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The Cost of Carbon Capture and Storage Demonstration Projects in Europe

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The Mission of SETIS is to support decision-making for the European Energy Technology Policy. SETIS has two key goals:

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- Develop an integrated approach for information and data exchange on energy technologies and capacities for innovation throughout Member States, international organisations and energy sectors.

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EXECUTIVE SUMMARY

The acceleration of development and the demonstration of carbon capture and storage (CCS) technologies are among the key objectives of the Strategic Energy Technology Plan (SET-Plan) of the European Union, which aims at enabling the rapid transition to a low-carbon economy. A Technology Roadmap, which constitutes the first step for the definition of a large-scale European Industrial Initiative (EII) for the demonstration and further development of CCS technologies, has already been developed jointly by the European Commission, the industry and the research community. The Roadmap describes the strategic and technological objectives of the EII and the actions required for the rapid commercialisation and the subsequent large-scale deployment of CCS; it proposes key performance indicators for monitoring progress and presents an indicative cost for the EII.

The core element of the CCS-EII is the construction and operation of up to 12 coal-fired CCS demonstration plants to prove the technical and economic feasibility of CCS using existing technology. The cost of this demonstration programme has been estimated to be between 8.5 and 13 billion Euros. This range of figures accounts for the additional costs of the CCS demonstration plants compared to the costs of similar conventional plants, as well as the cost of setting up and operating a network of these projects.

The cost of the demonstration programme has been estimated assuming the size and composition of the fleet of the CCS demonstration plants and by calculating, based on cash flow analysis, their additional discounted lifetime costs. The calculations presented in this report show that the additional costs of a 400 MW CCS demonstration project range are about 680 million Euros for coal plants and 550 million Euros for gas plants. In a carbon pricing environment, similar to that considered in the 2nd Strategic European Energy Review, the additional revenues required for making these demonstration projects competitive in the electricity market are 46 Euros per tonne of CO_2 avoided for coal plants and 77 Euros for gas plants. These calculations are very sensitive to the assumptions made with regards to the capital costs, the costs of CO_2 transport and storage, fuel and CO_2 prices, and the discount rate.

These additional costs have been estimated using reference values for the cost of the CO_2 capture technologies (pre- and post-combustion and oxyfuel), which have been set based on an extensive assessment of literature sources using a transparent methodology, thus reducing the uncertainty about the economics of CCS technologies.

1 INTRODUCTION

One of the key priorities of the European Union (EU) is the rapid transition to a low-carbon economy. This goal can only be realised through the acceleration of development of a diverse portfolio of low-carbon technologies with great potential, which, in turn, will enable the timely commercialisation and large-scale deployment of these technologies in the European energy sector [1-5]. A critical component of this portfolio of technologies is carbon capture and storage (CCS) in view of the fact that fossil fuels will remain the main source for electricity generation in Europe at least in the short to medium term [6], despite the significant ongoing efforts to promote renewable energy technologies and energy efficiency [7-8].

The EU has been supporting the research and development (R&D) of technologies that comprise the CCS chain, i.e. carbon dioxide (CO_2) capture, transport and underground storage, since the 1990's through the Framework Programmes. The results of the projects co-funded by the EU, in conjunction with those from industrial and national R&D activities, have contributed to the build-up of knowledge on the fundamental mechanisms of the capture, transport and storage of CO_2 and the concurrent development of CCS technologies. Today, most elements of the CCS chain of technologies have been commercialised, albeit at a scale much smaller than that required by the power generation sector and other carbon-intensive industries. Furthermore, available estimates, e.g. [9, 10], indicate that the capital costs of the first generation of power plants equipped with CCS technologies (called CCS plants hereafter) will be 35-90% higher than those of state-of-the-art conventional power plants that use the same fuel and employ a similar power generation technology. Similarly, operating costs, including fuel, will be 30-50% higher, mainly due to the significant reduction of efficiency of the power plant to which CCS is applied. Finally, despite the success of R&D projects in Europe and elsewhere, there are still concerns over the long-term safety of underground CO_2 storage. Therefore, the large-scale deployment of CCS requires further R&D to reduce costs and the efficiency penalty and a rigorous demonstration programme to test existing and developing technologies and their integration and to demonstrate their long-term operational availability and reliability.

The EU has made the demonstration of CCS technologies a priority in the context of the European Strategic Energy Technology Plan (SET-Plan) [4, 5]. The SET-Plan is a recent EU initiative that aims at accelerating the availability of low-carbon energy technologies in Europe through joint strategic planning; effective implementation through large-scale programmes, called European Industrial Initiatives (EIIs), dedicated to selected low-carbon technologies; increased financial and human resources; and, enhanced international cooperation. The European Commission, together with the industry, the research community and the Member States have proposed a Roadmap for the development of CCS technologies in Europe [11] and are currently working towards the establishment of an EII (CCS-EII). The objective of the CCS-EII is to demonstrate the commercial viability of CCS technologies in an economic environment driven by the emissions trading scheme (ETS) and in particular, to enable the cost-competitive deployment of CCS technologies in coal-fired power plants by 2020-2025 and to further develop the technologies to allow for their subsequent wide-spread use in all carbon-intensive industrial sectors.

Currently, discussions are ongoing to formulate a detailed implementation plan for the CCS-EII, prior to its launch. Based on the CCS Technology Roadmap [11], the CCS-EII will comprise a large scale demonstration programme for the construction by 2015 and subsequent operation of a fleet of up to 12 large-scale, first-of-a-kind CCS plants, exploring combinations of different capture, transport and storage options; a vigorous R&D programme focused on the improvement of power plant efficiency, the development of innovative capture technologies for power generation and other industrial applications, and the assessment of transport and storage options; and public outreach and international cooperation activities. All these actions need however to be further defined and prioritized; the timing of the commitment of resources needs to be aligned to the EII priorities; key performance indicators for the monitoring of technological progress need to be defined; and concrete projects have to be identified for rapid implementation.

The indicative cost of the CCS-EII, as reported in the Technology Roadmap, ranges between 10.5 and 16.5 billion Euros, of which, 8.5 to 13 billion refer to the demonstration programme. This cost range is comparable with that announced by the European industry. In particular, the Zero Emission Fossil Fuel Power Plant Technology Platform (ZEP ETP) has already proposed a CCS demonstration programme based on the construction and operation of up to 12 demonstration plants with the objective to make CCS technology competitive by 2020 [12]. The ZEP ETP has stated that the cost of this demonstration programme would be in the range of 7-12 billion Euros beyond the contribution of the industry, based on a recent report by McKinsey & Company [13]. These cost estimates significantly exceed current research and development investments on CCS in Europe, at international, national and corporate levels, which have been estimated to be €288 million in 2007 [14].

The aim of this report is to contribute to the ongoing discussion on the formulation of the Implementation Plan of the CCS-EII by describing the methodology used for the estimation of the costs of the CCS demonstration programme, as reported in the Technology Roadmap [11]. The financial needs have been estimated based on the calculation of the difference of lifetime capital and operating costs between CCS and conventional plants; and on assumptions concerning the composition of the CCS demonstration programme. The additional lifetime costs of a CCS demonstration plant have been estimated using reference values for the cost of the CO_2 capture technologies (pre- and post-combustion and oxyfuel), which have stemmed from an extensive assessment of literature sources using a transparent methodology, which alleviates to a significant extent the confusion about the economics of CCS technologies.

2 COSTING THE CCS TECHNOLOGIES – THE BACKGROUND

As a starting point of this analysis, this section of the report draws attention on key points concerning the economics of CCS. The aim is to provide the reader who has only a limited overview of the subject, with more in-depth information on the current state of knowledge with regards to the economics of CCS technologies so that the methodology described in the following sections is better comprehended.

- The total (capital and operating) costs of a CCS plant comprise the respective costs of the key processes along the CCS chain, i.e. CO_2 capture[1], transport and storage. If there is no need for very accurate cost estimates for a CCS chain, e.g. when only indicative costs are sought, the cost of each process can be estimated independently. This is typically the approach followed by most studies available in the literature, as well as by this report. If, however, accurate costs are needed, e.g. for a final investment decision, the costs of transport and storage should be calculated in conjunction with the cost of capture as the former depend on the type of the capture technology, the power plant size, its operational profile and capture rate, and the location of the power plant and the storage site.
- Carbon capture technologies at the scale needed for power plants have not yet been demonstrated. This implies that there is no prior experience in the manufacturing and hence in the costing of many of the components of the capture system at the required scale. Hence, most reported cost figures of individual components that make up the capture part of a power plant are only estimates, based on scaling up of smaller components used in other industries or on manufacturers' expert judgement based on experience from other (near-) proven technologies. This *inter alia* reduces the accuracy of any reported figures.
- Similarly, since there is no experience with the construction of CCS plants, any reported capital costs are only estimates. Such estimates can be produced based on expert judgement, or engineering and modelling work. The most credible means of producing reliable estimates is via FEED (Front-End Engineering Design) studies that rely on detailed designs of CCS plants using process flow modelling, followed by sizing and subsequent costing of the individual power plant components. The accuracy of FEED studies is about ±10%. The most accurate estimates result from the collaboration of a power utility with an engineering company and the engagement of the component suppliers. This is however a costly and time-consuming process, which is typically pursued only when firm decisions for the construction of a power plant have been made. A prefeasibility study is another alternative that provides credible figures, albeit less accurate. A prefeasibility study requires the development of a conceptual design and a less vigorous process flow model. Costing of components can be done based on generic standard costing methodologies. The accuracy of the resulting estimates is usually accepted to lie within the range of ±30%. Obviously, the accuracy of costs based solely on expert judgment cannot be gauged.
- The cost of a CCS plant depends, among others, on the adopted CO_2 capture technology, fuel type and composition, plant size and efficiency, degree of capture (capture rate), and plant location. It is noted that there are different technologies that could be used for each CO_2 capture method. For example, there are at least three different types of gasifier that could be used for an Integrated Gasification Combined Cycle (IGCC) CCS demonstration plant, which are associated with different plant layouts, and hence different process efficiencies and capital and operating costs; and

[1] *Capture costs also include the cost of CO_2 compression at a pressure necessary for the facilitation of its transport.*

for pulverised fuel (PF) coal plants with post-combustion capture, there are different types of boiler that can be employed, many alternative heat integration paths and diverse technologies for separating the CO_2 (e.g. amines, ammonia, etc.). Hence, technology choices can affect costs significantly. Plant efficiency also affects capital costs: since CCS plants will have lower efficiencies than conventional plants, they need to be designed and constructed with a larger fuel input than conventional power plants to maintain net electricity output. Therefore, the size and hence the cost of components of a CCS plant will depend on plant efficiency for a predefined net power output. Capital costs will also depend on the required availability of the plant: high availabilities (above 80%) for some types of CCS plant will require the construction of back-up components which will increase capital costs. Finally, costs will vary depending on the terrain and location/country of the plant.

- CO_2 transport via pipeline is an established technology[2]. Costs depend on the pipeline length, the terrain and the volume of CO_2 transported. Furthermore, compression along the pipeline may be needed in cases of long distance transport. Hence, transport costs are case-specific.
- CO_2 storage has been demonstrated. Costs[3] depend on the type, depth and shape of the geological formation, the depth, the storage process, which will affect the type and number of wells that will be drilled, the monitoring technique etc. Hence, storage costs are also case-specific.
- First-of-a-kind CCS demonstration plants will be more expensive to build than future commercialised CCS plants because they will not gain from the same economies of scale. Furthermore, manufacturers will be less certain about the performance of their plant and its components and therefore will charge more to offer the usual guarantees, or alternatively the utilities will include more risk provisions to cover potential start-up and operational problems.

Points to remember

- Costs of CCS technologies reported in the literature are only estimates, since CCS power plants have not yet been demonstrated.
- Capital cost estimates are reliable when they are supported by FEED or prefeasibility studies. The accuracy of such studies is about ±10% and ±30% respectively.
- Costs of power plants that use the same capture method (pre- or post-combustion, or oxyfuel) can vary widely depending on the chosen power plant layout and its components, fuel composition and plant location.
- The costs of transport and storage are case-specific and can be estimated accurately only after the locations of plant and storage sites have been identified and the storage process has been decided.
- Overall, there is uncertainty in CCS costs, which stems from the lack of experience in constructing and operating capture plants and their components, the range of technology options that can be used, and the assumption, rather than the calculation, for the costs of the transport and storage of CO_2 when the location of the power plant and the storage site are not known.

[2] *It is rather unlikely that CO_2 captured from the demonstration plants envisaged in the EII will be carried by ship due to the state of maturity and transport capacity of this technology option. In support of this argument it should be noted that only one out of the seven archetypal projects proposed by ZEP ETP [12] evisages CO_2 transport by ship.*

[3] *The option of injecting CO_2 for enhanced oil recovery is not considered in this report. In such a case, the storage process would be a net benefit rather than a cost.*

3 Review of Published Cost Figures for CCS Power Plants

A plethora of cost assessments for the first generation (demonstration) CCS plants are available in the literature. The most recent of them were used in this analysis for setting reference values for CCS costs, complemented by information provided to the European Commission by the industry directly, and the results of calculations made by the JRC, using an in-house costing tool. The sources of data used in this analysis are listed below:

1. *IEA Greenhouse Gas R&D Programme, Potential for improvement in gasification combined cycle power generation with CO_2 capture, PH4/19 (2003)* [15]*:* A prefeasibility study of IGCC-CCS plants (based on Shell and Texaco, now GE, gasifiers), performed by Foster Wheeler.
2. *IEA Greenhouse Gas R&D Programme, Improvement in power generation with post-combustion capture of CO_2, PH4/33 (2004)* [16]*:* A prefeasibility study of PF-CCS and natural gas combined cycle CCS (NGCC-CCS) plants, performed by Fluor.
3. *IEA Greenhouse Gas R&D Programme, Retrofit of CO_2 capture to natural gas combined cycle power plants, 2005/1 (2005)* [17]*:* A prefeasibility study of NGCC-CCS plants, performed by Jacobs Consultancy.
4. *IEA Greenhouse Gas R&D Programme, Oxy combustion processes for CO_2 capture from power plant, 2005/9 (2005)* [18]*:* A prefeasibility study of oxyfuel plants, performed by Mitsui Babcock.
5. *IPCC, Special Report on carbon capture and storage (2005)* [10]*:* Review of costs available in the literature by early 2005.
6. *IEA Greenhouse Gas R&D Programme, Estimating the future trends in the cost of CO_2 capture technologies, 2006/6 (2006)* [19]*:* Capital costs of the first CCS plants were calculated using the Integrated Environmental Control Model (IECM) developed by Carnegie Mellon University [20].
7. *EURACOAL, The future role of coal in Europe (2007) (produced by Prognos AG)* [21]*:* The report provides values for the capital costs of CCS plants without providing further supporting information.
8. *NETL, Cost and performance baseline for fossil energy plants, DOE/NETL-2007/1281 (2007)* [22]*:* Prefeasibility studies of IGCC-CCS, PF-CCS and NGCC-CCS plants, performed by a consortium of consultants.
9. *Climate Change Capital (CCC), Analysis of funding options for CCS demonstration plants (2007)* [24]*:* Literature review and reporting of average values from the literature, used by the ZEP ETP for the costing of the Platform's demonstration programme.
10. *European Power Industry (2007):* Cost values provided by various industrial stakeholders to the European Commission without any further supporting documentation.
11. *IEA, CO_2 capture and storage – A key carbon abatement option (2008)* [23]*:* The report lists values for the capital costs of CCS plants without providing further supporting information.
12. *JRC, PPC Model (2008):* Capital costs have been calculated using the JRC's in-house power plant costing tool that estimates the size of the individual functional elements of a power plant using mass balance analysis, and subsequently calculates the cost of these elements using reference cost values and appropriate scaling factors.

13. *Belfer Center, Realistic costs of carbon capture (2009)* [25]: Cost analysis of first-of-a-kind and N^th^-of-a-kind CCS demonstration plants, based on a literature review of costs reported mainly in US studies.

The above list is not exhaustive although it includes most of the recent literature. There are additional studies available to the JRC, which are however older assessments or studies that refer to other types of plant with components still in R&D phase, hence unsuitable for a demonstration project. For example, the recent report by IEA Greenhouse Gas R&D Programme 'CO_2 capture ready plants' [26] is not useful in the context of this analysis as the reported cost figures are based on the references [15, 16, 18] already listed above. Another example is the McKinsey & Company report [13], which has assessed the economics of CCS technologies. It has however assumed a generic coal-fuelled CCS plant, without providing further information on the capture technology considered.

These references have been grouped in four categories based on the degree of detail they use to justify the figures they report, see Table 1:

- Prefeasibility studies, which estimate costs based on process flow modelling followed by sizing and costing of the individual power plant components.
- Generic cost models, which estimate costs based on simple mass and energy balances of basic plant designs, followed by the sizing of the power plant functional elements and their costing based on scaling of reference costs.
- Literature reviews
- Expert opinion of organisations and the industry.

Table 1: Grouping of consulted references

Ref. No.	Name	Pre-feasibility study	Cost model	Literature review	Expert opinion of industry and organisations
1	IEA GHG (2003) [15]	•			
2	IEA GHG (2004) [16]	•			
3	IEA GHG (2005) [17]	•			
4	IEA GHG (2005) [18]	•			
5	IPCC [10]			•	
6	IEA GHG (2006) [19]		•		
7	Euracoal [21]				•
8	NETL [22]	•			
9	CCC [24]			•	
10	Industry				•[4]
11	IEA [23]				•
12	JRC		•		
13	Belfer Center [25]			•[5]	

[4] *Collection of cost figures reported by various companies.*

[5] *This paper assesses the costs of the first CCS plants based on the analysis of US design studies published before 2007 (i.e. 11 studies on PF and oxyfuel plants, 11 studies on IGCC plants and 4 studies on NGCC plants). Unfortunately, these studies have not been referenced in detail in the paper and hence could not be traced to be analysed in the JRC study as prefeasibility studies. The capital costs*

The grouping of references in such a way is of paramount importance for this analysis, since the perception of robustness of the reported cost figures in each reference is herein associated with the level of detail used for their justification. More specifically, the prefeasibility studies provide thorough justifications for both capital and operating costs and hence they are herein considered the most dependable, provided that their assumptions are sound. Cost models also provide details of the underlying cost calculations. The application of generic costing methodologies makes however such analyses less dependable than the prefeasibility studies. Literature reviews report capital cost figures from previously published works (prefeasibility studies, results of costing models or other literature reviews). In general, they do not contribute with new information; the reported values are however useful for providing an overview that could be used to benchmark results from this and future studies. Similarly, the reported values based on expert opinion of associations and the industry are not very useful for this type of exercise, as their authors do not justify the figures they report to allow for the evaluation and validation of the costing methodology used. They can only be used for rough comparison purposes.

3.1 Review of capital costs

The overnight specific capital investment cost[6] figures reported in the consulted references are shown in Table 2, according to the year of publication. This Table also shows the harmonised values of these costs, reported in 2008 Euros and reflecting the cost of technology as of the first quarter of 2009. In particular, figures in currency other than Euro have been converted to Euro based on the Eurostat exchange rates for the year that the costs are given in each reference[7] and then, if needed, converted to 2008 Euros using the annual average inflation rates for the Euro-area as reported by Eurostat. Finally, to account for the recent capital cost changes, the capital cost values have been modified as follows: initially all values were adjusted to the third quarter of 2008 using the Chemical Engineering Plant Cost Index (CEPCI) [27] and subsequently to the first quarter of 2009 using the IHS CERA Power Plant Capital Costs Index (PCCI) [28], due to the lack of availability of CEPCI data for 2009, at the time of writing of this report. It is noted that between the third quarter of 2008 and the first quarter of 2009, the costs of fossil fuel power plants declined by about 6% [28] due to the lowering of the prices of oil, steel, copper and other commodities and the economic slowdown that had an impact on the demand for new power plants. Since these cost figures refer to plants with different capacities, adopted technologies and processes, and performance characteristics, direct comparison should be done with caution.

from all these studies are however given in the annex of the Belfer paper, without further information, hence are herein treated as figures reported in a literaure review.

[6] *The term 'overnight specific capital investment cost' refers to the total expenditure for the construction and initial start-up of a power plant at a particular point in time, i.e. assuming instantaneous construction [33]. This is expressed in Euros per kilowatt of installed capacity (€/kW).*

[7] *When the reference year was not given it was assumed to be the year of publication. Furthermore, when costs for a specific type of plant were reported for a number of future years, the values considered in this analysis have been the ones that refer to plants built closer to the present.*

Table 2: Summary of capital costs reported in the literature for early CCS plants

Citing No.	Source	Type*	Reported Value	Unit	Harmonised Value €(08)/kW
IGCC with pre-combustion capture					
1	IEA GHG [15]	PS	1860	$(03)/kW	3004
2	IEA GHG [15]	PS	1495	$(03)/kW	2414
3	IPCC [10]	LR	1825	$(02)/kW	3230
4	IEA GHG [19]	CM	1831	$(02)/kW	3241
5	Euracoal [21]	EO	1620	€(06)/kW	1976
6	NETL [22]	PS	2390	$(06)/kW	2322
7	NETL [22]	PS	2431	$(06)/kW	2361
8	NETL [22]	PS	2668	$(06)/kW	2592
9	CCC [24]	LR	1600 ± 500	€(07)/kW	1870
10	Industry	EO	1080	€(07)/kW	1835
11	Industry	EO	2111	€(07)/kW	2467
12	Industry	EO	4848	€(07)/kW	5667
13	IEA [23]	EO	2550 ± 250	$(07)/kW	2175
14	JRC	CM	2100	€(05)/kW	2566
15	Belfer [25]	LR	2450 ± 650	$(05-06)/kW	2431
PF with post-combustion capture					
16	IEA GHG [16]	PS	1755	$(04)/kW	2021
17	IPCC [10]	LR	2096	$(02)/kW	3710
18	IEA GHG [19]	CM	1962	$(02)/kW	2578
19	Euracoal [21]	EO	1650	€(06)/kW	2012
20	NETL [22]	PS	2870	$(06)/kW	2788
21	CCC [24]	LR	1800 ± 550	€(07)/kW	2103
22	Industry	EO	1163	€(07)/kW	1677
23	Industry	EO	1181	€(07)/kW	1667
24	Industry	EO	1258	€(07)/kW	1641
25	Industry	EO	1576	€(07)/kW	2659
26	IEA [23]	EO	2750 ± 500	$(07)/kW	2345
27	JRC	CM	2250	€(05)/kW	2748
28	Belfer [25]	LR	2510 ± 400	$(05-06)/kW	2547
PF – oxyfuel					
29	IEA GHG [18]	PS	1951	€(05)/kW	2595
30	IEA GHG [19]	CM	2417	$(02)/kW	4279
31	Euracoal [21]	EO	1740	€(06)/kW	2122
32	CCC [24]	LR	1900 ± 800	€(07)/kW	2220
33	Industry	EO	1189	€(07)/kW	1709
34	IEA [23]	EO	2500 ± 400	$(07)/kW	2131
35	Belfer [25]	LR	2260 ± 400	$(05-06)/kW	2288
NGCC with post-combustion capture					
36	IEA GHG [16]	PS	869	$(04)/kW	1001
37	IEA GHG [17]	PS	1280	$(04)/kW	1491
38	IPCC [10]	LR	998	$(02)/kW	1766
39	IEA GHG [19]	CM	916	$(02)/kW	1622
40	Euracoal [21]	EO	1140	€(06)/kW	1390
41	NETL [22]	PS	1172	$(06)/kW	1138
42	CCC [24]	LR	1300 ± 300	€(07)/kW	1519
43	IEA [23]	EO	1100	$(07)/kW	937
44	JRC	CM	1200	€(05)/kW	1387
45	Belfer [25]	LR	1140 ± 150	$(05-06)/kW	1133

* PS: prefeasibility study, CM: cost model, LR: literature review, EO: expert opinion

3.1.1 Comparison of overnight capital costs of IGCC-CCS plants

The harmonised overnight specific capital costs of IGCC plants with pre-combustion capture (IGCC-CCS) are shown in Figure 1. They range from 1835 to 5669 €/kW. Both these values have been provided by the industry, hence it has not been possible to look into the methodology followed and the assumptions made for their calculation. It is also noted that the maximum value is significantly higher than the second largest reported value. This is likely due to the fact that the most expensive plant uses lignite as feedstock, which results in higher costs due to the additional equipment for lignite drying.

The prefeasibility studies report quite similar values: costs range between 2361 and 3004 €/kW with an average value of 2539 €/kW. This range in costs is likely due to the fact that three different gasifier types were evaluated. The JRC estimation (2566 €/kW) is quite in line with this average figure. The IECM model as was used in the IEA GHG study estimates a value that is 28% higher, due to the assumption of higher costs for the gasifier, the sulphur recovery and the CO_2 separation sub-systems, despite the fact that the components considered in this IEA GHG study were very similar to the ones considered in all prefeasibility studies.

Two literature reviews report figures, which are different from those of the analytical studies. The IPCC Special Report presents a value which is 27% higher than the average of the prefeasibility studies, possibly due to the fact that it has considered older analyses, which were published prior to 2005, when the uncertainty about the technology and hence about costs was higher than today; and Climate Change Capital reports a lower figure (1870 €/kW). On the other hand, the average value of the harmonised costs listed in Annex B of the Belfer paper (2431 €/kW) is quite close (5% lower) to the average value of the prefeasibility studies and the JRC estimation. The figures reported by IEA and Euracoal are also lower than the average estimations of the prefeasibility studies (by 14% and 22% respectively). As it is not described in detail how the latter figures have been calculated, this difference cannot be commented on. Finally, three industrial stakeholders have provided cost values for their IGCC-CCS projects which vary widely, ranging between 1835 and 5669 €/kW. Again, these differences cannot be commented on since the background information is not available.

Proposing a reference cost value, based on such a diverse pool of data is challenging and clearly subjective. In the context of this analysis, the reference value was calculated from the average values of the prefeasibility studies, the cost models, and the expert opinion of organisations[8], weighted in such a way to account for the robustness of data, as already described in the previous section. To this end, the weighting factors assumed for the averages of the prefeasibility studies, the cost models, and the expert opinions were 0.6, 0.3 and 0.1 respectively. Although this approach, subjective by definition, is rather imprecise, it does serve the purpose of this analysis by considering all related available information. Furthermore, a sensitivity analysis, which accompanies the cost analysis that follows, highlights the impact of uncertainty in capital costs to the total cost of a CCS demonstration plant. It is noted that the reference cost values will be continuously updated using this methodology as more data become available in the literature.

Based on the data and methodology presented above, the value of 2700 €/kW is proposed as the reference for the overnight specific capital costs of the demonstration IGCC-CCS plant. This figure is equivalent to the reference value published in mid-2008 by the European Commission in the frame of the 2nd Strategic European Energy Review (SEER) [9]. When expressed in 2005 Euros using the CEPCI values for January 2007 (as assumed in the 2nd SEER report), the current figure becomes just 5% higher than that of the 2008 reference value.

[8] *The figures from the literature reviews were not considered for the calculation of reference values.*

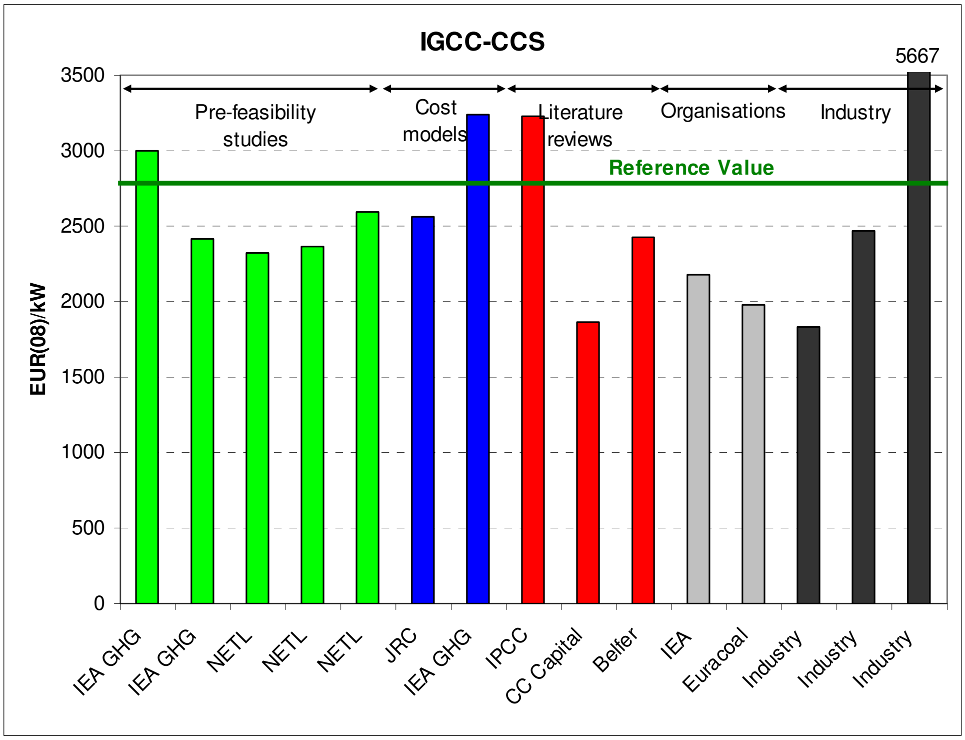

Figure 1: Harmonised overnight specific capital investment costs for the IGCC-CCS plant

3.1.2 Comparison of overnight capital costs of PF-CCS plants

The harmonised reported overnight specific capital investment costs for PF-CCS plants with post-combustion capture range between 1641 €/kW and 3710 €/kW (Figure 2). The lowest figure comes from the industry and the highest from the IPCC Special Report. The capital costs from the two prefeasibility studies are 2021 €/kW and 2785 €/kW with an average value of 2405 €/kW. The difference between the two figures is due to the higher costs of the CO_2 capture system in the NETL report (about 640 €/kW higher than in the IEA GHG report), despite the fact that both studies assume the same type of capture equipment, i.e. Econamine FG Plus by Fluor. The estimates from the cost models are in agreement with the results of the prefeasibility studies, being closer to the estimations by NETL: the JRC and IECM's estimations are 14% and 7% higher than the average of the prefeasibility studies respectively. The JRC figure is practically identical to the NETL result and the IECM value is 7% lower. As in the case of IGCC-CCS, the IPCC Special Report provides a higher value than the averages of the prefeasibility studies and cost models, while Climate Change Capital a lower value. The average harmonised value from the studies mentioned in Annex A of the Belfer paper is comparable with the average value of the prefeasibility studies and the result of the JRC cost model (6% higher and 7% lower respectively). Furthermore the figure reported by IEA is close to the average of the prefeasibility studies while that of Euracoal is 16% lower. Finally, the industry provided cost figures for four plants that range between 1667 €/kW and 2785 €/kW.

Following the methodology described in the previous section, the reference value for the specific capital cost of a demonstration PF-CCS plant is set to 2500 €/kW. This figure, after the necessary adjustments for inflation and cost escalation, is 9% lower than the 2008 reference value in the annex to the 2nd SEER. The reason for this change is the consideration of the NETL study in this analysis, which was not available at the time of preparing the analysis for the 2nd SEER.

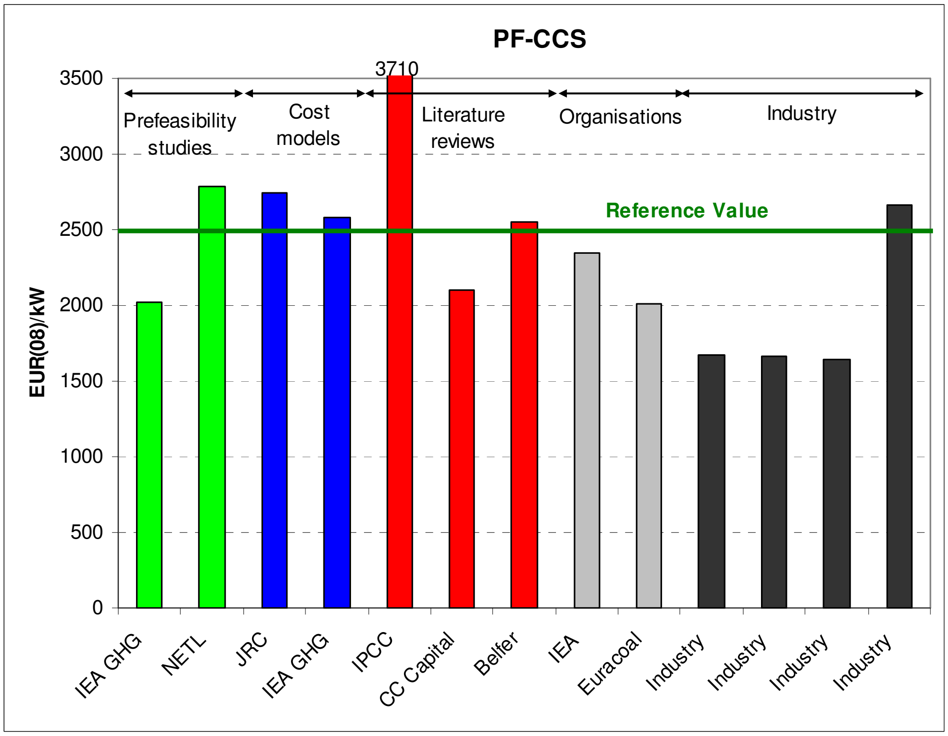

Figure 2: Harmonised overnight specific capital investment costs for the PF-CCS plant

3.1.3 Comparison of overnight capital costs of oxyfuel coal plants

Despite the increased interest of European stakeholders in oxyfuel combustion and the recent inauguration of a 30 MW_t pilot plant in Germany, cost figures in the literature about this technology are scarce. The reported values in the available literature are in the range of 2122 €/kW to 4279 €/kW, see Figure 3. The lowest figure comes from Euracoal and the highest from the IECM cost model as presented in [19]. Only one prefeasibility study was identified, which estimates the cost as 2595 €/kW. The average harmonised value from two studies mentioned in annex A of the Belfer paper (2288 €/kW) is 12% lower than the value from the prefeasibility study. The values from the IEA and Euracoal converge to a figure of 2127 €/kW. The estimations of IECM are much higher (4279 €/kW), due to the consideration of relatively expensive air separation units, boilers and steam turbines. It is noted that neither the JRC nor NETL provide cost figures for this technology. On the other hand, one industrial stakeholder reports a relatively low figure (1709 €/kW), which is however not supported by calculations.

Based on the adopted methodology a value of 2900€/kW is proposed as the reference specific capital cost for the oxyfuel technology. It is noted that the annex to the 2nd SEER [9] did not consider oxyfuel power plants.

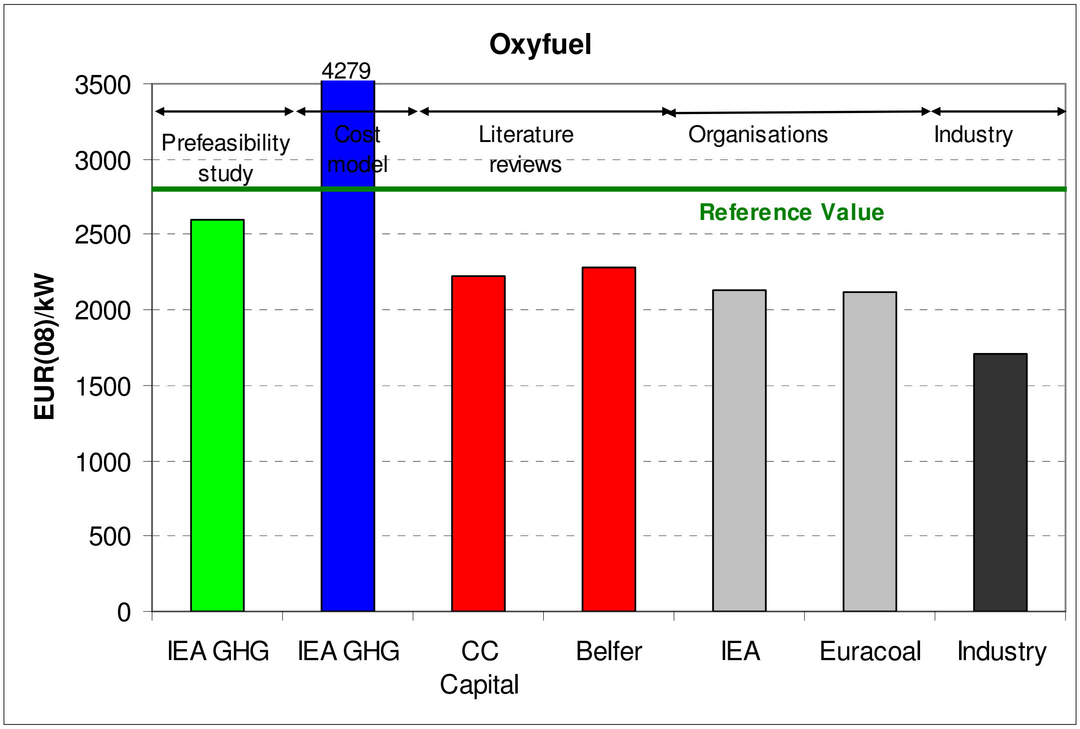

Figure 3: Harmonised overnight specific capital investment costs for the oxyfuel plant

3.1.4 Comparison of overnight capital costs of NGCC-CCS plants

The harmonised costs for NGCC-CCS plants with post-combustion capture range between 937 €/kW and 1766 €/kW, see Figure 4. The lowest value comes from the IEA report and the highest from the IPCC Special Report. The reported costs in the three prefeasibility studies range between 1001 €/kW and 1491€/kW, with an average value of 1210 €/kW. It is noted that the highest reported cost refers to a retrofit plant. The difference in these figures is due to the assumed costs for the CO_2 capture unit and to a lesser extent for the power island although all these studies consider the same type of equipment, i.e. F-class gas turbines and Econamine FG capture systems. This highlights the issue of accuracy of component costs, which in most cases can only be provided by the vendors. The cost models tend to converge to the upper range of the cost values reported in the prefeasibility studies. The IPCC Special Report provides a higher cost value, while the Climate Change Capital value lies within the range of the cost models and the prefeasibility study with the highest cost. The average harmonised value from the studies that appear in annex C of the Belfer paper (1133 €/kW) is 6% lower than the average of the prefeasibility studies. The value reported by IEA is in line with the prefeasibility studies (937 €/kW) while that of Euracoal is closer to the values of the cost models and the upper range of the figures reported in the prefeasibility studies. The industry did not provide the European Commission with cost values for this type of power plant.

The calculated reference value for the specific capital investment is 1300 €/kW. This figure is 11% lower than that of the 2008 reference value presented in the annex to the 2nd SEER [9], and reflects the expanded pool of information used in the current analysis.

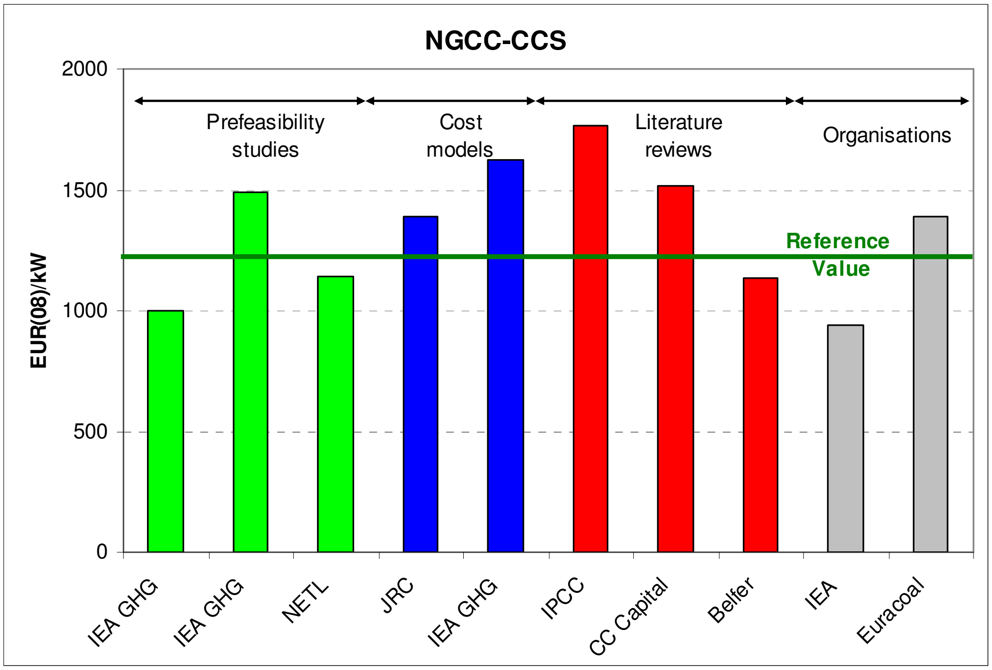

Figure 4: Harmonised overnight specific capital investment costs for the NGCC-CCS plant

Points to remember

- The capital costs of CCS demonstration plants reported in the literature are the results of prefeasibility analyses, cost models, expert opinion, or averages of previously reported values, hence the robustness of the publicly available information varies widely.
- There is higher uncertainty for the costs of some types of CCS-plants, stemming from the uncertainty in the cost of specific plant components and the small pool of available information.
- The following figures are proposed as reference values for the overnight specific capital costs of CCS demonstration projects:
  - IGCC-CCS: 2700 €(08)/kW
  - PF-CCS: 2500 €(08)/kW
  - Oxyfuel: 2900 €(08)/kW
  - NGCC-CCS: 1300 €(08)/kW
- In view of the uncertainty (about 30%) in the above figures, it appears that there is no significant difference in the capital costs between the different types of coal-fuelled CCS demonstration plant (2700 €/kW ±7%).

3.2 Review of operating costs and efficiencies of CCS power plants

The operating costs of a power plant comprise:

- The fixed operating and maintenance (FOM) costs, which are independent of the amount of electricity the plant generates, such as taxes and insurance, personnel, administration, and, typically, the annual overhaul.
- The variable operating and maintenance (VOM) costs, which are proportional to the amount of electricity generated and include the cost of consumables (chemicals, catalysts, etc), the cost of waste disposal and the cost of unscheduled repairs.
- The fuel and CO_2 costs[9], which depend on the efficiency of the power plant and the type of fuel utilised.

The setting of reference values for FOM and VOM costs of CCS plants is a challenging task. Information about FOM and VOM costs is very scarce in the literature. For example, from the literature sources considered in this analysis, only the prefeasibility studies provide such information, as well as the industry, however, for a limited number of cases. This is because the industry is very reluctant to publicise such figures for any power plant, as they reveal information about power plant performance, operating conditions and likely marginal cost pricing. Furthermore, even when such figures are available, their interpretation and comparison is not straightforward. Salaries vary between regions and countries, maintenance depends on power plant operating conditions and fuel used, and the distribution of the various cost elements between FOM and VOM is rather arbitrary. For example, depending on a utility's accounting practice, the annual overhaul may be included in the variable costs, or taxes excluded at all from reporting. Furthermore, the costs for FOM and VOM vary throughout the lifetime of a plant.

Table 3 summarises the reported costs for FOM and VOM (as well as for process efficiencies) from the literature sources used in this analysis. These values have been converted to 2008 Euros and have been harmonised (by excluding insurance and taxes when reported and by assigning scheduled maintenance costs to FOM) to facilitate the comparison of costs between technologies and the calculation of reference values. The reference values have been deduced from the average values reported by the prefeasibility studies and the industry, using as weighting factors the values of 0.8 and 0.2 respectively. The same approach was used to set the reference values for process efficiency.

The following comments can be made for the FOM and VOM costs of the various technologies:

- IGCC-CCS: There is a good agreement between the reported figures for both FOM and VOM costs in the literature. The difference in the reported values lies on the type of gasifier considered. The reference values for FOM and VOM are 75 €/kW and 2.1€/kWh respectively.
- PF-CCS: The reported figures for FOM and VOM costs in the literature are comparable. The reference values for FOM and VOM costs are 65 €/kW and 4.5 €/kWh respectively.
- Oxyfuel: There is a significant difference between the two reported figures. On the one hand, the value for FOM in the IEA GHG study seems high, while that for VOM low; on the other hand, there is no means of validating the figures reported by the industry. The values of 90 €/kW for FOM and 0.9 €/MWh for VOM have been assumed as reference values for this technology.

[9] In this analysis it is assumed that every power plant pays for each tonne of CO_2 emitted in the atmosphere according to the prevailing CO_2 price. In this context, CO_2 captured from CCS plants is not accounted for in the calculation of the CO_2 costs.

- NGCC-CCS: In general, there is a good agreement between the reported figures in the literature for FOM and VOM costs. It is noted that the highest FOM value refers to a retrofit plant. The reference values for FOM and VOM costs are 38 €/kW and 0.9 €/kWh respectively.
- Concerning process efficiencies, the reported figures for all coal-fired CCS technologies converge to a value of 35%, while for NGCC-CCS to 46%.
- The above mentioned reference values are comparable with those presented in the annex to the 2nd SEER [9]. The current reference values have relied on a wider pool of information.

Table 3: FOM, VOM and efficiency values from the literature for CCS demonstration plants

Source	Currency	FOM (per kW installed capacity)		VOM (per kWh generated)		Efficiency (% LHV[10])
		Reported value	Harmonised €(08)/kW	Reported value	Harmonised €(08)/kWh	
IGCC with pre-combustion capture						
IEA GHG [15]	$(03)	43.7	71	1.2	2.0	35
IEA GHG [15]	$(03)	43.7	71	1.5	2.3	32
NETL [22]	$(06)	87.4	81	1.8	1.6	34
NETL [22]	$(06)	88.0	82	1.8	1.6	35
NETL [22]	$(06)	93.0	86	1.9	1.8	34
Industry	€(07)	*	60	2.5	2.9	35
PC with post-combustion capture						
IEA GHG [16]	$(04)	69.4	80	3.5	4.1	35
NETL [22]	$(06)	65.8	61	5.2	4.8	29
Industry	€(07)	*	43	3.2	3.7	43
Industry	€(07)	*	42	5.0	5.8	43
PC-oxyfuel						
IEA GHG [14]	€(05)	77.9	104	0.1	0.1	35
Industry	€(07)	*	44	3.1	3.6	41
NGCC with post-combustion capture						
IEA GHG [16]	$(04)	49.5	56	0.5	0.6	45
IEA GHG [17]	$(04)	26.4	30	1.0	1.2	47
NETL [22]	$(06)	29.2	27	0.9	0.8	46

* The values provided by the industry are not shown.

[10] *LHV stands for Low Heating Value.*

Points to remember

- There is limited information available concerning the FOM and VOM costs of CCS plants. Nevertheless, there is a good agreement between the values in the literature for IGCC, PF and NGCC CCS plants.
- The following reference values for FOM and VOM costs are proposed:
  - IGCC-CCS: FOM: 75 €/kW VOM: 2.1 €/MWh
  - PF-CCS: FOM: 65 €/kW VOM: 4.5 €/MWh
  - Oxyfuel: FOM: 90 €/kW VOM: 0.9 €/MWh
  - NGCC-CCS: FOM: 38 €/kW VOM: 0.9 €/MWh
- The following reference values for efficiency are proposed:
  - IGCC-CCS: 35%
  - PF-CCS: 35%
  - Oxyfuel: 35%
  - NGCC-CCS: 46%

3.3 Review of published costs for CO_2 transport and storage

As was pointed out in Section 2, the cost of CO_2 transport and storage is case-specific. With regards to transport, it is expected that the first demonstration plants will use pipelines rather than ships to deliver the captured CO_2 to the storage sites. The capital costs of a pipeline are dictated by its length and diameter, which depends on the quantity of CO_2 that will be transported. In addition, there are other important factors that can influence pipeline costs. According to the IPCC Special Report on CCS [10], pipeline costs may increase in congested and heavily populated areas by 50% to 100% compared to a pipeline in remote areas, or when crossing mountains, natural reserves, rivers, roads, etc.; and off-shore pipelines are 40% to 70% more expensive than similar pipelines built on land.

Similarly, storage costs are site-specific. Costs will depend on the type of the geological formation that will be used for CO_2 storage, reservoir depth, geological properties and structure, etc. These factors will affect the length, type and number of injection wells, injection profiles etc. As the IPCC Special Report [10] points out, storage costs reported in dedicated studies lie within the range of 0.2-30 US$/t CO_2 stored, reflecting the diversity of properties of geological storage sites.

There are many views on how the CO_2 transport and storage infrastructure will evolve in Europe. There has been a perception that CCS demonstration plants will be built very close to potential storage sites for minimising the corresponding costs. On the other hand, proposals for CCS demonstration projects that have become public [29], tend to show that the location of the first CCS plants will be dictated by other factors, such as safety and public acceptance concerns that may require that CO_2 is initially stored offshore, or the existence of an old power plant that is suitable for retrofitting or refurbishing. For example, the Janschwalde project in Germany [30] foresees a 150 km long inland pipeline, the Thames cluster [31] in the UK and the Rotterdam Climate Initiative [32] 250 km offshore pipelines, etc. Hence, it is likely that the cost of CO_2 transport and storage will be initially high and then reduced, by building integrated pipeline networks or building CCS plants closer to the storage sites after experience from the demonstration projects has been acquired.

The JRC has been discussing the issue of CO_2 transport and storage costs with stakeholders interested in constructing CCS plants. Detailed case studies reveal that these costs may range between 5 €/t and 40 €/t in pipelines with capacities within the 2-3 Mt/y range, depending on the path selected for the pipeline. In the context of this analysis the JRC has assumed that the cost of CO_2 transport and storage for all CCS demonstration plants is 20 Euros per tonne of CO_2 captured, transported and stored. This figure is practically the same with that used by McKinsey & Company in their analysis [13]. In particular, the latter report assumes in its reference case for the demonstration projects that the CO_2 will be transported by 100 km on land and 200 km offshore at a cost of 15 Euros per tonne avoided, which is equivalent to 20.16 Euros per tonne captured (assuming a 10% efficiency penalty for the CCS plant).

Points to remember

- An accurate estimate of the CO_2 transport and storage costs for the CCS demonstration projects can be made only after the locations of the power plant and the storage site, the pipeline path and the type of the storage site are known.
- This cost may vary between 5€/t and 40 €/t.
- This study assumes that the cost of CO_2 transport and storage for all CCS demonstration plants is 20 Euros per tonne of CO_2 captured.

4 THE ADDITIONAL LIFETIME COSTS OF CCS DEMONSTRATION POWER PLANTS

The lifetime costs of a power plant comprise the initial investments for the construction of the infrastructure, the cumulative FOM, VOM, fuel and CO_2 costs incurred during its operational life, and, the revenues from the sales of electricity (and from any other by-products, which are however not considered in this analysis). Hence, the additional lifetime costs of a CCS demonstration plant compared to a reference state-of-the-art conventional plant that uses the same fuel and is of the same net electricity output entails the increased capital and operating costs of the power plant -including the total costs of the CO_2 capture system-, the pipelines, and the storage and monitoring facilities, reduced by the avoided CO_2 costs from the lesser amount of CO_2 that the CCS plant emits to the atmosphere.

In the context of this analysis, the lifetime costs of CCS demonstration plants have been calculated using the reference values for capital and operating costs presented in the previous section. The additional lifetime costs have been assessed based on the comparison of coal-fired CCS plants with a state-of-the-art supercritical coal-fired power plant without capture, and of the NGCC-CCS plant with a similar plant without CCS, following a methodology that is described below. Such an assumption could however be argued. A utility may decide to compare a CCS project with the most competitive conventional fossil fuel power generation technology, which may not necessarily use the same fuel as the CCS plant, or, make such a comparison based on an *a priori* decision on fuel, as in this case, for reasons such as the diversification of fuel usage in its fleet to reduce price and supply risks, or preference for a fuel type based on prior experience.

4.1 Methodology

The calculation of the lifetime costs of the reference conventional plant and the CCS demonstration plant, which in the context of this analysis are considered as investment projects, is based on the assessment of their economic feasibility through their operational life based on the cash flows estimated for each year of their operation.

The economic feasibility assessment is based on the assumption that the CCS plant sells electricity at a price equal to that of the reference conventional plant, which operates in a carbon-pricing environment and uses the same fuel, as mentioned above. The selling price is set equal to the levelised electricity production cost of the conventional plant. This is calculated through a discounted cash flow analysis based on the assumption that revenues from electricity sales of the conventional plant over its lifetime ensure a net profit that provides the investor with a predefined internal rate of return (IRR).

Subsequently, income statements, balance sheets and cash flow statements for the CCS plant are calculated, assuming that the CCS plant sells the same amount of electricity as the conventional plant. The additional costs of the CCS plant are presented both as a cumulative undiscounted expenditure over its lifetime and as a net present value (NPV) of all cash flows during the plant lifetime.

Finally, the additional revenues needed so that the CCS demonstration plant has the same economic performance with the conventional plant[11] are normalised to the amount of CO_2 avoided or CO_2 captured and to the amount of electricity generated.

The economic feasibility analysis is performed based on a set of assumptions concerning fuel and CO_2 prices and technology performance (*reference case*). This is complemented by a *baseline case* and a sensitivity analysis. The *baseline case* is identical to the *reference case* but it assumes that there is no CO_2 price, i.e. power plants do not have to pay for the CO_2 they emit. Hence the *baseline case* refers to the situation where there are no financial benefits from CO_2 capture. The sensitivity analysis aims at assessing the robustness of the calculated results with regards to variations in the assumptions, such as for capital and operating costs, fuel and CO_2 prices, the discount rate, capacity factors, etc.

4.2 Assumptions

The *reference case* is based on the following assumptions:

Project characteristics

- Financing: 100% equity
- Pre-tax discount rate: 10%
- Project lifetime: 20 years for both the conventional and the CCS demonstration plants
- Construction time: 3 years for the conventional and 4 years for the CCS plant, with an *a priori* defined expenditure profile.
- Start of operation: 2015
- Plant capacity: 400 MW net electrical output
- Capacity factor: 85%
- Capture rate of CCS plant: 85%

Technology characteristics

- CCS plants: According to the reference values proposed in Section 3 (also shown in Table 4)
- Reference conventional plants: According to the reference values presented in the annex to the 2nd SEER [9], harmonised to reflect costs at the first quarter of 2009 in 2008 Euros.
- Cost of CO_2 transport and storage: €20 per tonne captured

Table 4: Assumptions for the techno-economic performance of power plants

	Reference		CCS – Demonstration			
	PF	NGCC	IGCC-CCS	PF-CCS	Oxyfuel	NGCC-CCS
Capital Cost (€/kW)	1478	742	2700	2500	2900	1300
FOM (€/kW)	64	27	75	65	90	38
VOM (€/MWh)	0.9	0.05	2.1	4.5	0.9	0.9
Efficiency (%)	46	58	35	35	35	46

[11] *This implies that CCS plants become competitive with conventional power plants.*

Fuel and CO_2 prices

To ensure the compatibility of this analysis with previous assessments of the European Commission, this work adopts for fuel and CO_2 prices the values used in the 2nd SEER [9]. These values are shown in Table 5. As already mentioned above, there is no CO_2 price in the *baseline case*.

Table 5: Fuel and CO_2 prices [9]

	Coal price (€/GJ)	Natural gas price (€/GJ)	CO_2 price (€/t)
2015	2.2	6.6	35*
2020	2.3	7.1	41
2025	2.4	7.5	44*
2030	2.5	7.6	47
2034	2.6*	7.7*	50*

* Values assumed by the JRC

The following sensitivity cases have also been assessed:

1. *High CAPEX:* Increased capital and FOM costs for the CCS plant by 20%
2. *High VOM*: Increased VOM costs for the CCS plant by 20%
3. *High costs*: combination of Cases 2 and 3 above
4. *High fuel:* Higher fuel prices based on the HOP! Project [9], see Table 6.

Table 6: High fuel prices [9]

	Coal price (€/GJ)	Natural gas price (€/GJ)
2015	3.1	9.5
2020	3.8	12.2
2025	4.2	12.7
2030	4.5	14.2
2034	4.7*	15.0*

* Values assumed by the JRC

5. *Low T&S:* Lower CO_2 transport and storage costs (10 €/t).
6. *Ramp CF:* Ramping capacity factors for both the conventional and CCS plants taking into consideration start-up effects. It is assumed that the capacity factor of the conventional plant is 70% during the first year of its operation, reaching 85% in the second year. The capacity factor of the CCS plant is assumed to be 65% in Year 1, 75% in Year 2 and 85% in Year 3 and beyond.
7. *Low CF:* The CCS plant operates at 80% capacity throughout its lifetime.
8. *Short LT:* Shorter lifetime for the CCS plant (10 years) assuming that the installed capture technology becomes obsolete in a relatively short time. In this case, the discount rate used is still 10% but the IRR of the demonstration CCS plant is set equal to the IRR of the conventional plant achieved after 10 years of operation.
9. *Low DR:* Lower discount rate (8%).

4.3 Results

4.3.1 Additional undiscounted lifetime expenditure

The additional undiscounted lifetime expenditure of a CCS demonstration plant ranges between 570 and 850 million Euros depending on the technology, see Figure 5. On average, the additional undiscounted lifetime expenditure of a 400 MW coal-fired CCS demonstration plant is around 645 ± 100 million Euros, while that of the gas-fired plant is 30% higher. The calculations show that the PF-CCS plant has the lowest additional costs, followed closely by the IGCC-CCS plant. Their cost difference is however only 37 million Euros, hence in essence, there is no difference in the additional undiscounted costs between these two plant types.

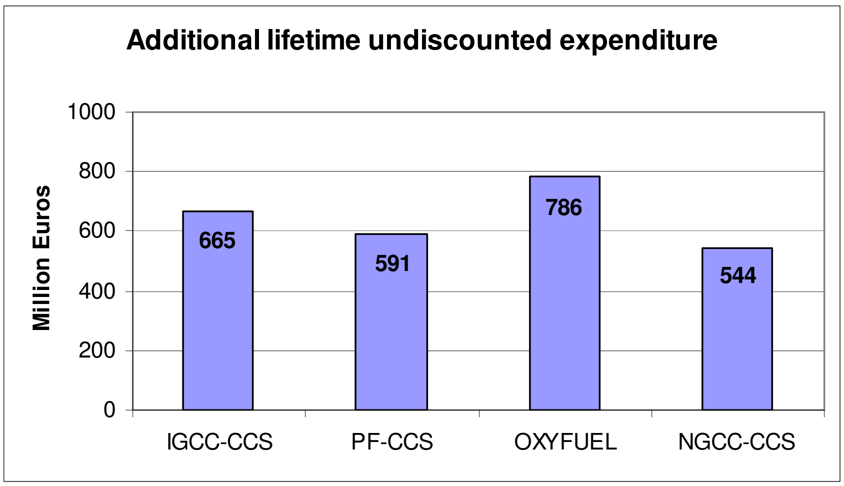

Figure 5: Additional undiscounted lifetime expenditure of a 400 MW demonstration CCS plant compared to a reference conventional plant with the same net capacity

Compared to a reference conventional power plant, a CCS demonstration plant has higher capital costs, additional costs for the transport and storage of the CO_2, higher FOM and VOM costs and higher fuel costs due to the efficiency penalty. These additional costs are counterbalanced to some extent by 'avoided' CO_2 costs since the CCS plant emits only a small fraction of the CO_2 emitted by the conventional plant.

The most important contributor to the additional undiscounted costs of a coal-fired CCS plant is the CO_2 transport and storage, followed by capital and fuel costs. This is shown in Figure 6 for the case of IGCC-CCS plant, where the cost of transport and storage accounts for almost half of the undiscounted additional costs, followed by the additional capital costs (30% of the total) and fuel costs (16%). PF-CCS and oxyfuel plants show similar patterns. For the NGCC-CCS plant, lifetime fuel costs are the main contributor to additional undiscounted costs (48% of the total), followed by the cost of transport and storage and the additional capital costs. The contributors to the additional undiscounted expenditure of the different types of CCS plant are shown in Figure 7.

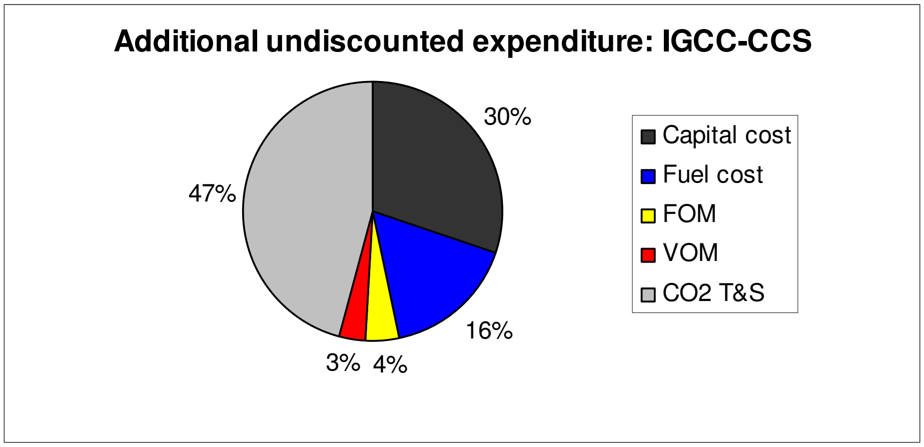

Figure 6: Breakdown of the additional undiscounted expenditure for a demonstration IGCC-CCS plant

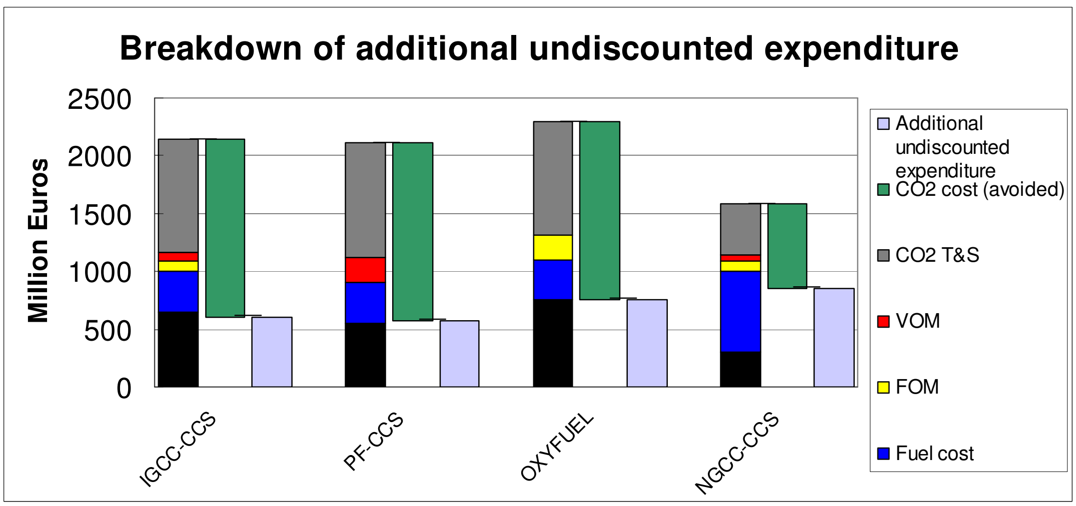

Figure 7: Breakdown of additional undiscounted costs for CCS demonstration projects

The break-down of additional undiscounted lifetime expenditure helps explaining the difference between the coal- and gas-fired plants. Although the total additional costs for a gas plant are lower than those for a coal plant (by about 30%), cumulative cost savings from CO_2 which is not emitted by the NGCC-CCS plant are only about 50% of those from the coal plants, due to the lower carbon intensity of natural gas. Hence, the additional undiscounted lifetime expenditure of the NGCC-CCS plant is larger than that of any coal-fired CCS plant.

The role of the CO_2 price is highlighted in the *baseline case*, which assumes that a power plant does not pay for the CO_2 it emits. In this case, a CCS demonstration plant does not benefit financially from capturing (i.e. not emitting) the CO_2 it generates whilst still carries all the costs mentioned above, in the hypothetical situation that it still operates as in the *reference case*. The additional undiscounted lifetime expenditure then ranges between 1600 and 2300 million Euros depending on the technology.

4.3.2 Project economics

The picture portrayed above changes when the additional lifetime expenditure is discounted to the first year of power plant operation. The difference in net present value between a 400 MW CCS demonstration project and the corresponding conventional power plant project (which is by definition set equal to zero), is shown in Figure 8. The additional discounted costs of the coal-fired CCS demonstration plants are on average 680 ± 100 million Euros, while for the NGCC-CCS plant are calculated to be 550 million Euros. For the coal-fired projects, the largest contributor to the additional discounted costs is the additional discounted capital costs (650 ± 100 million Euros), followed by the discounted CO_2 transport and storage costs (420 million Euros) and fuel costs (145 million Euros). It is noted that the discounted avoided CO_2 costs are 620 million Euros and nearly balance out the additional discounted operating (fuel, FOM, VOM and CO_2 transport and storage) costs. Among the coal-fired options, PF-CCS demonstrates the lowest additional discounted costs (590 million Euros) followed closely by IGCC-CCS (660 million Euros). The situation for NGCC-CCS plants is different, due to the higher importance of fuel costs. The discounted capital and fuel costs are 300 million Euros each and the CO_2 transport and storage costs are 190 million Euros, while the discounted avoided CO_2 costs are 300 million Euros. The breakdown of the additional discounted costs is shown in Figure 9.

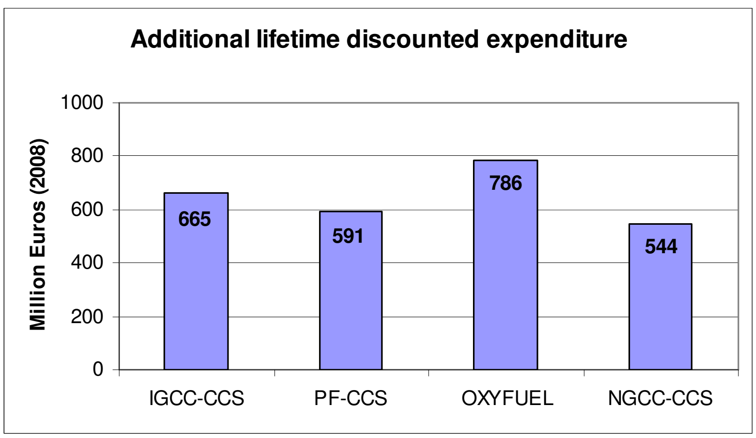

Figure 8: Additional undiscounted lifetime expenditure of a 400 MW demonstration CCS plant compared to a reference conventional plant with the same net capacity

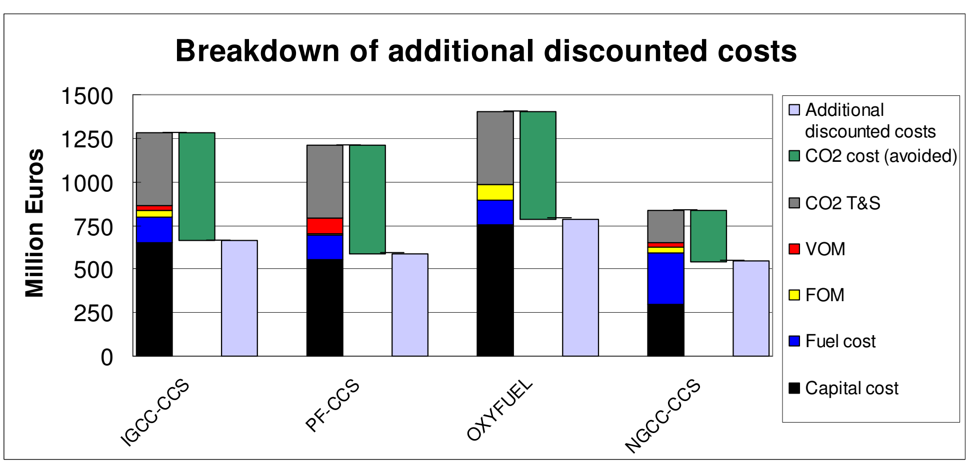

Figure 9: Additional discounted costs for a 400 MW CCS demonstration plant, showing the contribution of discounted capital and operating expenditure

4.3.3 Normalised additional revenue

A useful reference is to normalise the additional cost of a CCS project to the amount of CO_2 avoided or CO_2 captured. The annual quantities of CO_2 avoided compared to the reference conventional plant and those captured throughout the operation of the CCS demonstration plant have been calculated based on the fuel carbon intensity, plant efficiency and operating conditions. They are shown in Table 7[12]. The normalisation procedure calculates the additional revenue per tonne of CO_2 (either avoided or captured) that brings the CCS project to the required IRR of 10%. In other words, a subsidy per tonne of CO_2 (either avoided or captured) is assumed for the CCS project, and this subsidy is adjusted until the NPV is zero, i.e. until the CCS demonstration plant becomes competitive with the conventional power plant.

Table 7: Annual CO_2 avoided and captured by the CCS demonstration plants in the reference case

Plant type	Avoided ('000 t)	Captured ('000 t)
Coal-fired	1770	2463
Gas-fired	841	1112

The results are presented in Figure 10 and Figure 11. The required additional revenue per tonne of CO_2 avoided for the coal-fired CCS demonstration plants ranges between 40 €/t and 53 €/t, with an average value of 46 €/t. The difference between PF-CCS and IGCC-CCS is 5€/t. The corresponding figure for the NGCC-CCS plant is 77 €/t. The required revenue normalised to the quantity of CO_2 captured ranges between 29 €/t and 38 €/t for the coal-fired CCS plants with an average value of 33 €/t. The corresponding figure for the NGCC-CCS plant is 58 €/t.

It is reminded that these figures have been calculated having assumed a CO_2 price. In the *baseline case* where there is no CO_2 price, the average values for additional revenue per tonne of CO_2 avoided and captured for the coal-fired CCS plants are 87 €/t and 62 €/t respectively. The corresponding figures for the NGCC-CCS plant are 118 €/t and 90 €/t.

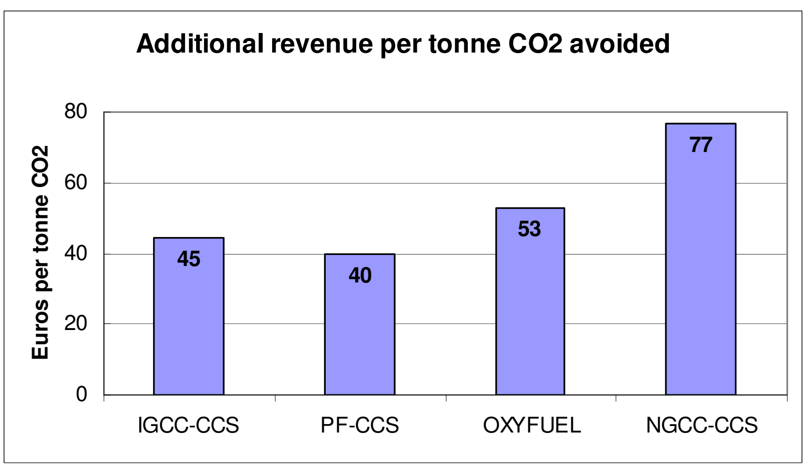

Figure 10: Additional financial support per tonne of CO_2 avoided

[12] *These calculations imply that each demonstration coal plant will capture 49.3 Mt CO_2 during its lifetime and will avoid 35.4 Mt. The corresponding figures for the gas plant are 22.2 Mt and 16.8 Mt.*

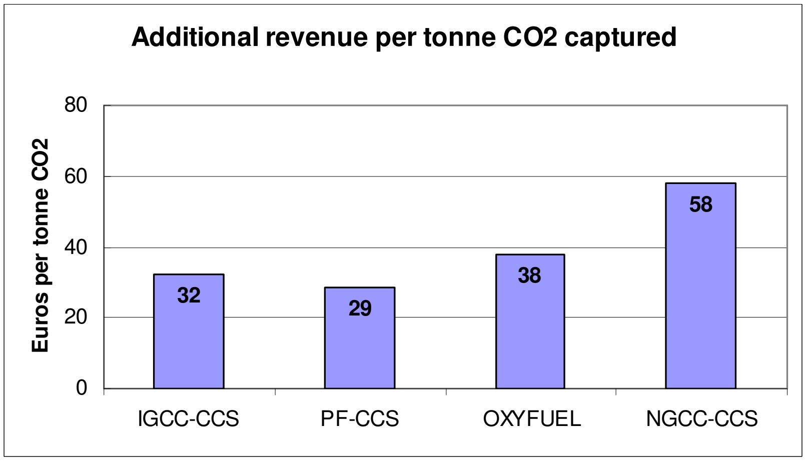

Figure 11: Additional financial support per tonne of CO_2 captured

Similarly, the additional discounted costs of a CCS demonstration project can be normalised to the amount of electricity generated during its lifetime, using a procedure similar to that used for normalising the additional costs to the amount of CO_2 avoided or captured. This figure represents the additional levelised cost for the CCS demonstration plant compared to a similar conventional plant, or, in other words, the financial support required by the CCS demonstration plant per unit of electricity generated, in order for the CCS project to be competitive with conventional power plants.

Under the assumptions of the *reference case*, the additional levelised cost of coal-fired CCS demonstration plants ranges between 23.3 €/MWh and 31.0 €/MWh depending on the technology, while for the NGCC plant, it is 21.5 €/MWh. This represents an increase of the order of 27% to 36% on top of the levelised cost of the conventional technology in the reference case, for all CCS plant types.

4.3.4 Sensitivity analysis

As already mentioned above, a sensitivity analysis has been preformed to assess any dependencies of the above results on the key assumptions of the *baseline case*, namely on capital expenditure (CAPEX) and FOM costs, VOM costs, fuel costs, CO_2 transport and storage (T&S) costs, the capacity factor (CF) and the discount rate (DR).

The results of the sensitivity analysis for the additional discounted lifetime costs of the CCS demonstration projects and for the additional revenue per tonne of CO_2 avoided are summarised in Figure 12 and in Figure 13 respectively.

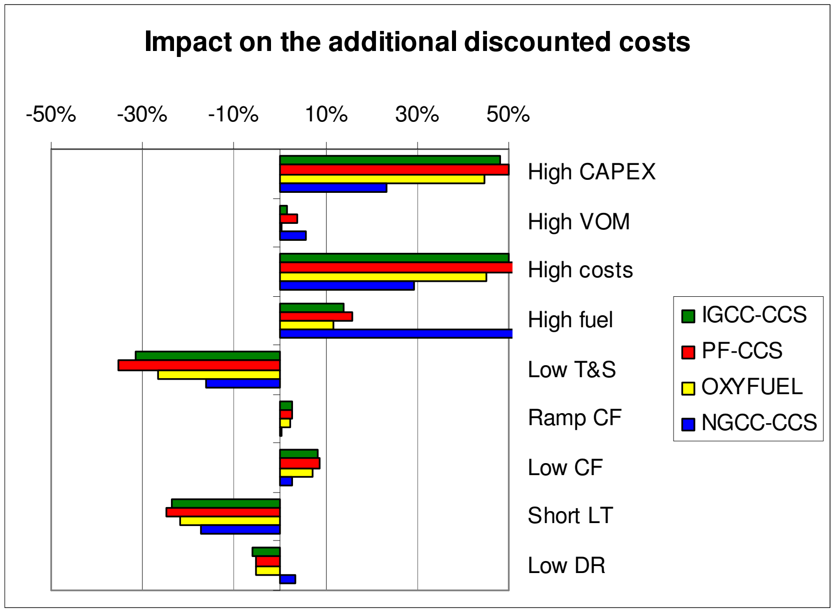

Figure 12: Sensitivity analysis - Impact on the additional discounted costs

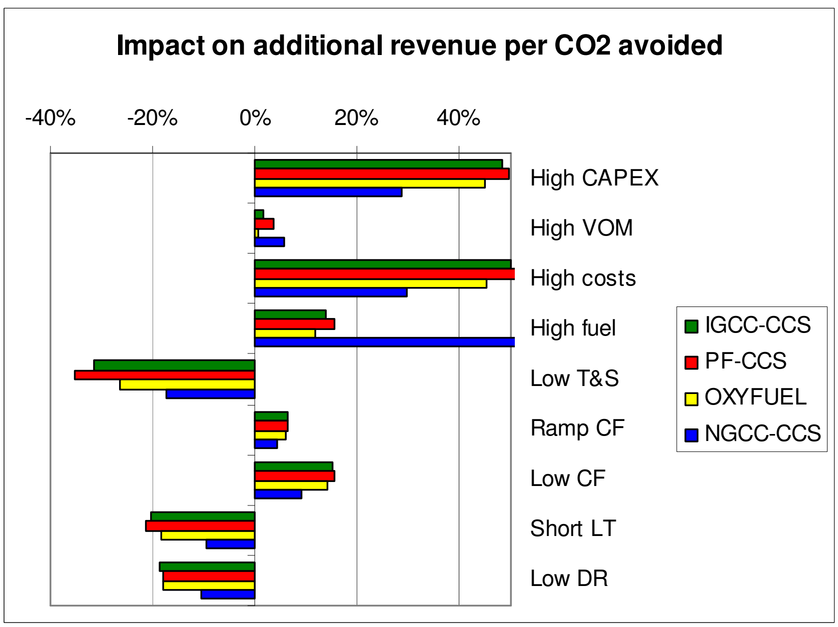

Figure 13: Sensitivity analysis - Impact on the additional financial support per tonne of CO_2 avoided

The following conclusions can be drawn from the sensitivity analysis:

- Capital costs play a very significant role in the economic assessment of CCS demonstration projects. In this analysis, a 20% increase in the capital and FOM costs of a coal-fired CCS demonstration plant results in a 45-50% increase in the additional discounted costs and in the normalised additional revenue (per CO_2 avoided). The corresponding figures for the NGCC-CCS project and 23% and 29% respectively.

- The VOM costs do not affect significantly the cost analysis. A 20% increase in VOM costs increases the additional discounted costs and the normalised additional revenue by up to 6% for all CCS projects.
- Halving the costs of transport and storage results in a reduction of the additional discounted costs and the needs for additional revenue by 27-35% for the coal projects and by 16% for the gas project.
- The assumption of a ramping capacity factor does not affect significantly the cost analysis. The additional discounted costs increase by up to 3% and the normalised additional revenue by up to 7% for all projects.
- The decrease in the operational life of the demonstration plant to 10 years increases the additional discounted costs of the coal plants by 22% to 25% and the normalised additional revenue by 20%. The effect on the NGCC-CCS project is less important, as the additional discounted costs are reduced by 17% and the normalised additional revenue by 10%.
- A decreased capacity factor for the CCS plant to 80% can increase the additional discounted costs by 3-9% and the normalised additional revenue by 9-15% due to the resulting reduction of CO_2 avoided emissions.
- A decrease in the discount rate from 10% to 8% results in a decrease in the additional discounted costs of the coal plants by 5%. On the other hand, the additional discounted costs increase by 3% for the NGCC-CCS project, as significant operating costs are accrued at later years of the project, as explained above. The discount rate has a significant effect on the normalised additional revenue as this value is reduced by 18% for coal plants and 10% for the gas plant, due to the reduced profitability of the projects.
- Fuel prices influence the economic performance of the gas plant more than that of coal plants. While, overall, the fuel prices in the sensitivity analysis are 70% higher than in the *reference case*, the additional discounted costs and the normalised additional revenue for the coal plants increase by 12-14%, while for the gas-plant by 89%.

This sensitivity analysis highlights that the key factors that affect the economic performance of a CCS demonstration plant are:

- Capital costs, hence R&D and demonstration efforts should be steered towards cost reductions.
- The cost of CO_2 transport and storage, highlighting the need for locating the capture plant as close as possible to the storage site.
- The lifetime of the demonstration CCS project, which should be similar to that of conventional power plants.
- The discount rate and the fuel and CO_2 prices

4.3.5 Comparison with the results of the McKinsey study

In September 2008, McKinsey & Company published a report [13] entitled 'Carbon Capture & Storage: Assessing the Economics", which was subsequently used by the ZEP ETP as the basis of costing their demonstration programme [12]. The McKinsey report estimates a *CO_2 cost,* which is equivalent to the normalised additional revenue per tonne of CO_2 avoided, calculated in this study.

The McKinsey report looks only into coal technologies and assumes a generic CCS demonstration plant, without identifying the underlying capture technology. The key differences in the assumptions between the McKinsey report and this analysis are summarised in Table 8. These differences are not substantial with the exception of the costs for CO_2 emissions, since the McKinsey Report makes the economic analysis on the assumption that there is no CO_2 price, as in the *baseline case* of this work. It is noted that the difference in assumed plant size, although will affect the magnitude of additional costs it does not influence the normalised costs since emissions, and hence quantities of CO_2 captured or avoided, scale with plant size.

McKinsey estimates the *CO_2 cost* for the CCS demonstration coal plants within the range of 60-90 Euros per tonne of CO_2 avoided, with a representative value of 72 €/t, which refers to a PF-CCS plant. On the other hand, the values calculated in this analysis for the coal-fired CCS demonstration plants range between 40 €/t and 53 €/t, see Figure 10. The value calculated for the PF-CCS demonstration plant is 39.7 €/t.

To reconcile this difference, an additional case has been analysed based on the assumptions made by the McKinsey Report. The original value of 39.7 €/t calculated in this report was adjusted to 71.5 €/t, when the McKinsey assumptions were applied, which is only 0.5 €/t lower than the McKinsey figure, see Figure 14. This result tends to show that both studies have developed a similar costing methodology. In conclusion, the main reason for the difference between the JRC and the McKinsey results is the exclusion of CO_2 costs from the latter analysis.

Table 8: Key assumptions of the McKinsey study and this study

Parameter	McKinsey & Company [13]	This study (*Reference case*)
Plant size	300 MW	400 MW
Discount rate	8%	10%
Coal price	Constant: 65 €/t (assumed herein to be equivalent to 2.65 €/GJ)	Evolving between 2.2 €/GJ and 2.6 €/GJ
CO_2 price	None	Evolving between 35 €/t and 50 €/t
Incremental CAPEX	1000 €/kW	1022-1422 €/kW (depending on the technology)
Incremental FOM	2.5% of CAPEX	1 €/kW – 26 €/kW (depending on the technology)
Incremental VOM	None mentioned	0 - 1.2 €/MWh (depending on the technology)
CO2 transport cost	15 €/t avoided (equivalent to 20.16 €/t captured)	20 €/t captured
Efficiency penalty	10%	11%
Capacity factor	80% for CCS and 86% for conventional	85% for all plants

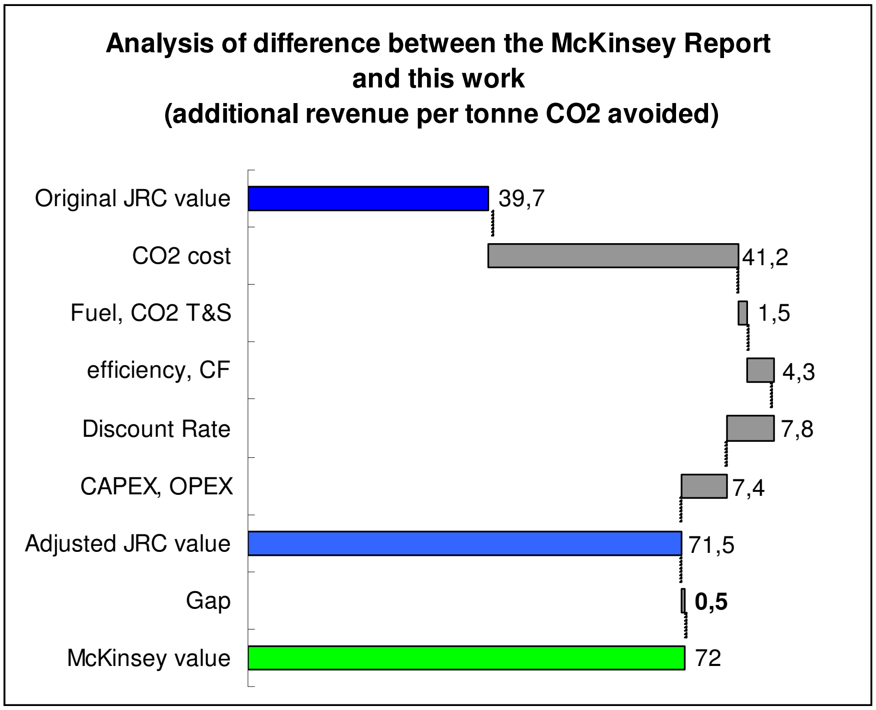

Figure 14: Analysis of the difference in additional costs for a PF-CCS demonstration plant between the McKinsey Report and this work

Points to remember

- The additional discounted lifetime costs of a 400 MW CCS demonstration plant compared to a similar conventional plant are about 680 million Euros for coal-fired technologies and 550 million Euros for gas-fired technologies.
- The level of financial support needed by the CCS demonstration plants so that they become competitive to similar conventional plants is about 46 Euros per tonne of CO_2 avoided for the coal-fired plants and 77 €/t for the NGCC plant, under the assumptions of this study and in particular for the CO_2 price. The equivalent figures per tonne of CO_2 captured are 33 €/t and 58 €/t respectively.
- The CO_2 price has a major impact on the required level of financial support. In the absence of a CO_2 price, the financial support required to make CCS demonstration plants competitive are estimated to be about 87 Euros per tonne of CO_2 avoided for coal plants and 118 Euros for gas plants.
- The most important factors that can influence the economics of a CCS demonstration project are the additional capital costs of the power plant, the costs of the CO_2 transport and storage, the lifetime of the demonstration project and the discount rate. The economic analysis is less sensitive to the VOM costs and the capacity factor.
- The results of this study are comparable with the results of the recent study by McKinsey. Their difference lies mainly on the lack of consideration of a CO_2 price in the latter study.

5 THE COST OF THE EUROPEAN CCS DEMONSTRATION PROGRAMME

In September 2009, the European Commission announced a Communication on the additional R&D and demonstration investments in low carbon energy technologies required for the facilitation of the rapid transition to a low carbon economy [5]. The financial gap between current and needed investments was calculated by assessing the cost of actions for meeting the needs for development and demonstration of each of the SET-Plan energy technologies described in [4]. The needs for each of these technologies have been elaborated in the SET-Plan Technology Roadmaps [11], which represent the seeds for the forthcoming European Industrial Initiatives (EIIs), as explained in the Introduction of this report. In this context, the Roadmaps also describe the strategic and technology objectives, propose key performance indicators for monitoring progress; and provide estimates of the indicative costs, for each of the forthcoming EIIs.

In the case of CCS technologies, the Roadmap envisages two groups of Actions that aim at: (i) proving existing technologies, and, (ii) developing more efficient and cost-competitive technologies. In essence, the first group is focused on demonstration and the second on R&D. More specifically, the demonstration component of the CCS Roadmap envisages the construction and operation of up to 12 coal-fired plants and the establishment and operation of a network of CCS projects to facilitate knowledge sharing and promote joint activities. The cost of the demonstration component of the CCS Roadmap was estimated jointly by the European Commission and the industry to be in the range of 8.5 – 13 billion Euros[13].

This cost range has been calculated by the Commission based on the following assumptions:

- The demonstration programme comprises 12 projects[14]. This reflects the maximum size for the demonstration fleet, as has been supported by the European Council in March 2007 [34]. Hence, the estimated cost figure represents a possible upper limit for the cost of the CCS demonstration programme. This fleet of demonstration plants would support a comprehensive portfolio of diverse capture and storage technologies, with a positive impact on the commercialisation of CCS technologies.
- The CCS demonstration fleet comprises coal-fired plants only, as indicated in the strategic objective of the CCS Roadmap.
- An equal number of PF-CCS, IGCC-CCS and oxyfuel plants constitute the demonstration programme. This assumption was made to avoid a prejudgement on the technology portfolio of the CCS demonstration programme, which is currently under discussion between the Member States, the industry and the European Commission.
- The cost of the demonstration programme is the sum of the additional discounted costs of each of the CCS plants, as calculated in the previous section of this report.
- The additional cost of each CCS plant ranges between the reference value, shown in Figure 8, and the value that corresponds to increased capital and operating costs by 20%, which is a typical value to account for contingencies (see Case 3 '*high costs*' of the sensitivity analysis).

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[13] *This range also includes the costs for the setup and operation of the project network.*

[14] *It is also assumed that each demonstration plant has a net capacity of 400 MW.*

Based on these assumptions and the calculations for the additional discounted costs presented in the previous section, the cost of constructing and operating a fleet of 12 demonstration plants of the PF-CCS, IGCC-CCS and oxyfuel type (four plants per each plant type) has been calculated to range between 8.2 and 12.2 billion Euros. The actual cost will depend on the characteristics of each of the demonstration plants, and the size (number of plants) and composition of the CCS demonstration fleet that will be constructed.

This cost range is quite similar to that reported by the industry. In their recent document, ZEP ETP stated that the EU demonstration programme should comprise 10-12 projects that would cost 7-12 billion Euros [12]. Based on an analysis of the technological gaps within the CCS chain, the industry has determined that, in theory, 7 CCS demonstration projects (called archetypal projects) should be sufficient for the demonstration of the technology: one of the NGCC-CCS type and two plants from each of the coal-fired types. Filling all the technological gaps and accounting for the possibility that archetypal projects may not be successful due to high technological risk, the number of projects, according to the industry, should increase to 10 or 12.

The cost of the 7 archetypal projects, calculated based on the additional costs described in the previous section of the report, is 5 – 7 billion Euros. Assuming that the fleet of 10 demonstration plants comprises the 7 archetypal projects and 1 additional coal plant per capture type, then the additional cost is raised to 7 – 10 billion Euros. Finally, a fleet of 12 plants, consisting of the previously mentioned 10 plants and additional PF-CCS and NGCC-CCS plants would cost between 8 and 12 billion Euros. Overall, the cost of 10-12 CCS demonstration projects, both coal- and gas-fired, would be in the range of 7 and 12 billion Euros, depending on the composition and size of the demonstration fleet.

Points to remember

- Estimates made by the European Commission and the industry indicate that the cost of the European CCS demonstration programme, and in particular the cost of constructing and operating a fleet of up to 12 CCS demonstration plants, will be in the range of 8 – 12.5 billion Euros.

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Abstract

The acceleration of development and the demonstration of carbon capture and storage (CCS) technologies are among the key objectives of the Strategic Energy Technology Plan (SET-Plan) of the European Union, which aims at enabling the rapid transition to a low-carbon economy. A critical element for the commercialisation of CCS is the construction and operation of up to 12 coal-fired CCS demonstration plants. The cost of this demonstration programme has been estimated to be between 8.5 and 13 billion Euros.

This cost has been estimated assuming the size and composition of the fleet of the CCS demonstration plants and by calculating, based on a cash flow analysis, their additional discounted lifetime costs. The calculations presented in this report show that the additional costs for a 400 MW plant range between 680 million Euros for coal-plants and 550 Euros for gas plants. Assuming a CO_2 price as in the scenarios developed for the second European Strategic Energy Review, the additional revenue required for making these demonstration plants competitive in the electricity market are 46 Euros for coal plants and 77 Euros for gas plants per tonne of CO_2 avoided. These calculations are very sensitive to the assumptions made with regards to the capital costs, the costs of CO_2 transport and storage, fuel and CO_2 prices and the discount rate.

These additional costs have been estimated using reference values for the cost of the CO_2 capture technologies (pre- and post-combustion and oxyfuel), which have stemmed from an extensive assessment of literature sources using a transparent methodology, which alleviates to a significant extent the confusion about the economics of CCS technologies.

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