technology and the treatment of gases containing

impurities still needs dedicated effort in terms of research and development. It is too early to name the CCTS technology as a "silver bullet" against climate change.

7. The total costs of CCTS remain uncertain in the absence of large-scale pilot plant successful operating. Evidence from related technologies (NO_x or sulfur removal) has shown that an initial cost increase during the diffusion phase is likely due to new standards ore advanced technological concepts. Additionally, the carbon price risk, further increases uncertainty on future benefits of CCTS. Policies should address this issue by establishing a credible carbon price path in the future high enough to incentivize CCTS investment, which is valid for most of the innovative low-carbon energy technologies.
8. Major institutional obstacles to CCTS are the regulation of the transport infrastructure, and issues of storage. In a perspective of 2050, it is likely that an integrated network is the least-cost perspective for CO_2-transport. Future regulation needs to specify the allocation and financing principles, and access for 3rd parties. In particular, it is unlikely that the private sector alone has sufficient incentives to care for the network development. Low cost storage capacity such as depleted fossil fuel reservoirs is scarce and increases the possibility of players to exhibit market power. Regulation should aim at providing not only 3rd party access to the pipelines but also to storage. What seems even more critical is the rising public rejection of onshore storage. In case of evasion to off-shore storage, the total costs of CCTS would further increase.
9. The European emission trading scheme has proven not very effective when it comes to fostering innovation in the energy sector. The short term planning horizon of the scheme and other design issues result in uncertain but volatile carbon prices which have failed to overcome the inertia of the sector. This is characterized by large-scale and long-lasting investment, a concentrated industry and risk averse players. Therefore, complementary policy instruments are required to fulfill the two targets, emission reduction and technological change.
10. Sufficient financial incentives are currently provided to kick-start large demonstration projects, so that "money plays no role". Governments have earmarked significant financial resources. The stimulus packages following the economic crisis have accelerated already ongoing tendencies. Among the major OECD-countries pursuing CCTS projects, there is at least $ 13.5 bn. available for supporting early CCTS-projects. Governments have even problems in disbursing the money, due to hesitation of actors to go forward. Thus, the € 1.05 bn. earmarked in the EU economic recovery program for six CCTS projects may be "saved" since they are unlikely to be disbursed by summer 2010.
11. In addition to the technical, financial, and institutional aspects there are also obstacles to CCTS-diffusion due to market structure considerations. The study by Geske and Herold (2010) highlights the problem of the CCTS-business model in a liberalized, largely renewables based electricity market. Applying a real options approach, the authors insist on the role of a stable and

high CO_2-price that is required to make investing into and operating a CCTS installation financially viable. What is more, given the high uncertainty about prices and technology, companies have a natural tendency to delay investments in capture, transportation, and storage technology.

12. An additional inherent obstacle is the current market structure, with a large number of incumbent coal burning enterprises, and an oligopoly of carbon capture equipment suppliers. A break-through of CCTS would challenge a lucrative model for both sides (equipment suppliers and utilities). Thus, one should not count on incumbent coal burning utilities to push significantly for CCTS.
13. Based on the above analysis, we derive the following policy conclusions:
    - If CCTS deployment continues at the current, slow pace, there is a real danger that European coal supply security be in danger. Therefore, the conventional policy measures, such as laid out in detail by the IEA (2009) Roadmap, should be continued, and accelerated, but also be complemented by more consequent measures, such as obligatory carbon-capture ready technology, and active state involvement in pipeline development.
    - There is no reason to delay CCTS demonstration projects any longer. The readily available billions of Euros and Dollars should be rapidly implemented. In cases where industry does not respond, the level of incentives needs to be raised to a reasonable level. If there is still no reaction, pilot demonstration projects should be carried out by public research institutions or additional support instruments should be thought.
    - The financial uncertainty surrounding future projects should be reduced. In the absence of clear CO_2 price corridors and signals, regulatory certainty can be created, e.g., by obliging new power plants in include a “capture-ready” option.
    - Whereas CO_2 capture should be left to industry, the state bares a crucial role in the development of the transportation and storage infrastructure. CO_2-transportation infrastructure should be sited and the necessary planning steps be carried out. The execution of the construction and operation can be tendered to the private sector, or carried out by a state-owned network company. Synergies with the other energy network infrastructure (gas, electricity) should be considered.

1 Introduction

Over the last years, coal use has risen at a rate of 4.9% per year despite increasing awareness of the greenhouse gas problem (WCI, 2010). Carbon capture, transport and storage (CCTS) could provide a link bringing together the use of fossil fuels and CO_2 emission reduction. The Intergovernmental Panel on Climate Change (IPCC, 2005) has concluded that CCTS can contribute between 15-55% of the cumulative emission reduction effort to 2100, providing it with a central role within a portfolio of low carbon technologies needed to address climate change. The International Energy Agency (IEA 2008) analyzed a number of global GHG reduction scenarios and concludes that CCTS is “the most important single new technology for CO_2 savings” in both power generation and industry. The IEA found that attempting to stabilize emissions without CCTS is estimated to be 71% more expensive; equivalent to US$ 1.28 trillion annually in 2050. According to the IEA (2009) “Technology Roadmap” the next 10 years are a critical period for CCTS (IEA, 2009). In the IEA “Blue Map” scenario, total investment into 100 capture plants, a minimum of 10,000 km of pipelines and storage of 1.2 $GtCO_2$ are required to make CCTS a serious abatement technology by 2050.

There is a real danger that the ambitious development plans in CCTS demonstration over the next decade will not be met. Our extended CCTS project database shows that the 2020 IEA target won’t be reached if things continue on the speed and scale observed over the past decade, although things have accelerated. This is due to a lack of determination of public authorities to overcome the significant obstacles inherent in CCTS, and the hesitation of industry to embrace a technology that might challenge the entire business model of coal electrification. Also, the business model of CCTS plants (base- and mid-load) is incompatible with the dispatch of a largely renewable based electricity system that values flexibility more than base load.

Concretely, this may lead to a supply security “paradox”: while sufficient coal is available worldwide, and can be supplied to Europe without major dangers of disruption, the use of this coal for electrification and other purposes may be restricted, because the failure of CCTS provides a barrier to continued traditional use of coal.

This deliverable is structured in the following way: Chapter 2 outlines unresolved technology questions which need to be answered so that CCTS can become an effective CO_2 mitigation option. In Chapter 3, we compare the requirements on CCTS demonstration projects outlined in the IEA Blue Map scenario with the actual state and show that there exists a serious gap. Given the various barriers on the market for innovative energy technologies we draw on instrument complementary to the European emission trading scheme to accelerate the diffusion of CCTS in Chapter 4. Chapter 4.2.5.2 summarized global CCTS demonstration projects. An extensive CCTS project database is attached in the Appendix.

2 Unresolved Issues along the Value-Added Chain

The near term technology options available for carbon capture, transport and storage are well known on a smaller or medium scale, on component level or from applications different to CCTS. The up-scaling of the technology and application to large CO_2 emitters like coal fueled power plants raises new questions which can only be answered in demonstration projects.

2.1 Upstream: CO_2 capture

The capturing of CO_2 is done for a couple of decades in the chemical industry, but also in the energy sector. Near-term available technologies, such as post-combustion and pre-combustion capture and the oxy-fuel technology differ in maturity and have thus different time horizons of commercial availability. We will focus on these 1st generation capture technologies only.

The choice for the appropriate capture technology is mainly driven by the fuel and the resulting CO_2 concentration in the flue gas (Table 1).

Table 1: CO_2 concentrations and pressure of different combustion cycles

Flue gas	CO_2 concentration $\%_{vol}$ (dry)	Pressure of gas stream [bar]
Natural gas fired boilers	7-10	1
Gas turbines	3-4	1
Oil fired boilers	11-13	1
Coal fired boilers	12-14	1
IGCC after combustion	12-14	1
IGCC synthesis gas after gasification	8-20	20-70
IRCC synthesis gas after reforming	13-17	20-40

Source: Betz et al. (2005)

2.1.1 Post-combustion capture

The post-combustion technology was first applied in the 1980s for the capture of CO_2 from ammonia production plants. The captured CO_2 is used in food production e.g. to carbonate soft drinks and soda water. Post-combustion chemical absorption technologies represent one of the most commercially available CO_2 capture technologies. However, the technology is used only for the treatment of very clean gas mixtures containing no or few impurities such as dust, SO_x, NO_x (Kanniche et al., 2010). Plants operating are capable of capturing between 1000 tCO_2/d, up to 4000 tCO_2/d. To comply with the emissions of a 1 GW lignite power plant up-scaling to 13 $ktCO_2/d$ would be required (Vallentin, 2007).

The CO_2 is separated from the flue gas by passing through a continuous scrubbing system. The system consists of an absorber and a desorber. Absorption processes utilize the reversible chemical reaction of CO_2 with a solvent such as Monoethanolamin (MEA). The physical absorption in a pressure swing absorption-desorption system (Benfield process) avoids the use of the toxic, environmental hazardous and highly corrosive chemical MEA. However, this process requires higher pressure (15 bar) and concentrations of CO_2 in the flue gas (>10%). Calculations by Kothandaraman et al. (2009) conclude that for a CO_2 content of 12% in the flue gas, the minimum reboiler load without energy recuperation is 0,88 MWh/tCO_2. Due to the high pressure requirements and impurities in the flue gas this process is mainly applicable to IGCC and IRCC plants. The MEA process in comparison is calculated to require at least additional energy for the reboiler of 1.17 MWh/tCO_2. Including compression, this corresponds to a loss in thermal efficiency of a coal fired plant of 25%.

The high compatibility to existing power plants (retrofitting) makes this technology the most attractive mid-term option.

The chilled ammonia process uses ammonia, a toxic, reactive, and corrosive gas, instead of MEA. The process is carried out at temperatures between 0 to 10°C, therefore cooling of the flue gas is required. The advantage of the process is the lowered energy demand for the desorber, lower than 0.55 MWh/tCO_2 (Darde et al., 2009). In comparison to MEA, the solvent does not degrade and has a high carbon dioxide capacity. A pilot plant that uses chilled ammonia to capture CO_2 was launched by Alstom, the Electric Power Research Institute (EPRI) and American Electric Power in Oologah, Oklahoma, USA. The purpose of the project is to test the process, which was granted a patent in 2006, and to demonstrate low ammonia emission.

To sum up, major problems remaining in the field of post-combustion capture are: impurities in the flue gas, the handling of large volumes of gases, the handling of toxic chemical, the high efficiency losses of the power plant and a further decreased ability to follow load changes.

2.1.2 Pre-combustion capture

Pre-combustion capture refers to the treatment of CO_2 and H_2 after the gasification process of coal, biomass or the steam reformation of natural gas. CO_2 and H_2 can be separated by physical absorption, as the mixture of gases is under pressure and contains of a high concentration of CO_2 (Table 1). The hydrogen fires a gas turbine and a subsequent steam turbine or can be used as fuel for fuel cell vehicles. The gasification process can either be undertaken with ambient air or with pure oxygen. The latter process increases efficiency of the gasification and separation process. However, the separation of oxygen from nitrogen as it is supposed to be undertaken in the oxy-fuel process requires investment into an air separation unit (ASU) and increases auxiliary power.

The physical adsorption process can be based on methanol or dimethylether (Selexol process) as well as on active amine-based chemical solvent (MDEA). The process is less expensive in terms of investment costs and efficiency losses compared to the treatment of a mixture of flue gases as done for post-combustion capture.

Rezvani et at. (2009) estimate the investment costs for a 450 MWe IGCC plant including CO_2 capture and compression to 1602 €/kW to 1909 €/kW depending on the specific technologies applied. The energy penalty, according to Kanniche et al. (2010) is around 22 points, dropping from 43% to 33.5%.

Pre-combustion capture is not applicable to existing power plants other than IGCC or IRCC. Therefore, the technology is mainly an option for industrial applications in the absence of IGCC power plants.

In the US, four IGCC power plants have been constructed with financial support by the Department of Energy (DEO) ranging from 107 to 580MWe. Other plants operate for instance in Italy, Spain, Japan and in the Netherlands.

Table 2: IGCC utilities

Company	Country	Start-up	Size [MWe]	Fuel
Kentucky Pioneer Energy	USA	12/1994	580	High-sulfur bituminous coal and refuse derived fuel
Tampa Electric Company	USA	11/1991	250	-
Pinion Pine IGCC Project	USA	08/1992	107	-
Wabash River Coal Gasification Repowering Project	07/1992	07/1992	260	High-sulfur bituminous coal
ISAB Energy IGC	Italy (Sicily)	1999	512	Asphalt
Elcogas IGCC Power Plant	Spain	1998	335	High ash local coal and petroleum coke
Nippon Oil Corporation Refinery	Japan	2003	342	Asphalt residue
William Alexander plant	Netherlands	1994	253	
Sarlux plant	Italy	2000	548	

Source: Various publicly available data

Due the limited number of power plants operating, the coal based IGCC technology itself is still in the demonstration phase. The main barrier are the high investment costs, e.g. between 1.2 to 1.6m US$ per MW capacity excluding CO_2 capture and compression (EIA, 2009). However, those cost estimations have proven unrealistic, as many IGCC coal projects have come with much higher investment. An example is the 2.156 bn US$ Mesaba Projects (531 MW) (DOE, 2010). If CO_2 would be captured additional investment of 1 bn US$ would be needed for compression, transport and storage infrastructure.

Proven refinery-based plants are not based on coal due to the increasing process complexity, nor do they use the hydrogen for power generation. The high investment costs need to be brought down to a level on which they allow for competition with other capture technologies, e.g. by developing economic and efficient hydrogen selective membranes.

2.1.3 Oxy-fuel technology

The oxy-fuel process aims at the separation of the flue gas before the combustion. CO_2 from conventional combustion processes is present as a diluted gas in the flue gas, resulting in costly capture using e.g. amine absorption. By combusting fuels in a pure O_2/CO_2 atmosphere (up to 60% O_2), one achieves a sequestration-ready gas stream, containing of CO_2 and H_2O. First attempts to develop and apply the technology have been carried out in the 1980s, motivated by the oil industry. Combustion of fuel in a pure oxygen atmosphere is further undertaken in the glass and steel industry to benefit from higher flame temperatures.

The energy efficiency of a coal-fired oxy-fuel power plant is around 8–10 % lower than of air-based systems. This decrease of efficiency is primarily based on the energy consumption for the ASU and the CO_2 compression systems. On the other hand, it is expected that the efficiency can be improved by a better integration of the system components (Buhre et al., 2005).

Oxy-fuel combustion technology can be implemented as a retrofit technology for pulverized fuel boilers; however, it affects combustion performance and heat transfer patterns. There remain a couple of additional open questions. First, the combustion in a pure O_2/ CO_2 atmosphere is not realized. For older power plants the leak air reaches levels of 10%, and for new plants still up to 3%. The presence of incondensable gases (oxygen, nitrogen, argon) in the CO_2 flow transported in the supercritical state can cause vibrations and shock loads in the pipeline, which can cause mechanical damage (Kanninche et al., 2010).

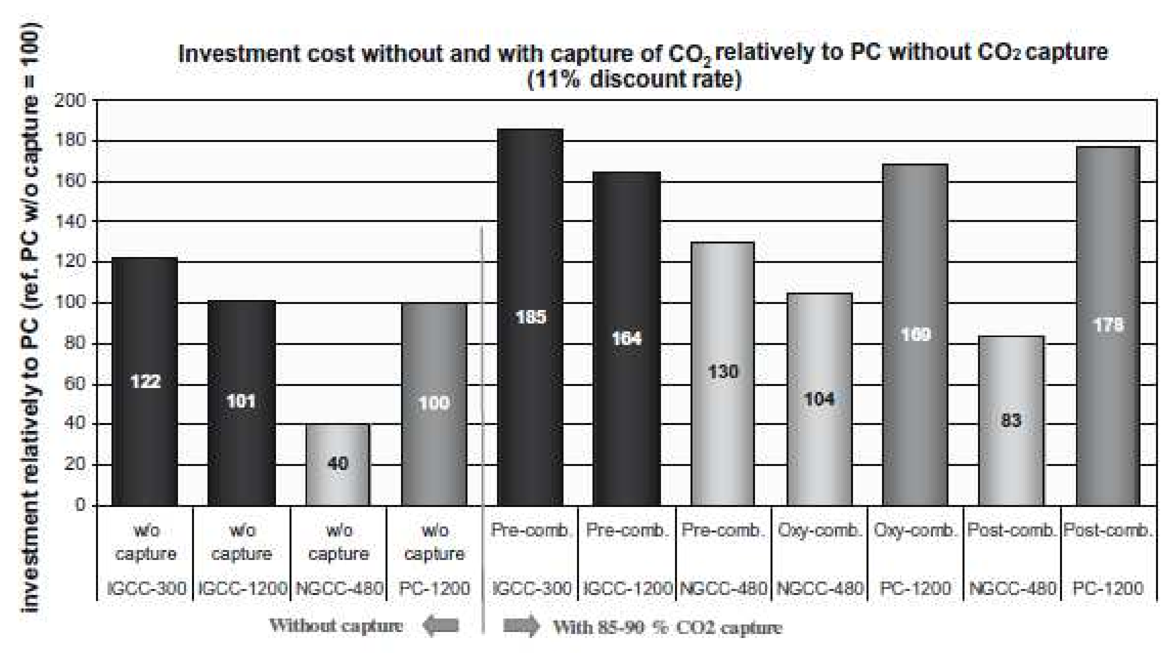
To summarize, open technical questions with regard to the oxy-fuel technology are the reduced efficiency, which may further decrease if additional SO_x removal is required. The technology is not demonstrated on a larger scale, so there may be unforeseen technical problems. The higher temperatures of the flue gas does no longer allow for the electric removal of ash but expensive ceramic filters. It has been proven by Vattenfall that a capture rate of 99% can be reached, yet this increases cost and complexity of the process and a capture rate of 90% is more realistic.

2.1.4 Economics

Due to the energy penalty and the higher capital expenditure of CCTS plants, the costs of electricity production will increase. The true costs of CO_2 abatement by means of CCTS remain unknown in the absence of up-scaled demonstration plants; likewise the expected benefits for electricity producers are uncertain given the uncertainty on future carbon prices. Recent estimations calculate higher costs than it was done a couple of years ago. This is a well known phenomenon observed for a larger number of innovative energies technologies. A study by Rubin et al. (2006) states that the costs for flue gas desulphurization or NO_x removal increased due to new standards and changes in the technology. What is needed most are mid- and large-scale demonstration projects to validate the technology and to illustrate further development paths for this technology.

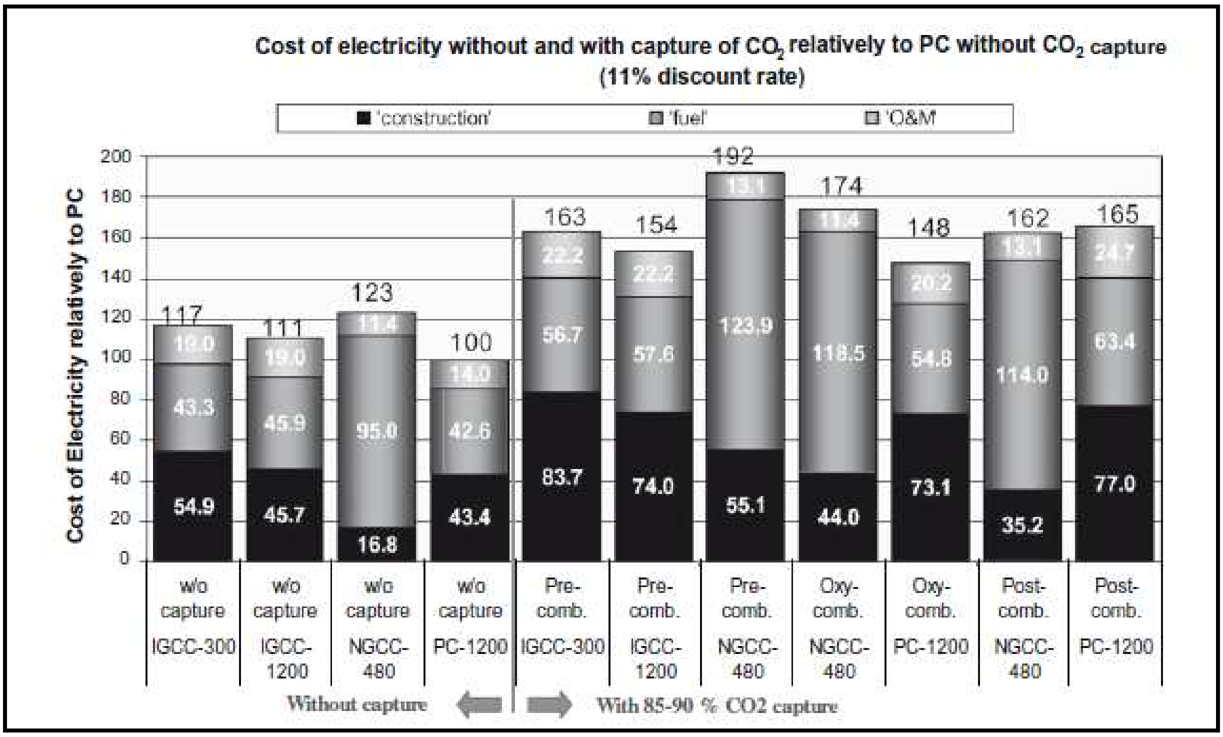
Figure 2 summarizes the estimated mark-up in investment costs for CCTS technologies compared to a standard pulverized coal plant and Figure 2 shows the resulting mark-up in electricity production costs.

Figure 1: Investment cost of different systems with and without CO_2 capture



Source: Kanniche et al., 2010

Figure 2: Production cost (construction, fuel, operation and maintenance) of the different systems with and without CO_2 capture



Source: Kanninche et al., 2010

2.2 Midstream: CO_2 transport

Pipeline transportation is commonly understood as the only economic transport solution onshore which is capable to carry the quantities emitted by large scale sources such as power plants. Transport faces no significant technological barriers and is usually carried out in liquid or super-critical state in order to avoid two-phase flow regimes. CO_2 pipelines, representing a typical network industry, are characterized by very high upfront investment costs. These are sunk in nature and vary between 0.2 million (± 60%) and up to 1 million Euro (± 40%) per km for pipelines with a nominal diameter of 200 mm (1,200 mm), respectively. Variable costs are comparatively insignificant and primarily include expenditures for fueling compressor. In summary, CO_2 transportation costs vary between less than 1 Euro and more than 20 €/tCO_2 being a function of the transportation distance and the CO_2 flow (IPCC, 2005).

Another important question regarding to the future CO_2 sector is the shape of the network and its regulation. In the case of regionally dispersed sources and sinks, and long transport distances, the benefits of a meshed, interconnected pipeline network increases. Such a system is also favorable from a system security perspective and cross border transport and storage of CO_2. The trade-off between point-to-point and meshed CO_2 transport will be an important issue for Europe. Transport over longer distances is likely to become important for the implementation of CCTS in some European countries.

Especially the southern European states lack geological formations suitable for CO_2 on a larger scale. According to Chrysostomidis et al. (2009), an integrated network would offer the lowest average cost per ton of CO_2 if sufficient capacity utilization is achieved relatively early in the life of the pipeline. Without incentives to encourage the development of optimized networks project developers are likely to build point to point pipelines as those offer lower costs for the first movers and a lower capacity utilization risk.

Important regulatory questions concern the ownership of the network, competition regulation and the degree of vertical integration. For ownership, options range from completely private to completely public. High uncertainty about the size and configuration of the pipeline network stems from uncertainty about future policies but also from uncertainty about the suitability of geological formations to sequester captured CO_2. Apotheker (2007) proposes government participation for risk mitigation and to account for the public good character of such a network.

Vertical integration by firms along the CCTS value added chain is a mean to avoid successive monopolies and efficiency losses resulting from double marginalization. Vertical integration might also be used to achieve anticompetitive effects such as the creation of barriers to entry and the strengthening of own market power by rising rivals costs or exacerbating market entry. Those questions correspond strongly to the shape of the future network which remains undefined and requires a quantification and qualification of storage sites on a European level (see Herold et al., 2010).

The transport of CO_2 thus faces a sort of a hen or egg problem know from other network industries: no transport network will evolve until storage sites are identified and the first capture plants are under construction while no investment into CCTS plant can be expected unless legal, regulatory and economic question of the future network are answered.

2.3 Downstream: CO_2 storage

CO_2 injection into reservoirs is done for a couple of decades but only a few operations aim at the permanent storage of CO_2, such as under the Sleipner Field, Norway or in In Salah, Algeria. Storage of CO_2 comes with a portfolio of technology options, yet not all are applicable in Europe due to economic reasons or due to a lack of the required geologic formations. Enhanced oil recovery, practiced for decades in the US, as well as enhanced gas recovery, require oil and gas fields which still hold a significant quantity (60%) of the original oil in place. Alternatively, storage can take place in depleted fields, yet without the monetary benefit of fossil fuel production. As mature oil and gas reservoirs have held crude oil and natural gas for millions of years, they come with a low risk of leakage. However, in the Alberta Basin of western Canada, more than 300,000 oil and gas wells have been drilled, while in Texas more than 1,500,000 wells have been drilled (Celia et al., 2002). As often no records exist on the exact number, location or shape, those wells increase the risk of leakage.

Figure 3 shows estimations on the geographic allocation of CO_2 sinks and sources in Europe, with only limited potential for storage in fossil fuel reservoirs. Storage in saline aquifers seems to hold the majority of the EU storage potential, followed by the storage of CO_2 in coal seams. The enhanced coal-bed methane recovery (ECBM) aims at deep coal seams which cannot be exploited at reasonable cost. Especially China shows a major interest in that technology due to the possible extraction of methane (natural gas) by injecting CO_2 into the coal seam (Vallentine, 2007). One barrier is the swelling of coal after the CO_2 injection which lowers its permeability and thus the amount of CO_2 which can be injected.

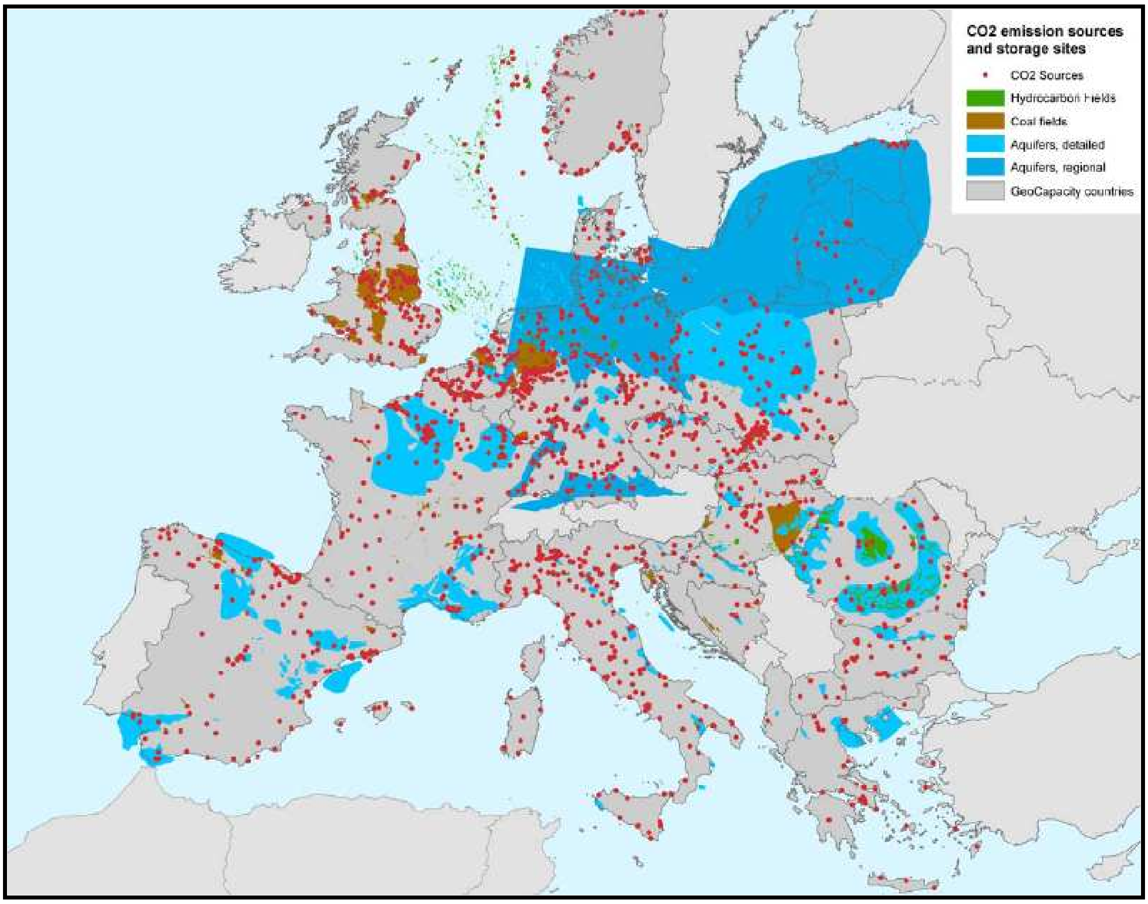
Saline aquifers potentially could hold a storage potential of 1000 up to 10000 $GtCO_2$ (IPCC, 2005). Yet they are also associated with high uncertainty not only concerning their pure physical potential, but also which formation can be used and over which time frame. Saline formations tend to have a lower permeability than do hydrocarbon-bearing formations, and work is directed at hydraulic fracturing and other field practices to increase injectivity. They further contain minerals that could react with injected CO_2 to form solid carbonates. The carbonate reactions have the potential to be both a positive and a negative feature. They can increase permanence but they also may plug up the formation in the immediate neighborhood of an injection well. Research seeks injection techniques that promote advantageous mineralization reactions.

Due to environmental concerns, the storage of CO_2 in the ocean is not seriously considered. Yet, storage in oil or gas fields under the seabed offer an attractive alternative to the “not in my backyard” (NIMBY) problem observed in many countries. Although it might increase acceptance, it comes with costs much higher compared to onshore storage.

The storage of CO_2 in geologic formations requires a sufficient permanence and the complementing monitoring. The IPCC (2005) estimates that up to 600 Gt of carbon could be stored by the end of this century. A 0.1% leakage rate would mean that 0.6 GtC would be released to the atmosphere from storage only. The leakage rate of individual formations is unpredictable and can vary between no leakage and unforeseen high rates. Low leakage is acceptable, but has to be monitored over a time horizon exceeding firms planning horizon and makes governmental intervention necessary. The European Commission has proposed that liability should go over to the public 20 yeas after storage closure. The German proposal for a CCTS legislation suggested that liability should go to the public 30 years after site closure and long-term safety has been proven.

Abrupt leakage could have negative impact on the environment, ecosystems, the accounting of GHG inventories and public acceptance. Ironically the steps along the value chain which inhibit the least uncertainty and risk from a technical point of view, transport and storage, are exposed to the highest level of public awareness and rejection. There is rising concern that the public rejection can form the most stable barrier to the large-scale implantation of CCTS. Potential CCTS actors should focus on this point specifically as there remain only limited and expensive alternatives, such as seabed offshore storage.

Figure 3: Estimated CO_2 sinks and sources in Europe



Source: EU GeoCapacity (2009)

3 CCTS demonstration

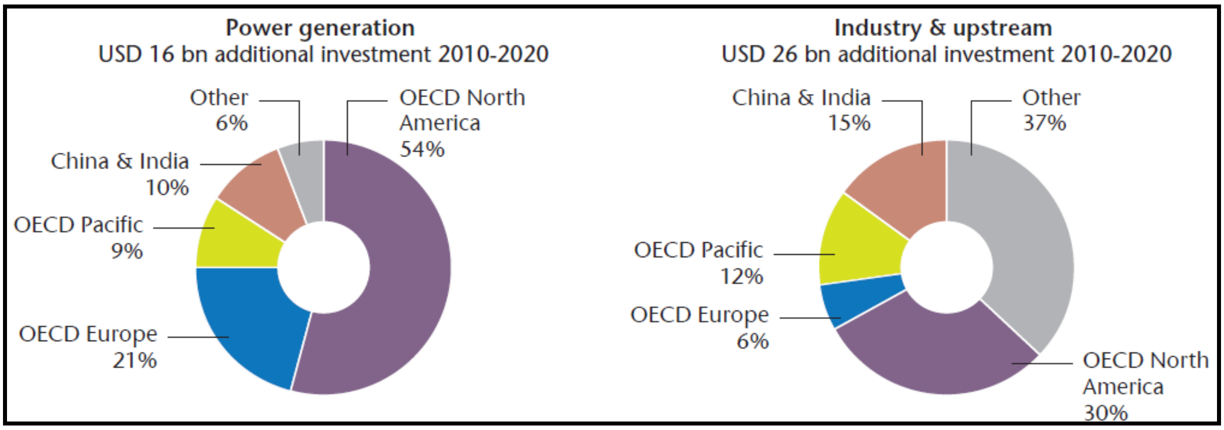
The IEA (2009) has developed a roadmap providing detailed milestones on key developments of the CCTS technology and its environment needed in order to achieve the overall goal of halving the annual CO_2 emissions of 2005 in 2050. To meet the overall CO_2 reduction targets the scenario declares the need for 3400 projects world-wide until 2050. All 3400 projects together demand project investments of trillion 3 US$ which is equal to 3% of the total expenditures needed to achieve the roadmap goal. About half of them will be undertaken in the power generation sector while 14% will be conducted by the upstream sector and the rest of the projects will by situated in the industrial sector. For transportation facilities a demand for 200,000-360,000 km of pipelines is estimated for 2050. In general pipelines are mostly needed in North America, China and OECD Europe where CCTS efforts are highly concentrated. In these regions a cumulated daily transportation capacity of 11.5-14.5 Mt is necessary for 2050. The demand for storage capacity will have to be met by the world-wide development of storage facilities accumulating to 145 Gt CO_2 in 2050. On the technology side the scenario fulfillment requires the commercial availability of capturing facilities with capture rate of >85% for all types of fuel. Moreover all capture systems working on efficiency levels of 45% and beyond have to be equipped with capturing facilities and pulverized fuel ultra supercritical (USC) boilers are ready for commercial use.

In order to enable such a broad application and level of development of the CCTS technology the roadmap also sets milestones for the short term horizon. In line with the announcements of the G8 in 2008 to develop 100 CCTS projects in the period from 2010 to 2020 the scenario calculates with an annual founding of 10 projects per year until 2020. Half of these projects should be situated in North America. Total direct and indirect investments into CCTS will have to cumulate to about 200 bn US$ until 2020. Especially in non-OECD countries CCTS efforts will have to be incentivized. Required funding is estimated to be 1-2 bn US$ per year until 2020. But also in the OECD countries the funding level for CCTS demonstration projects is recommended to rise to 3.5-4 bn US$ per year (

Figure 4).

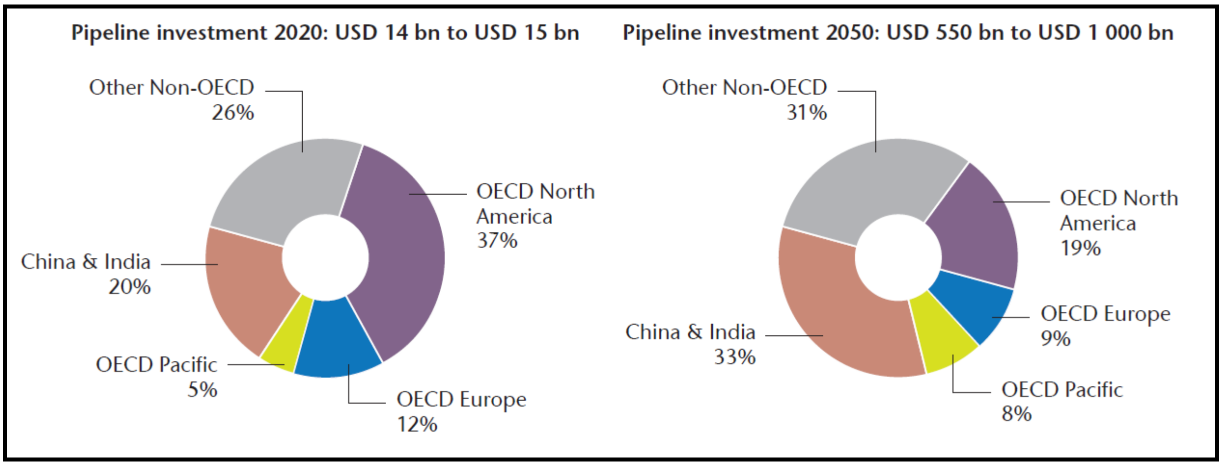
For each step of the CCTS process chain the roadmap sets a list of requirements. At the capturing step a reduction of the power penalty through increased process efficiency and increased operating pressure and heat are determined to be vital for the further development of the CCTS technology. To be in line with the roadmap, large scale power plant application has to be proven by 2015. The scenario calculates with a reduction of the capital cost by 10-12% until 2020 . However, Geske and Herold (2010) show by applying a real options approach that investment into CCTS is mainly driven by stable CO_2 prices and thermal efficiency improvements of the technology.

Figure 4: Additional investment needs for CCTS over the next ten years



Source: IEA, 2009

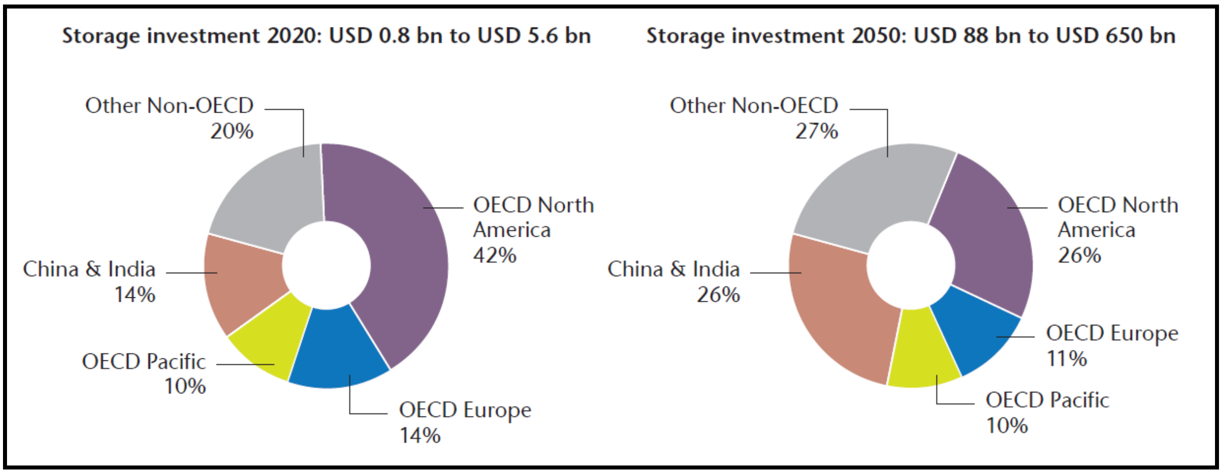
Figure 5: Global CO_2 pipeline development 2010-50



Source: IEA, 2009

Storage exploration is seen as a precondition for broadly deployed pipeline construction efforts. The roadmap recommends the conduction of publically funded exploration programs delivering reliable information especially on capacities of storage facilities accompanied by the definition of safety criteria and respective regulation, all before 2012. In 2020 developed storage capacity of 1.2 Gt CO_2 is required.

Figure 6: Global storage potential and investment by region



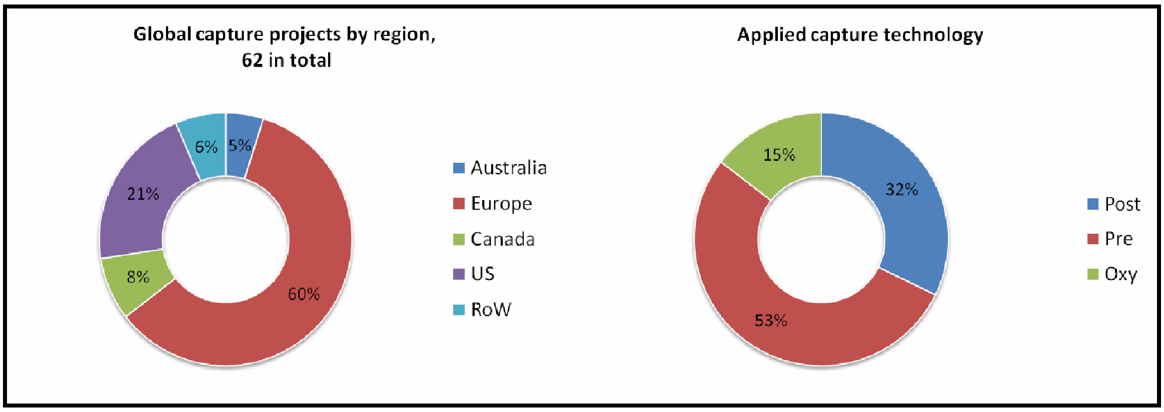
Source: IEA, 2009

The blue map scenario highlights the tremendous need for CCTS demonstration projects which will, according to our database, not be realized by 2020. Of the 62 projects included in our database, only 7 projects are operating. Their size, ranging from 5 to 35 MW_{th}, qualifies them as pilot plants only. Among the several announced projects, only few have entered into the planning process or even have seen the start-up of construction. Our database, build up over the last two years, further indicates a delay in the planning or construction process for most of the projects. Therefore, one critically needs to distinguish between proposed projects on the one hand, and project likely to be realized in the mid-term on the other. Chapter 4.2.5.2 summarizes demonstration projects which will receive public funding and therefore have a high probability of realization if certain milestones are reached. Not all of these projects will test the technology for power generation. For example, the majority of the Canadian projects focus on CO_2 storage (i.e. enhanced hydrocarbon recovery).

Under the assumption that all of the projects in our database will be realized by 2015 there still remains a gap of 40 projects to reach the IAE blue map scenario. This gap is even higher with respect to the local projections. Only Europe could reach the IEA forecast by 2020 given the number of announced projects (see also Figure 7).

The IEA requires global investment of 57 bn $US until 2020. Governments have already committed at least between 13.5 bn US$ to 16 bn US$, depending on the revenues from EU emission allowances. It remains to be seen whether the European Recovery Programme will be able to kick-start the development of six large capture projects.

Figure 7: Global storage potential and investment by region



Source: Own depiction

4 Incentivizing CCTS at the European Level

Innovations do not fall like manna from heaven, nor do they enter a market by themselves. It requires dedicated effort in each phase of technological maturity - research, demonstration, deployment and diffusion - to successfully introduce a technology. Governments can support this process by applying instrument helping to overcome not only technology specifics but also other market barriers.

4.1 Market barriers

The energy sector is characterized by a high level of inertia of the current system with less chance that big changes can be expected in the short or medium term. Energy markets depend on highly specific infrastructure, which lowers compatibility of new technologies and they often are characterized by significant market distortions. Energy policies support standard fossil fuel technologies despite the GHG problematic and other externalities. Electricity markets usually are rather concentrated industries with limited number of firms. Less competition also means less pressure of staying ahead of competitors. Despite the ongoing liberalization of electricity markets, the industry remains highly regulated. This further lowers incentives to innovate as there is a risk that the regulator may prevent firms from reaping the full benefit from successful innovation. Innovation and diffusion of new technologies are highly related to uncertainty arising out of incomplete information. Firms involved in R&D face rather skepticism about their own success among investors who will demand a higher risk premium. This in turn could result in illiquid capital markets for funding the technological development process. (Jaffe et al., 2005).

Information is a public good. The innovating firm hence creates knowledge externalities, so-called spillovers. As a consequence, innovators cannot reap the total benefit from their R&D efforts while still bearing all costs. According to Reis and Traca (2008: p589), ”it is by now established wisdom that lack of appropriability of the returns from R&D is a key deterrent to innovative activity and, therefore to economic growth.” Politics can respond to that market failure by enforcing private property rights or by funding innovation.

Fischer (2007) however concludes that policy support is only justified if some spillovers are given and at least a moderate pollution internalization policy is in place. Thus, an intense R&D policy cannot necessarily compensate for a deficient internalization policy. Both instruments need to be understood as complementary to achieve long-term environmental protection through technological change.

4.2 Shortcomings of the European emission trading scheme

According to Jaffe et al. (2005), “market failures associated with environmental pollution interact with market failures associated with the innovation and diffusion of new technologies”. The objective of the European emission trading scheme (EU ETS) is often associated with two targets: first, to limit emission in an efficient way among sectors and economies and second to promote technological change in greenhouse gas (GHG) intensive sectors. We argue that the second objective is not achieved by the ETS alone and additional policy instruments are required to promote technological change on the desired scale and speed.

The EU ETS has shown as insufficient to set incentives to innovate and invest into large scale technologies such as CCTS. This is based on several shortcomings in the current design, which call for additional policy instruments. These shortcomings are the short term trading periods, a grandfathered over-allocation, and national instead of a European allocation plan which result in low but volatile markets prices (Groenenberg and de Coninck, 2008). Thus, firms avoid investment into high risk, high cost long term technology. Raising carbon prices to a level at which they alone would induce technological change in the short-term is likely doomed to fail due to the political reality. Therefore, a portfolio of additional instruments to compensate for the shortcoming of the EU ETS and to incentivize investment into CCTS is discussed.

4.2.1 CCTS obligation

Technology obligations, in contrast to a given emission level which limits pollution, specify the type of abatement equipment or method to be used. A technology obligation therefore rules out by definition that firms select and use the least-cost abatement method. They also come with the highest risk of technology look-out and the risk of picking losers. In this case, a technology may turn out to be only second best compared to alternatives but due to the obligation, a major investment has been undertaken in the past. Then, switching to the socially desired alternative would turn that investment into a sunk cost, thereby increasing the costs for the alternative, yet socially desired technology. To limit that risk, the CCTS technology should be made mandatory only if a portfolio of capture technologies is proven. A general obligation can raise the system costs for CCTS drastically by forcing electricity producers to apply the technology in areas where no sufficient storage capacity is given.

Another option is the obligation to build all new power plants as capture-ready. This raises the plant costs only moderately, but guarantees that a high number of power plants are compatible to a more mature CCTS technology in the future. The UK adopted this approach, mandating all new-build power plants greater than 300 Mw to be capture-ready.

4.2.2 Low-carbon portfolio standard

Portfolio standards are an obligation for consumers or retailers to source a minimum percentage of their electricity from specific sources or fuels (Groenenberg and de Coninck, 2008). They are often combined with tradable permits, thus increasing flexibility and reduce compliance costs. A portfolio standard burdens all the costs and risks upon the electricity producers, which will pass it onto the consumers. In the UK, a portfolio standard for renewable energy has proven as less effective to promote investment into wind energy compared to feed-in tariffs approaches in other countries. Due to the nature of tradable certificates, investors are exposed to market risk. As long as the price for the certificates remains high, investment will occur. This eliminates the shortage of CCTS-based electricity and the prices will go down eventually. Taking into account the price risk, investors tend to apply the cheaper and better established technology, which lowers pressure to further innovate (Butler and Neuhoff, 2004).

Portfolio standards set very strong incentives to cut down costs and develop a technology further, but also imply the risk of picking losers. Therefore, this should be seen as an option if the CCTS technologies have reached a sufficient level of market maturity.

4.2.3 Feed-in tariff

A feed-in tariff (FIT) guarantees either a fix price or a market premium for CCTS-based electricity feed into the grid. Feed-in systems have proven very effective in stimulating investment in renewable generation technologies, as evinced by the fast expansion of wind-power generation in Denmark, Germany, and Spain. Feed-in schemes are simple and transparent and can be adjusted according to political targets. They provide private investors with a reliable long-term perspective and have impressively attracted investments in the renewable energy technology sector (Groenenberg and de Coninck, 2008).

To compensate for the risk of over- or under-shooting a target, the tariff should be linked to a minimum or maximum level for the amount of low carbon electricity compensated. Continuously downward adjustment of the tariff ensures high pressure for further innovation and cost reduction. According to the design, FIT can put the cost burden either on the electricity consumers or the tax payer, which could be quite high as evidence from the German renewable sector shows.

4.2.4 Carbon price guarantee

Under the EU ETS captured and stored CO_2 is counted as not emitted and CCTS installations will not be provides with emission allowances. Otherwise, a too large number of permits could flood into the carbon market, lowering the price and cannibalize future investment incentives into low-carbon energy technologies. A carbon price guarantee would compensate investors for the price risk for the tradable CO_2 emission certificates by offering the option to sell excess permits at a fixed price to a public authority. By doing so, the carbon price risk is burdened by the public. The appropriate price to pay for excess certificates would be difficult to determine. First, capture costs will vary over installations and second asymmetric information between the industry and policy makers would allow for the abuse of market power.

4.2.5 Investment support

4.2.5.1 General considerations

Given the high investment costs for the CCTS technology (Figure 1), capital markets may fail to finance projects with a high inherent risk of failure. By funding demonstration projects, governments are put into a strong position as it increases the influence on technology decisions and this can help to ensure that knowledge gained in demonstration projects spreads into the market, leading to a faster diffusion. However, governments are usually not best informed when it comes to select the appropriate project or technology. Therefore, a risk of locking-out promising options remains. Under the European Economic Recovery Program (EERP), four out of six public founded CCTS projects are based on the post-combustion capture technology (see below). Given the highest level of commercial maturity this might be justified. Yet one could also argue that up-scaling of a proven technology should left to the industry and the focus should be more set to innovative capture technologies.

Investment subsidies can be used to incentivize innovations in various stages of technological maturity, but is most suited for the initial demonstration.

Investment support for CCTS alone may fail to incentivize investment on the scale desired. While e.g. renewable energy technologies mainly bear from high upfront investment- but low variable cost, CCTS significantly lowers the plants efficiency. Additional instrument may therefore be needed to compensate for low carbon prices. As direct investment support puts a relatively high cost burden on governments, a risk of neglecting other promising low carbon technologies remains (Groenenberg and de Coninck, 2008).

4.2.5.2 Cases

4.2.5.2.1 The European Energy Programme for Recovery

The European Energy Programme for Recovery (EEPR) is part of the European Economic Recovery Plan presented by the Commission on 26th November 2008. The EEPR has a budget of almost four billion Euros to co-finance specific energy projects especially in the field of gas and electricity interconnections (2.365 billion), offshore wind energy (0.565 billion), and carbon capture and storage (1.05 billion). The EEPR funding is to contribute to the implementation of the projects and it is not to exceed 80% of the eligible costs (MEMO/09/543).

In December 2009 the commission chose six carbon capture and storage projects out of twelve proposals. Five of the six schemes are awarded an initial subsidy of 180 million Euros, with the same sum coming from national governments. The Italian project will receive 100 million Euros (Reuters, 2010). The following sums up the most important criteria on which decision-making is based: projects had to demonstrate the ability to capture at least 80% of produced CO_2 and the ability to transport and geologically store CO_2 safely underground. In power installations, CO_2 capture had to be demonstrated on an installation of at least 250 MW capacity.

Selection criteria are the following: the proposed projects had to be able to reach the investment stage by the end of 2010 and the full financial package (own financial contribution, other financing sources) had to be sound. All necessary permits would be obtained shortly.

The final award criteria were weighted as: there were no sufficient other sources of financing (points 35/100). The requested funding per tone of CO_2 has to be reduced in the first 5 years of operation (points 15/100). The extent to which the project applies innovative technologies and the commitment to diffuse the technological advances to other European operators (points 15/100). All components (base installation, CO_2 capture, transport and storage) would be operational by the end of 2015, demonstrating the full chain from CO_2 capture to storage (points 35/100). The following projects will receive public funding:

Jänschwalde/Germany (Leader: Vattenfall, EU funding: 180 million €). Based on an already existing 3000 MW coal power plant both, the demonstrating of the oxy-fuel and post-combustion technology is aimed at. All storage options are still open and further investigated in detail. However, storage could turn out to as the critical factor, as it is unclear if permission for CO_2 storage could be obtained. The German legislation either allows for the use of geothermal heat or carbon storage. There is increasing request for the permission of geothermal use notable in rural districts around potential storage options. The construction of the new CCTS boiler should start in 2011.

Porto-Tolle/Italy (Leader: Enel Ingegneria e Innovazione S.p.A.,EU funding: 100 million €). The project is integrated into a new 660 MW coal-fired plant and will test post-combustion technology in a unit corresponding to 250 MW electrical output. Storage will take place in an offshore saline aquifer (200km distance to the plant). Total costs are estimated to 800 million €.

Rotterdam/Netherlands (Leader: Maasvlakte J.V. / E.ON Benelux and Electrabel, EU funding: 180 million €). This project is part of the Rotterdam Climate Initiative and will test the post-combustion technology at a scale of 250MW. Storage will take place in a depleted offshore gas field (25 km distance to the plant). Total costs are estimated to 1.2 billion €.

Belchatow/Poland (Leader: PGE EBSA, EU funding: 180 million €). The 250MW post-combustion capture unit will demonstrate the entire CCTS value chain. Three different saline aquifer sites will be explored (61 km, 72 km, 140 km distance to the plant). Operation of a full-scale 850 MW demonstration plant is scheduled to 2015.

Compostilla/Spain (Leader: ENDESA Generacion S.A., EU funding: 180 million € and 280 – 450 million € in the form of EU Emission Allowances). A 30MW pilot plant will be up-scaled to a 320MW demonstration plant by 2015, testing the oxy-fuel and fluidized bed technology. Storage will take place in a saline aquifer (100 km distance to the plant).

Hatfield/United Kingdom (Leader: Powerfuel Power Ltd., EU funding: 180 million €). This project is part of the Yorkshire Forward Initiative. A 900 MW power plant will be built to demonstrate the integrated gasification combined cycle (IGCC). Storage will take place in an offshore gas field (175 km distance to the plant). Total costs for the IGCC unit are estimated to 800 million £.

There are four more projects on the reserve list, which would fill in if the original projects could not meet all of the criteria: Huerth/Germany, Eemshaven/Netherlands as well as Kingsnorth and Longannet in the United Kingdom.

4.2.5.2.2 300 million CO_2 certificates

On February 2nd 2010, EU member states agreed on the use of the revenues from the sale of 300 million CO_2 certificates from the New Entrants Reserve of the EU ETS. Earnings will finance CCTS demonstration projects (200 million certificates) and innovative renewable energy technologies (100 million certificates). Depending on the price for which the allowances are sold, up to 6 billion Euros could become available for CCTS. The agreement proposes to fund eight CCTS projects, with at least one but not more than three out of each technology concept. Storage in hydrocarbon reservoirs must be demonstrated in one project and storage in aquifers in at least three.

Selection of projects for funding will take place in two rounds of calls for proposals with funds covering 50% of the additional costs of the demonstration plant. The disbursement of cash to projects will take place annually, based on performance. If the proposal is going to be adopted by the EU Parliament and Council, the project funding decision could be expected by the end of 2011.

4.2.5.2.3 United Kingdom (tender approach)

In 2007 the UK government announced to award the winner of its CCTS competition around £1 billion to help funding a commercial scale CCTS project by 2009. The project has to cover the full chain of the CCTS technology on commercial scale, must be based on sound engineering design, and has to set out the quantum of financial support requested, be at least 300MW, and capture and store around 90% of the CO_2 emissions. The project must start to demonstrate the full chain of CCTS between 2011 and 2014.

However industry hesitated to submit proposals so only three projects were considered potential candidates, Longannet, RWE npower's station at Tilbury in Essex, and E.on's plans for a new coal plant at Kingsnorth in Kent. The British funding program has slowed down from its original timetable and the long-running competition had discouraged other firms from coming forward with project proposals. (Jowit, 2009). The UK CCTS competition involved sealed bids so companies have claimed that they are therefore unable to disclose any information. RWE npower was first to drop plans to build a new coal plant at Tilbury in Essex, and left the competition. As E.on has also pulled out of the competition only Scottish Power/Iberdrola is left which does not meets all of the targets that the UK set when it announced the competition in 2007.

To speed things up, the UK government has committed to helping fund up to four CCTS plants in the UK. The first – the competition winner - will be funded by the Treasury, but any further plants will be funded primarily from a levy on energy bills.

4.2.5.2.4 Canada

The Government of Alberta has introduced a legislation that provides the legal authority to administer the 2 billion US$ in provincial funding for carbon capture and storage (CCTS) to four large-scale projects (Source: Government of Alberta, 2010):

Project Pioneer (Leader: TransAlta, funding: 436 million Ca$). The project will utilize leading-edge technology to capture CO_2 which will be used for enhanced oil recovery (EOR) in nearby conventional oil fields, or stored almost three kilometers underground. The project is expected to capture one million tones of carbon dioxide annually beginning in 2015.

Shell Quest Project (Leader: Shell, funding: 745 million Ca$). Quest will capture and store 1.2 million tones of carbon dioxide annually beginning in 2015 from Shell’s Scotford upgrader and expansion, near Fort Saskatchewan.

Alberta carbon trunk line (Leader: Enhanced Energy Inc, funding: 495 million Ca$). The project includes a 240 kilometer pipeline that will transport CO_2. The initial supplies of CO_2 will come from the Agrium Redwater Complex and once built, the North West Upgrader. North West Upgrading will upgrade bitumen from Alberta’s oil sands and the captured CO_2 will be transported to depleting conventional oilfields and used in enhanced oil recovery (EOR).

Swan Hills Synfuels (Leader: Swan Hills Synfuels, funding: 285 million Ca$). The in-situ coal gasification (ISCG) project will access deep coal seams. These seams, which are about 1,400 meters below surface, have traditionally been considered too deep to mine. Wells will access the seams and be used to convert the coal underground into a clean synthetic gas known as syngas. The syngas will be used to fuel new high-efficiency power generation and the CO_2 created during this process will be captured and used for enhanced oil recovery (EOR).

4.2.5.2.5 USA

The US Secretary of Energy announced that 2.4 billion US$ from the American Recovery and Reinvestment Act will be used to expand and accelerate the commercial deployment of carbon capture and storage (CCTS) technology (Abercrombie, 2009). The main projects are:

Clean Coal Power Initiative: 800 million US$ will be used to expand DOE’s Clean Coal Power Initiative, which provides government co-financing for new coal technologies that can help utilities cut sulphur, nitrogen and mercury pollutants from power plants. The new funding will allow researchers broader CCTS commercial-scale experience by expanding the range of technologies, applications, fuels, and geologic formations that are tested (DOE, 2009)

Industrial Carbon Capture and Storage: 1.52 billion US$ will be used for a two-part competitive solicitation for large-scale CCTS from industrial sources. The industrial sources include, but are not limited to, cement plants, chemical plants, refineries, steel and aluminium plants, manufacturing facilities, and petroleum coke-fired and other power plants. The second part of the solicitation will include innovative concepts for beneficial CO_2 re-use (CO_2 mineralization, algae production, etc.) and CO_2 capture from the atmosphere. The rest of the money is allocated to smaller projects.

4.2.5.2.6 Australia

Australia allocated 2.4 billion Aut$ to part-fund carbon capture and storage "flagship" projects. $2 billion will be invested over nine years in the Carbon Capture and Storage Flagships program. The projects are expected to comprise the development of a carbon dioxide storage hub and support for a range of technologies to capture carbon dioxide from coal-fired power stations. It is hoped that along with the existing $400 million National Low Emissions Coal Initiative and the Co-operative Research Centre for Greenhouse Gas Technologies, the CCTS Institute and the Flagships program will ensure that Australia continues to be a world leader in the development of clean coal technology (Australia Office of energy. The following projects are suggested (Australian Government, 2009):

Wandoan: 334 MW Integrated Gasification Combined Cycle (IGCC) coal generation project aimed at sequestering 2.5 Mt CO_2 per year. It was chosen for further assessment because it is close to both an abundant supply of black coal and a good potential CO_2 storage site.

Zerogen: 400 MW IGCC coal generation project aimed at sequestering 2 Mt CO_2 per year. The project is near prospective geological formations for CO_2 storage that are under assessment

Collie South West Hub project: aiming to sequester 3.3 Mt CO_2 per year from nearby industry. The Hub was chosen because it is near potentially suitable storage sites and a large source region for CO_2 capture – the industrial centers of Kwinana and Collie.

CarbonNet hub project: aiming to sequester 3-5 Mt CO_2 per year from nearby industry. CarbonNet was chosen because it is near potentially suitable storage sites, both onshore and offshore, as well as having the potential to bring together a range of CO_2 capture projects from a large industrial region.

4.2.6 Public-private partnership

Public-private partnership can play a key role in the development of the transport infrastructure. The development of a meshed pipeline network would require higher investment in the beginning but could enable less expensive CO_2 transport for a higher number of CCTS actors. As individual players are unlikely to bear the risks and the costs of such a network development, this is another example of the collective action problem (Groenenberg and de Coninck, 2008). According to Boeuf (2003), a range of issues needs to be addressed before a proper structure for a public-private partnership can be elaborated, so as to minimize financial and societal risks during design, construction, and operation for the parties involved (EC, 2003). Shortcomings of the PPP approach are the underestimation construction and equipments costs and construction delays, the overestimation of revenues, and negligence of issues related to social acceptance.

Commonly used forms of PPP arrangements are the so-called Build-Operate-Transfer (BOT) and Design-Build-Finance-Operate (DBFO) structures. The first concept would refer to the network financed and owned by the public sector, while a private party is contracted to design, build and operate the network. This approach allocates the risks in design, construction and operation to the private sector.

The DBFO approach allocates the financial risk to the private party. The network would be owned by the private sector during the contract period and recovers costs through public support. The public sector has a modest role only. It will ultimately own the facility and possibly provide part of the funding (Groenenberg and de Coninck, 2008).

5 Conclusions and Policy Recommendations

This report summarizes the findings of Work Package 5.3 of the SECURE project, with regard to the role of carbon capture, transport and storage (CCTS) for the future of European coal supply security. The executive summary puts forwards one main thesis: CCTS is the real threat to European supply security with coal. This thesis is substantiated in the subsequent report, with more technical details and some case study evidence.

The real issue in European supply security regarding coal is the absence of an economically and politically sustainable use of the coal for electricity, liquefaction, gasification, etc. Whereas earlier deliverables in this Work Package 5.3 “Coal Sector” have indicated that there are few risks for European energy supply with (steam) coal, there is an implicit supply security threat, i.e. that coal will no longer be an essential element of European energy supply because the CCTS roll-out will be delayed or not be carried out at all.

According to the IEA “Technology Roadmap” the next 10 years are a critical period for CCTS (IEA, 2009). There is a real danger that the ambitious development plans in CCTS demonstration over the next decade will not be met. This is due to a lack of determination of public authorities to overcome the significant obstacles inherent in CCTS, and the difficulties of industry to embrace a technology that might challenge the business model of coal electrification. Also, the business model of CCTS-plants (base-mid load) is incompatible with the dispatch of a largely renewable based electricity system that values flexibility more than base load.

Based on the above analysis, we derive the following policy conclusions:

If CCTS deployment continues at the current, slow pace, there is a real risk that European coal supply security be in danger. Therefore, the conventional policy measures, as laid out in detail by the IEA (2009) Roadmap, should be continued, and accelerated, but also be complemented by more consistent measures, such as obligatory carbon-capture ready technology, and active state involvement in pipeline development.

There is no reason to delay CCTS demonstration projects any longer. The readily available billions of Euros and Dollars should be rapidly implemented. In cases where industry does not respond, the level of incentives needs to be raised to a reasonable level. If there is still no reaction, pilot demonstration projects should be carried out by public research institutions or additional support instruments should be thought.

The financial uncertainty surrounding future projects should be reduced. In the absence of clear CO_2 price corridors and signals, regulatory certainty can be created, e.g., by obliging new power plants in include a “capture-ready” option.

Whereas CO_2 capture should be left to industry, the state bears a crucial role in the development of the transportation and storage infrastructure. CO_2-transportation infrastructure should be sited and the necessary planning steps be carried out. The execution of the construction and operation can be tendered to the private sector, or carried out by a state-owned network company. Synergies with the other energy network infrastructure (gas, electricity) should be considered.

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7 Appendix: CCTS Database: capture projects

Project Name	**Location**	**Leader**	**Feedstock**	**Size MW**	**Capture Process**	**CO_2 Fate**	**Start-up**	**Current project status**	**Cost estimation**	**Public funding**
Abu Dhabi project	Abu Dhabi	Masdar	Various industrial	Various	Various	EOR	2013	Planning	$ 2 bn	
Callide-A Oxy Fuel	Australia	CS Energy	Coal	30	Oxy	Seq	2011	Construction	$ 200 Mio	
Wandoan	Australia		Coal	334	Pre	Seq				
ZeroGen	Australia	ZeroGen	Coal	400	Pre	Seq	2015	Planning	A$ 4.3 bn	
Maritsa	Bulgaria	BEH	Lignite	600	Pre	EOR/EGR	Undecided	Announced	€ 850 Mio	
Fort Nelson	Canada	PCOR	Gas	Gas Process	Pre	Brine Res	2012	Feasibility Study		
Boundary Dam	Canada	SaskPower	Coal	120	Oxy	EOR	2015	Announced	$ 1.4 bn	
Bow City	Canada	BCPL	Coal	1000	Post	EOR	2014	Announced		
Project Pioneer	Canada	TransAlta	Coal		Post		2015	Planning		
Shell Quest Project	Canada	Shell	Gas	Various	Pre	Seq/EOR	2015	Planning		
GreenGen	China	GreenGen	Coal	250 (pilot) 600	Pre	Seq	2010 2015	Announced		
NZEC	China	UK,EU,China	Coal	Undecided	Undecided	Seq	2014	Announced		
Hodonin CEZ	Czech Republic	CEZ	Lignite, Biomass	105	Post	Depleted oil & gas field	2015	Planning		
Ledvice CEZ	Czech Republic	CEZ	Lignite	660 (CR)	Post	Saline aquifer	2015	Planning		
Kalundborg	Denmark	DONG Energy	Coal	600	Post	Saline aquifer	2016	Planning		
Aalborg	Denmark	Vattenfall	Coal	410	Post	Saline aquifer	2013	Planning		
Meri Pori	Finnland	Fortum	Coal	400	Post	Unknown	2015	Planning		
Total Lacq	France	Total	Gas	35	Oxy	Seq	2010	Operating	€ 60 Mio	
Schwarze Pumpe	Germany	Vattenfall	Coal	30 (pilot) 300 (demo) 1000	Oxy	Seq / EOR	2008	Operating	€ 70 Mio (pilot)	
Jänschwalde	Germany	Vattenfall	Coal	375	Oxy & Post	EGR	2015	Planning	$ 1.58 bn	180 Mio, EEPR
Wilhelmshaven	Germany	E-ON	Coal	5,5 (pilot)	Post	Deep saline aquifer	2010	Planning completed	10 Mio € (pilot)	
Großkrotzenburg/Staudinger	Germany	E-ON/Siemens	Coal	510	Post		2010	Construction		
Niederhausem	Germany	RWE	Coal	Pilot Project	Post		2009	Operating	9 Mio €	
Brindisi	Italy	Enel &Eni	Coal	242	Post	Seq	2010	Construction		
Porto Tolle	Italy	Enel	Coal	660	Post	Saline formation in sea	2015	Planning	€ 800 Mio	100 Mio, EEPR
Saline Joniche	Italy	SEI	Coal	1320 (CR)	Post	Undecided	Undecided	Announced		

Project Name	Location	Leader	Feedstock	Size MW	Capture Process	CO$_2$ Fate	Start-up	Current project status	Cost estimation	Public funding
Nuon Magnum, Eemshaven	Netherlands	Nuon	Coal	1200 (CR)	Pre	Seq	2013	Construction		reserve list, EEPR
Maasvlakte, Rotterdamm	Netherlands	Rotterdam Climate Initiative E.ON Benelux,Electrabel	Coal	1040 (CR)	Post	EGR	2015	Construction	€ 1.2 bn	180 Mio, EEPR
Eemshaven RWE	Netherlands	RWE	Coal	40	Post	Depleted oil & gas field	2016	Planning		
Rotterdam CGEN	Netherlands	CGEN NV	Coal, Biomass	450	Pre	Depleted oil & gas field	2013	Announced		
Rotterdam Essent	Netherlands	Essent	Coal, Biomass	1000	Pre	Depleted oil & gas field	2016	Announced		
Statoil Mongstad	Norway	Statoil	Gas	630 CHP	Post	Seq	2011	Construction	$ 2.7 bn	
Tjeldbergodden	Norway	Shel/Statoil	Gas	700	Post	EOR	2011	Planning		
Belchatow	Poland	PGE EBSA	Coal	858	Post	Undecided	2011 (pilot project), 2015	Planning/Construction		180 Mio, EEPR
Siekierki	Poland	Vattenfall	Coal	480 (CR)	Post	Undecided	2016	Planning		
Kędzierzyn	Poland	PKE	Coal	300	Pre	Seq	2014	Planning	1300 Mio €	
Compostilla	Spain	ENDESA	Coal	30 (pilot), 500 (demo)	Oxy	Deep aaline aquifer	2010 (pilot), 2015	Planning	€ 500 Mio	180 Mio, EEPR, (280-450 Mio EU Allowances)
Puertollano	Spain	Bellona	Coal, Petcoke	14	Pre	Saline aquifer	2009	Construction	18,5 Mio €	
E.ON Karlshamn	Sweden	E.ON	Oil	5	Post	Undecided	2009	Operating	€ 11 Mio	
Scottish & Southern Energy Ferrybridge/Yorkshire	UK	SSE	Coal	500(CR)	Post	Seq	2012	Planning	£ 250 Mio + 100 Mio CCS	
Teesside	UK	CE	Coal	800	Pre	Seq	2015	Announced	$ 1500 Mio	
Powerfuel Hatfield	UK	Powerfuel	Coal	900	Pre	EOR	2014	Construction	$ 1.6 bn	180 Mio EEPR + 180 Mio (UK)
Longgannet	UK	Scotish Power	Coal	300	Post	Undecided	2014	Testing 1 MW prototype	£ 1 bn	reserve list, EEPR
Drym	UK	Progressive Energy	Coal	450	Pre	Undecided	Undecided	Announced		
Immingham	UK	ConocoPhillips	Gas	450	Post	Seq	2010?	Construction		
Aberthaw	UK	RWE		3 (pilot), 25 (2. phase)	Post		2010	Construction	£ 8.4 Mio	
Onllwyn	UK	Valleys Energy	Coal	450	Pre		2014	Planning		

Project Name	Location	Leader	Feedstock	Size MW	Capture Process	CO$_2$ Fate	Start-up	Current project status	Cost estimation	Public funding
Renfrew	UK	Doosan Babcook, DECC, Scotish/Southern Energy		40	Oxy		2009	Operating		
Pleasant Prairie	USA	AEP	Coal	5	Post	Seq	2008	Operating		
AEP Alstom Mountaineer	USA	AEP	Coal	30 235	Post	Seq	2009	Operating	$ 800 Mio	$334 Mio
Williston	USA	PCOR	Coal	450	Post	EOR	2014	Announced		
Kimberlina	USA	CES	Coal	50	Oxy	Seq	2010	Announced		
AEP Alstom Northeastern	USA	AEP	Coal	200	Post	EOR	2011	Announced		
Plant Barry	USA	MHI	Coal	25 (pilot) 160 (demo)	Post	Seq	2011	Planning		$ 295 Mio
Antelope Valley	USA	Basin Electric	Coal	120	Post	EOR	2012	-		
Appalachian Power	USA	AEP	Coal	629	Pre	Undecided	2012	Announced	$ US Mio	
WA Parish	USA	NRG Energy	Coal	60	Post	EOR	2013	Planning		
Wallula Energy Resource Center	USA	Wallula Energy	Coal	700	Pre	Seq	2014	Announced	$ 2.2 bn	
Hydrogen Energy California	USA	HEI	Petcoke	390	Pre	EOR	2014	Planning		$ 308 Mio
Trailblazer	USA	Tenaska	Coal	765	Post	EOR	2014	Planning		
ZENG Worsham-Steed	USA	CO2-Global	Gas	70	Oxy	EOR	Undecided	Announced		

Abbreviations: Capture processes:
“Pre” - Pre-Combustion Capture
“Post” - Post-Combustion Capture
“Oxy” - Oxyfuel process

CO2 fate:
“EOR” - Enhanced oil recovery
“EGR” - Enhanced gas recovery
“Seq” - Sequestration
“Brine Res” - Brine (salt water) reservoir

Project Name	**Location**	**Leader**	**Feedstock**	**Size MW**	**Capture Process**	**CO2 Fate**	**Operation**	**Current project status**	**Cost estimation**	**Public funding**
Restructuring/ Dormant										
FutureGen	USA	FutureGen Alliance	Coal	275	Pre	Seq	2009			
BP Carson (DF2)	USA	Hydrogen Energy	Petcoke	500	Pre	EOR	Re-Structuring		$ 2 bn	
E.ON Killingholme	UK	E.ON	Coal	450	Pre	Seq	Dormant	Cancelled?		
Monash Energy	Australia	Monash	Coal	60 k bpd	Pre	Seq	Dormant	Cancelled?		
UAE Project	UAE	Masdar	Gas	420	Pre	EOR	Delayed	Cancelled?		
Greifswald	Germany	Dong Energy						Cancelled?	$ 2-3 bn	
RWE Goldenbergwerk, Huerth	Germany	RWE	Coal	450	Pre	Seq	2015	Postponed?	2 bn €	reserve list, EEPR
Kingsnorth	UK	E-ON	Coal	800 (CR)	Post	Depleted Gas Field	2014	Postponed?	£ 1 bn	reserve list, EEPR
Sargas Husnes	Norway	Sargas	Coal	400	Post	EOR	2012	Postponed?	$ 700 Mio	
Naturkraft Kårstø	Norway	Naturkraft	Gas	420 (CR)	Post	Undecided	2011-2012	Postponed?	$ 1.8 bn	
ZENG Risavika	Norway	CO2-Norway	Gas	50-70	Oxy	Undecided	Undecided	Postponed?		