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Cost and Performance of Carbon Dioxide Capture from Power Generation

INTERNATIONAL ENERGY AGENCY

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INTERNATIONAL ENERGY AGENCY

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Executive summary

Energy scenarios developed by the International Energy Agency (IEA) suggest that carbon capture and storage (CCS) from power plants might contribute by 2050 to around 10% of the energy-related carbon dioxide (CO_2) emission reduction required to stabilise global warming (IEA, 2010). Since CO_2 capture from power generation is an emerging technology that has not been demonstrated on a commercial scale, related cost and performance information is based on feasibility studies and pilot projects and is still uncertain.

This paper analyses techno-economic data for CO_2 capture from power generation, including CO_2 conditioning and compression, in order to support energy scenario modelling and policy making. Cost and performance trends are shown based on estimates published over the last five years in major engineering studies for about 50 CO_2 capture installations at power plants. Capital cost and levelised cost of electricity (LCOE) are re-evaluated and updated to 2010 cost levels to allow for a consistent comparison. Presented data account for CO_2 capture but not transportation and storage of CO_2. They are estimates for generic, early commercial plants based on feasibility studies, which have an accuracy of on average ±30%. The data do not reflect project-specific cost or cost for first large-scale demonstration plants, which are likely higher.

For coal-fired power generation, no single CO_2 capture technology outperforms available alternative capture processes in terms of cost and performance. Average net efficiency penalties for post- and oxy-combustion capture are 10 percentage points relative to a pulverised coal plant without capture, and eight percentage points for pre-combustion capture compared to an integrated gasification combined cycle. Overnight costs of power plants with CO_2 capture in regions of the Organisation for Economic Co-operation and Development (OECD) are about USD 3 800 per kW (/kW) across capture routes, which is 74% higher than the reference costs without capture. Cost figures vary substantially depending on the type of power plant type and fuel used. The relative increase in overnight costs compared to a reference plant without CO_2 capture is a comparably stable metric across studies. It is thus recommended for estimating cost if limited data are available. Projected LCOE is on average USD 105 per megawatt hour (/MWh). Average costs of CO_2 avoided are USD 55 per tonne of CO_2 (/tCO_2) if a pulverised coal power plant without CO_2 capture is used as a reference.

For natural gas-fired power generation, post-combustion CO_2 capture is most often analysed and appears the most attractive near-term option. Average cost and performance projections include net efficiency penalties of eight percentage points for post-combustion CO_2 capture from natural gas combined cycles. Overnight costs are USD 1 700/kW including CO_2 capture, or 82% higher than the reference plant without capture. LCOE is USD 102/MWh and costs of CO_2 avoided are USD 80/tCO_2 if a natural gas combined cycle is used as a reference.

Cost estimates stated above are average figures for OECD regions. Cost data for installations in China indicate significantly lower costs compared to the above-mentioned figures. All overnight costs include a contingency for CCS plants to account for unforeseen technical or regulatory difficulties. LCOE and costs of CO_2 avoided do not include a CO_2 emission price.

Harmonisation of costing methodologies is needed in order to simplify technology comparisons. Though a similar approach is used for estimating cost and performance across studies, specific methodologies, terminologies and underlying assumptions are inconsistent.

Broader assessments of CO_2 capture from power generation in non-OECD countries are still underrepresented, though according to global energy scenarios deployment of CCS in these regions might have to exceed expected levels in OECD countries.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) concludes a significant reduction of worldwide greenhouse-gas (GHG) emissions is required in order to stabilise the global average temperature increase at 2.0°C to 2.4°C above pre-industrial levels. Equivalent CO_2 emissions need to be cut by at least 50% by 2050 compared to the year 2000 (IPCC, 2007).

The IEA regularly analyses pathways for reducing energy-related CO_2 emissions. Compared to a business-as-usual Baseline Scenario, carbon capture and storage (CCS) from power generation could contribute in 2050 to 10% of the required global reduction in energy-related CO_2 emissions (IEA, 2010). Apart from CCS in power generation, CCS from industrial and upstream applications is expected to provide a similar emission reduction. CCS is thus a potential key contributor to CO_2 emission mitigation, in addition to other important aims such as improving energy efficiency and increasing renewable power generation.

CCS has been applied commercially in the oil and gas industry for several decades. This includes technologies along the CCS value chain such as solvent-based separation of CO_2 from gas streams, transportation of CO_2 by pipeline and storage of CO_2 in aquifers. CO_2 is also used for enhanced oil recovery (EOR).

CCS is however still an emerging technology in the power sector, where it has not yet been demonstrated at large scale. Applying CCS to full-size power plants requires scale-up of commercially available CO_2 capture processes. Consequently, current cost and performance information related to CCS from power generation is limited to estimates from engineering studies and pilot projects. This is different to established power technologies for which cost and performance data of commercial units are well known and regularly summarised (OECD, 2010).

A dedicated review of published data is needed to track latest CCS developments. The quality of techno-economic data for CCS will likely improve once additional information from the first commercial-scale demonstration plants, which are currently in planning, become available. Meanwhile, best-possible estimates of cost and performance of power plants with CCS are required as input for energy scenarios and as a basis for clean energy policy making. Against this background, this paper summarises and analyses techno-economic data on CO_2 capture from power generation that were published over the last five years.

Scope of analysis

CCS applied to power generation is an emerging technology. Techno-economic data for CO_2 capture from power generation thus remain uncertain; a fact that is further amplified by current unprecedented economic uncertainties resulting from the recent global financial crisis.

Most energy scenarios that analyse climate change mitigation paths expect that CO_2 capture will contribute substantially to global CO_2 emission reduction in the coming decades. The IEA *Energy Technology Perspectives 2010 (ETP 2010)* publication estimates that by 2050 around 10% of the emission reduction will stem from CO_2 capture from power generation alone compared to a business-as-usual Baseline Scenario (IEA, 2010).

This analysis aims to illustrate cost and performance trends related to CO_2 capture from power generation over the last five years. This chapter gives an overview about types of data that are analysed and describes which specific capture cases and publications are considered in this study.

Analysed techno-economic data and key target metrics

This working paper evaluates key data that are commonly required as input for energy scenario modelling and general energy policy support, such as:

- power plant type
- fuel type
- capacity factor
- net power output
- net efficiency
- overall CO_2 capture rate
- net CO_2 emissions
- capital cost
- operation and maintenance (O&M) cost
- year of cost data
- location of power plant

Published techno-economic information is reviewed and re-evaluated in order to compare results of different studies. Updated data are provided for the following key metrics:

- overnight costs
- levelised cost of electricity (LCOE)
- cost of CO_2 avoided

Cost and performance data are required for both the power plant without capture (also referred to as reference plant) and for the power plant with capture.

This analysis focuses on fundamental techno-economic information typically used for cross-technology comparisons under consistent boundary conditions. Cost data presented in this study are generic in nature and not meant to represent costs of specific CO_2 capture projects, which are likely to be different. Investment decisions about individual CCS plants will depend on numerous case-specific boundary conditions such as (among others): national or regional policy and regulatory frameworks; emission and power markets; the experience and risk profile of the investor; or available incentive and financing structures. In addition, local ambient conditions and available fuel qualities can have a strong impact on the capture technology choice and its viability.

Cost and performance information for the transport and storage of captured CO_2 will need to complement data for CO_2 capture. Transportation and storage data are even more difficult to generalise compared to CO_2 capture process data, given that they are very site-specific or even unique for every single project. Because of this complexity, available storage capacities and associated costs still remain subject to significant research in many regions of the world. Unlike CO_2 capture from power generation, a number of large-scale CO_2 transport and storage projects however exists that are operating today and which can provide some, albeit limited, data on the associated costs. Techno-economic data related to the transport and storage of CO_2, in particular related to CO_2 storage capacities, are not covered in this paper, but improving related knowledge is essential. Consequently, the IEA and other organisations are addressing this challenge in separate, dedicated work streams.

Evaluated CO_2 capture processes

This working paper analyses CO_2 capture from power generation. CO_2 capture from industrial applications is evaluated through the forthcoming United Nations Industrial Development Organisation (UNIDO) roadmap, and is thus not discussed (UNIDO, 2010).

The study focuses on CO_2 capture from new-build coal- and natural gas-fired power generation plants with at least 80% overall capture rate. Only commercial-scale power plants over 300 MW net power output are considered. Data for biomass-fired installations are still scarce in comparison to coal- and natural gas-fired power plants. They are thus not systematically evaluated in this working paper, but a case study with biomass co-firing is included for comparison.

This paper focuses on early commercial installations of CO_2 capture from power generation and does not cover demonstration plants. Cost and performance information related to "first-of-a-kind" CO_2 capture demonstration plants is often not representative of commercial units that are installed later, for example since they are sub-optimally or overdesigned. Significant large-scale commercial deployment of CCS technology for power generation applications is not expected to take place prior to the year 2020. Therefore, cost and performance data considered in this study are primarily estimates for early commercial CO_2 capture processes from power plants that would be in service around 2020.[1]

Only capture technologies that have been demonstrated on a significant pilot scale (or even at a commercial size in other industries) are considered in this analysis. Novel technologies for CO_2 capture from power generation that are in an early phase of development, such as membrane-based processes, are not covered. The general improvement potential for CO_2 capture from power generation in the future by technological learning is discussed in Chapter 4.

Data selected for analysis

Techno-economic studies on CO_2 capture from power generation are numerous. In this paper, CO_2 capture cost and performance data of selected studies are reviewed, re-evaluated and updated to current cost levels. Only studies by organisations that performed broad comparisons across all capture routes are considered. Publications by authors that are focusing their analyses on individual or a very limited number of capture technologies are not included. In order to limit the re-evaluation of older data to a reasonable time horizon, only studies that were published

[1] Not all of the reviewed studies provide explicit timelines or a definition of the level of commercial deployment associated to their performance and cost estimates, and some reports envision full-scale commercial deployment already earlier.

over the last five years (between 2006 and 2010) are covered. In rare cases, the underlying original data might stem from earlier years.

Re-evaluating and comparing cost and performance data across studies presents a major challenge. There are differences in the types of data published, and in the cost estimation methodologies used. In addition, there is often limited transparency with respect to underlying boundary conditions and assumptions.

The studies selected for further analysis in this working paper exhibit a broad coverage of evaluated capture routes and used a consistent evaluation methodology for assessing their individual capture cases. In addition, they are typically based on an engineering-level analysis and provide detailed cost and performance estimates and information on key boundary conditions, which allow for further processing and analysis.[2] Techno-economic data from studies by the following organisations are included in this working paper:

- Carnegie Mellon University – CMU (Rubin, 2007; Chen, 2009; Versteeg, 2010)
- China-UK Near Zero Emissions Coal Initiative – NZEC (NZEC, 2009)
- CO_2 Capture Project – CCP (Melien, 2009)
- Electric Power Research Institute – EPRI (EPRI, 2009)
- Global CCS Institute – GCCSI (GCCSI, 2009)
- Greenhouse-Gas Implementing Agreement – GHG IA (Davison, 2007; GHG IA, 2009)
- National Energy Technology Laboratory – NETL (NETL, 2008; NETL, 2010a-f)
- Massachusetts Institute of Technology – MIT (MIT, 2007; Hamilton, 2009)

In the event several evaluations were made by organisations on the same capture process over the last five years, only the most recently published data are included in this analysis.

It is likely there are additional studies that should be considered in future analysis. The author would appreciate suggestions of additional studies that match the general selection criteria and should be considered in potential updates of this review. Since similarly broad and detailed studies were not found for other regions, the analysed studies are limited to CO_2 capture installations in the United States, the European Union and China.

The selected studies are based on data from bottom-up engineering studies, which perform cost and performance estimates based on detailed process flow sheet data that account for main equipment or process unit islands. They provide, at a minimum, the main cost and performance data for the base power plant, the CO_2 capture process and a CO_2 compression unit for compressing and pumping the separated CO_2 to a supercritical pressure for transportation. Besides the core CO_2 capture and compression units, other additional major equipment and utility systems are required. This includes equipment for oxygen generation, fluid handling, exhaust pre-treatment for drying or purification, and compression and pumping, which is accounted for in all the selected studies.

CO_2 transport and storage are not evaluated in most of the publications, and any data on CO_2 transport and storage is not considered in this paper. Most cost estimates used in this study are based on the assumption that processes and process equipment are proven technologies or, at least, have been demonstrated on a commercial scale. Thus costs required for research, development and initial deployment in demonstration plants are not included.

[2] Several studies are not considered as the level of detail regarding costs or boundary conditions is insufficient for further analysis under this study (e.g. ENCAP, 2009; McKinsey, 2007).

Though it is often not explicitly stated, the group of analysed studies generally assumes that CO_2 capture and compression is integrated into a new power plant and benefits from at least a minimum infrastructure, which is typical for an industrial site. This includes availability of engineering and local human resources, equipment, utility and fuel supply, access to the power grid and appropriate options for transporting and storing separated CO_2. In addition, for such new-build, brown-field installations, the study assumes full flexibility in terms of plant integration and optimisation.

This working paper does not analyse the impact of retrofitting CO_2 capture to existing power plants. Incremental costs of adding CO_2 capture to those plants could be higher than the incremental costs shown in the reviewed studies, since these existing plants were designed with no considerations for future CO_2 capture.

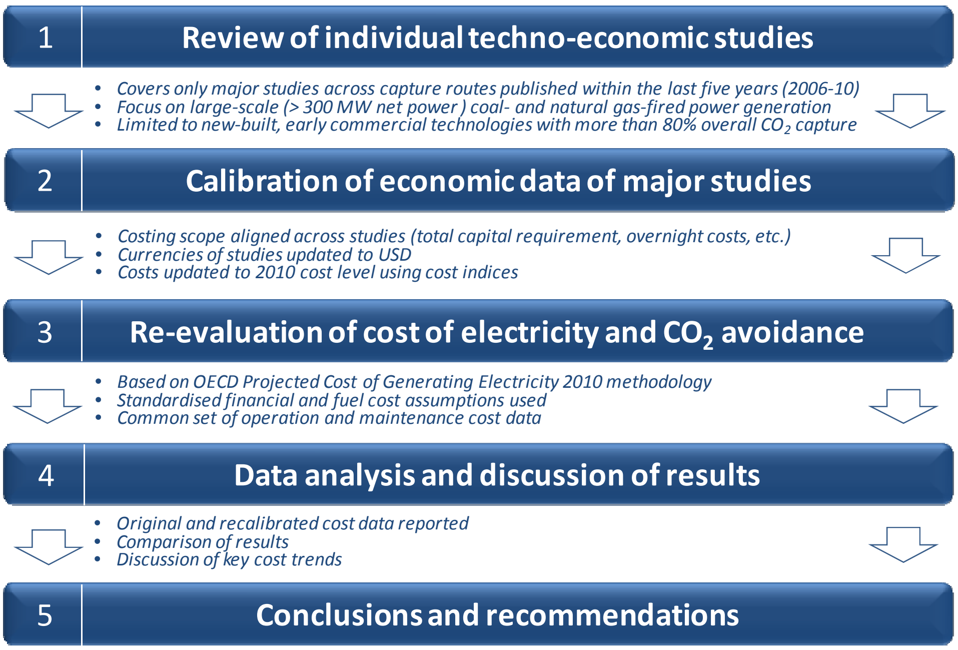
Approach and methodology

The fundamental approach used in this study to review and analyse published techno-economic information on CO_2 capture is illustrated in Figure 1. In a first step, applicable literature on the subject is researched and reviewed. In order to allow a comparison of cost data from different years, economic data of the selected studies are calibrated by aligning their scope and by updating their cost to 2010 USD cost levels using market exchange rates and process equipment cost indices. Performance-related data are not recalibrated for reasons that are outlined in more detail further below.

Subsequently, updated cost data are used to re-evaluate LCOE and cost of CO_2 avoided of the different capture cases. To provide consistency with previous work by the OECD, the methodology and underlying assumptions are based on the same approach that was taken by the OECD *Projected Costs of Generating Electricity 2010* analysis, which for simplicity is hereafter referred to as *PCGE 2010* (OECD, 2010).

Common financial and operating boundary conditions and fuel prices are applied for all cases. Cost and performance trends across studies are identified based on the updated data. Further details of the calibration methodology, including a description of limitations of the analysis, are provided in this chapter.

Figure 1. Illustration of the methodology for data analysis



Cost of generating electricity calculation

LCOE is commonly used as a measure of comparing generating costs of different power generation and capture technologies over a plant's economic life. LCOE is equal to the present value of the sum of discounted costs divided by the total electricity production.

This study uses a LCOE model that was jointly developed by the IEA and the Nuclear Energy Agency (NEA) with support of a diverse group of international experts and organisations for the

PCGE 2010 publication. The underlying philosophy and methodology behind the calculation is discussed in detail in the OECD publication and not repeated in this paper.

Based on IEA and NEA convention, a key assumption of the LCOE approach is that the interest rate used for discounting costs does not vary over the lifetime of the project under consideration. A real discount rate of 10% is used for all cases in this study, which is the higher of two discount rates defined in the *PCGE 2010* study. This figure is chosen for this study because of an anticipated higher technical and financial risk associated with investments in CCS technologies in the early phase of commercialisation. It should be noted that apart from considerations about technology maturity, other factors (such as the type of plant ownership) influence the cost of financing a project. This would be reflected in the applicable discount rates.

LCOE is also used as a basis for providing estimates of costs of CO_2 avoidance for different capture technologies. Further background on the terminology, including how to derive CO_2 avoidance costs are extensively discussed in previous publications. This includes important considerations related to selecting a meaningful reference power plant without CCS for calculating cost of CO_2 avoided (IPCC, 2005; GCCSI, 2009).

It is important to note that in contrast to the OECD *PCGE 2010* publication, reported LCOE data do not include a USD 30/tCO_2 emission price, since this approach is less common for CCS-related cost comparisons. Hence in this working paper no CO_2 emission price is added for calculating LCOE.

Conversion and calibration of cost data

Several methodologies are used to estimate economic data, in particular capital costs, of CO_2 capture from power generation. There is neither a standardised methodology nor a set of commonly agreed on boundary conditions, which adds to the complexity of comparing data from different studies. Moreover, some factors are often not fully transparent, such as costing methodologies, sources of costs, the exact scope of data as well as assumptions on individual cost parameters. As a consequence, it is not straightforward to transform techno-economic information from different studies into a comparable set of data.

Though there is no consistently applied approach for cost evaluation, similarities exist throughout studies in terms of how CO_2 capture costs are conceptually assessed. Cost data are usually split into capital costs (related to the construction of equipment), fuel costs, and non-fuel operating and maintenance costs (related to the process and its equipment). These costs are commonly used together to calculate the first year cost of electricity (COE) or LCOE over the lifetime of the plant.

Sources of capital costs are often not clearly stated in publications. Typically, costs are based on estimates for main equipment or process islands that are provided by vendors or taken from equipment cost databases. Often equipment costs are readjusted (using scaling laws) to the specific process conditions, and costs are added for installation and indirect expenses required for the complete construction of the plant.

Assumptions about additional capital expenses vary across studies or are not clearly reported. Examples of these additional capital costs include engineering and overhead, commissioning expenses, or process and equipment contingencies. In some instances, the same terms are used differently.

For consistency with previous OECD studies – and in order to reduce the impact of project-specific cost elements – this study uses overnight costs as the key metric for quantifying capital cost. According to OECD terminology, **overnight costs** include:

- pre-construction or owner's costs;
- engineering, procurement and construction (EPC) costs; and
- contingency costs.

Overnight costs assume a power plant could be constructed in a single day. They reflect technological and engineering costs in a particular country but avoid impacts of the specific financial structure that is in place to realise construction. While for real projects investors need to pay close attention to total capital requirements, overnight costs are useful in particular for energy scenario modellers, policy makers and utilities for comparisons of costs at an early stage of assessment.

Overnight costs exclude interest during construction (IDC). IDC is added for LCOE calculations in order to account for the actual time it takes to construct the power plant. This also includes related equipment outside the power plant boundary (such as transmission lines or railroads for coal transportation), and the costs of financing construction before the power plant becomes operational.

Pre-construction or owner's costs are miscellaneous additional costs directly incurred by the owner of a project such as owner's staff, land, permitting, environmental reporting and facilities. Owner's costs are subject to much confusion. Most CCS-related cost studies do not provide the precise scope and content of owner's costs. Or, sometimes other cost elements such as start-up costs, contingencies or fees are lumped into a single owner's cost factor on top of EPC costs. Owner's costs can vary widely from project to project depending on whether it is publicly or privately owned. They remain a major uncertainty across all studies.

Engineering, procurement and construction costs typically cover the required total process capital. This includes direct and indirect costs for equipment and labour, general supporting facilities, but also costs related to engineering and project management, home office, overhead or technology fees.

Contingency costs are included in order to reflect cost uncertainties due to the level of project definition, the risk related to technology maturity and performance, or unforeseen regulatory difficulties.

Overnight costs are used as a basis for LCOE calculations in this working paper. Several studies reviewed use alternative terminologies or have a different scope with respect to key capital cost figures.

Capital cost data published by MIT and GCCSI already include IDC; these costs are recalculated in this paper to represent overnight costs without IDC. If originally published cost data do not include owner's costs, these are added to capital cost. This applies to data by MIT and NETL.[3] Total capital requirement and total plant costs are published by EPRI. Total plant costs without owner's costs are used from EPRI as a basis for the analysis performed under this study. Owners cost are added in this case.

The currency for reporting economic data used in this report is US dollar (USD). Cost data reported in other currencies are converted to USD using the conversion rate of the year of the costs as published, unless a conversion rate is provided in the original publication.[4]

Apart from a currency conversion, it is also necessary to account for changes in installed equipment cost over time. Since published information does not allow for a detailed escalation on a component-by-component basis, general cost indices are used to recalibrate cost to current

[3] Apart from data from NETL (2010a), which already include owner's cost.

[4] Resulting exchange rates: USD 0.146 per CNY (NZEC, 2009) and USD 1.35 per EUR (GHG IA, 2009).

levels. In this study, published cost data are updated to 2010 cost levels using the Chemical Engineering Plant Cost Index, CEPCI (CE, 2010).

In summary, calibration of capital cost data includes:

- Calibration to overnight costs estimates (by adding owner's costs or subtracting IDC);
- Conversion of the original currency to USD; and
- Calibration of costs as quoted to 2010 cost levels by using cost indices.

Unless otherwise stated (*e.g.* with respect to fuel cost assumptions), the same boundary conditions are applied to all data regardless of the location of the power plant foreseen by the authors of the studies. Publication years, project locations and currencies of the reviewed studies are shown in Table 1.

Table 1. Overview of general boundary conditions of reviewed studies

Organisation	CCP	CMU	EPRI	GCCSI	GHG IA	NETL	NZEC	MIT
Publication year(s)	2009	2007, 2009, 2010	2009	2009	2007, 2009	2008, 2010	2009	2007, 2009
Project location	EU	US	US	US	EU	US	CHN	US
Currency	USD	USD	USD	USD	USD, EUR	USD	CNY	USD

Cost location factors are not applied in this study. Instead, for each data point shown in this working paper the location of the power plant is provided as specified in the original study. This is helpful since differences in local cost levels, in particular related to labour cost and productivity, are expected for different locations. A sensitivity analysis of location-specific costs for CO_2 capture installations can be found in the literature (GCCSI, 2009).

Conversion and calibration of performance data

The technical performance of power plants with CO_2 capture is typically summarised in terms of plant efficiencies, power output and CO_2 emissions. Terminology related to performance evaluation is used consistently throughout techno-economic studies. Key performance and operational parameters reported include the net efficiency or heat rate, the net power output, specific CO_2 emissions, and the plant capacity factor or load factor.

Performance estimates in published studies are usually based on fundamental mass and energy balances from process flow sheets of the power plant and the CO_2 capture and compression process. Analyses are commonly based on process simulation as it is typically performed to assess general feasibility or for front-end engineering and design (FEED) studies. Standardised (ISO) ambient conditions are usually assumed for the studies.

Nonetheless, important differences in relevant technical assumptions can apply, for example in terms of fuel types or qualities, CO_2 compression and pumping discharge pressures, or assumptions regarding cooling water characteristics (*e.g.* Zhai, 2010). Due to the complexity of the processes or limited detail provided in published information, it was impossible to recalibrate performance results across the breadth of studies under consideration. Though performance-related data are not re-evaluated in this analysis, it is important to note that differences in performance assumptions can have a substantial impact on results. The potential impact varies across capture and power plant technologies, and is discussed in more detail in the scientific literature (*e.g.* Rubin, 2007).

Published overall CO_2 capture rates are between 85% and 100%. Data are not scaled to a standardised capture rate, since reported cases likely represent the most cost-effective or advantageous operating conditions. Furthermore, some capture processes would be limited in their flexibility in terms of achievable capture rates. To enable a comparison (on a consistent level) of cost data across technologies at slightly different capture rates, costs of CO_2 avoided are included in this paper.

CO_2 purity is above 99.9% for solvent-based post- and pre-combustion capture processes. Oxy-combustion can achieve a similar purity level. However, some oxy-combustion capture plants result in a higher level of non-condensable gases and contaminants in the separated CO_2. This depends on the purity of supplied oxygen and fuel, the level of air in-leakage into the boiler, the process design and intensity of purification. This study does not calibrate cost or performance data with respect to CO_2 purity. However, oxy-combustion data with CO_2 purities lower than 99.9% are marked accordingly when results are presented.

Re-scaling of cost and performance data to a common net power plant output, for example by using power-scaling laws, was considered even though reported net power outputs show a relatively moderate spread across data points. However, it is not applied since scaling can lead to misleading results for capture processes that rely on using multiple trains of equipment due to current size limitations.

Boundary conditions and assumptions

Financial and operational boundary conditions, such as construction times, project lifetimes and capacity factors are adopted from the OECD *PCGE 2010* publication. The parameters used in this working paper are listed in Table 2, together with assumptions typically used by different organisations.

Contributions of owner's costs range between 5% and 25% across individual studies. This study assumes an average contribution of owner's costs to overnight costs of 15%. For re-evaluating LCOE, IDC is calculated separately for each case.

The *PCGE 2010* study assumes a 15% contingency cost for power plants with only a small number of installed facilities. This contingency accounts for unforeseen technical or regulatory difficulties, and is added to the LCOE calculation in the last year of construction. In the *PCGE 2010* study, it is applied for nuclear power plants, off-shore wind and CCS.[5] For all other technologies, a 5% contingency is added. This working paper follows the same approach. Contingency cost calculations are based on EPC cost.

[5] This does however not apply to data for nuclear power plants in France, Japan, Korea and the United States, where a large number of nuclear plants are already installed.

Table 2. Techno-economic assumptions typically used by different organisations, and in this analysis

Organisation	CCP	CMU	EPRI	GCCSI	GHG IA	NETL	NZEC	MIT	This study (based on OECD, 2010)
Discount rates	10%		9-10%	9%	10%	10%	10%		10%
Owner's cost			5-7%	15%	7%	15-25%	7%	10%	15%
Capacity factor, coal		75%	80%	85%	85%	85%	85%	85%	85%
Capacity factor, natural gas	95%	75%			85%	85%			85%
Economic life, coal		30 yrs	30 yrs	30 yrs	25 yrs	30 yrs	25 yrs	20 yrs	40 yrs
Economic life, natural gas	25 yrs	30 yrs		30 yrs	25 yrs	30 yrs			30 yrs
Construction time, coal		4 yrs		4 yrs	3 yrs	3 yrs		3yrs	4 yrs
Construction time, natural gas					3 yrs				2 yrs
Contingencies with CCS	20%	5-30%	13-14%	5-20%	10%	15-20%	10%		15%

Values of by-products or waste generated in the power plants, such as sulphur, gypsum and slag or ash, are assumed a zero net cost. At the end of the project lifetime, 5% of overnight costs is applied in cost calculations for decommissioning. Assumptions on fuel prices vary across regions and are summarised in Box 1.

Box 1. Fuel price assumptions

Common fuel prices that remain constant over the entire lifetime of the plant are assumed for evaluating electricity generation costs. This study uses for consistency fuel prices for bituminous coals and natural gas as defined in the OECD *PCGE 2010* publication (even though in particular natural gas prices are currently lower). Sub-bituminous coals and lignite are typically not traded on an international level. Hence for these coals national fuel price assumptions are used. Since across the data covered by this review sub-bituminous coals and lignite are only used in US plants, fuel prices as reported by DOE/NETL are assumed (NETL, 2010e). Following similar considerations, the fuel price for biomass, which is only used in a single case for co-firing, is based on assumptions from the underlying study (GHG IA, 2009).

In summary, the following fuel prices are assumed in this study:

OECD Europe

- Bituminous coal: USD 3.60 per gigajoule (/GJ) (USD 90/tonne)
- Natural gas: USD 9.76/GJ (USD 10.30/MBtu)
- Biomass: USD 11.32/GJ

United States

- Bituminous coal: USD 2.12/GJ (USD 47.60/tonne)
- Natural gas: USD 7.40/GJ (USD 7.78/MBtu)
- Sub-bituminous coal: USD 0.72/GJ (USD 14.28/tonne)
- Lignite: USD 0.86/GJ (USD 13.19/tonne)

China

- Bituminous coal: USD 2.95/GJ (USD 86.34/tonne)
- Natural gas: USD 4.53/GJ (USD 4.78/MBtu)

Conversion between lower (LHV) and higher heating value (HHV) thermal plant efficiencies is simplified based on IEA conventions, with a 5% difference for coal and 10% for natural gas.

LCOE also accounts for variable and fixed O&M costs. In contrast to fixed O&M costs, variable O&M costs include all consumable items, spare parts, and labour that are dependent on the output level at a given plant. For processes that are not yet commercially available, it is common to approximate both variable and fixed O&M costs by a using a percentage estimate of the capital cost. This approach was also taken in the above-mentioned OECD study. O&M costs of large-scale, commercial CO_2 capture installations at power plants still remain uncertain. Hence a constant fraction of 4% of the installed capital costs for reference plants without CO_2 capture and for plants with capture is applied as the basis for O&M cost assumptions across all case studies. Since the impact of individual O&M assumptions is reduced, this approach also simplifies comparisons between LCOE results.

Reported CO_2 emissions include only emissions related to the power plant combustion process. Equivalent life-cycle CO_2 emissions are higher due to additional emissions from the acquisition and transport of raw materials, power transmission and depending on the specific end-use. Recent life-cycle analyses of coal- and natural gas-fired power plants have been published by the US Department of Energy (NETL, 2010b-e).

In addition, LCOE figures provided in this report reflect private costs only, without considering external costs with respect to environmental and health-related impacts – which are particularly difficult to quantify. External costs cover externalities at all stages of the production process such as construction, dismantling, the fuel cycle and operation, which are converted into monetary value. A recent European study provides estimates of external LCOE associated with power generation technologies. The impact assessment focuses on potential damage on human health, building materials, crops and ecosystems, and due to climate change. For Germany external costs of fossil-fuelled power generation with CCS are estimated in the order of USD 1.8/MWh in the year 2025 (using year 2000 cost levels), compared to about USD 4.6/MWh for fossil fuel power generation without CCS (NEEDS, 2009).

Cost and performance results and discussion

In this working paper cost and performance data for CO_2 capture from power generation are reviewed, recalibrated and updated to 2010 cost levels. The results of this analysis are presented and discussed in this chapter.

Main case studies

Only CO_2 capture cases that are covered by several studies are included in this report. The evaluation of coal-fired power generation focuses on post- and oxy-combustion CO_2 capture from supercritical (SCPC) and ultra-supercritical pulverised coal (USCPC) boilers as well as pre-combustion CO_2 capture from integrated gasification combined cycles (IGCC). Post-combustion CO_2 capture is also analysed for natural gas combined cycles (NGCC).[6]

Hence, results for four main CO_2 capture cases are presented:

- *Post-combustion CO_2 capture from coal-fired power generation using amines*
- *Pre-combustion CO_2 capture from integrated gasification combined cycles*
- *Oxy-combustion CO_2 capture from pulverised coal power generation*
- *Post-combustion CO_2 capture from natural gas combined cycles*

Post-combustion CO_2 capture using ammonia is a potential near-term alternative to amine-based solvents. A similarly detailed analysis is not possible for ammonia-based solvents since only few related data are presented in the analysed studies. Available data are nonetheless listed in the Annex of this working paper for reference.

Biomass-fired power generation with CO_2 capture is not evaluated in depth since information is rare compared to coal- and natural gas-fired plants. A single data point for post-combustion capture from coal-fired power plants with 10% co-firing of biomass is however added in the results presented in this chapter for comparison.

As outlined above, results report cost and performance estimates for new-build, early commercial plants. All cost data, including LCOE and cost of CO_2 avoided, cover costs related to the capture and compression of CO_2 to supercritical pressures, as well as the conditioning of CO_2 for transportation (but not for CO_2 transport and storage). Generally, CO_2 capture costs are considered to represent the bulk of the costs of integrated CCS projects. CO_2 transport and storage costs can still be significant depending on the local availability and characteristics of storage sites, and are thus crucial additional economic factors to consider in any project-specific evaluation or energy scenario modelling work.

To illustrate cost and technology development trends, CO_2 capture data shown in the following tables and figures are sorted by the year of the cost information as provided in the original publication. Key data are shown for reference cases with (w/) CO_2 capture and without (w/o) CO_2 capture. Cost of CO_2 avoided is a useful metric for comparing economics of a specific CO_2 capture process against alternative CO_2 capture technologies. An appropriate reference case without CO_2 capture needs to be chosen for specific assessments. In a specific new-build CCS project, this reference would be the most economical power generation alternative without CCS that meets all project-specific requirements (*e.g.* regarding plant availability or operating flexibility). This

[6] Across reviewed studies, only a single case is available for each pre- and oxy-combustion capture from NGCC; thus, these capture routes are not included in this review.

reference plant does not necessarily have to be based on the same power generation technology or use the same fuel.

Since it is difficult to define a universally applicable reference technology, cost of CO_2 avoided in this study is calculated using the same power plant type with and without capture. For IGCC with CO_2 capture, cost of CO_2 avoided is also presented using a PC reference based on data published by the same organisation. Cost of CO_2 avoided for coal-based oxy-combustion capture is based on a PC reference case without CO_2 capture, with data from the same organisation.

Most techno-economic data available from the reviewed studies describe capture installations in the United States, followed by studies on European power plants.[7] An analysis of CO_2 capture cost and performance in China is included in this analysis. Broad assessments across CO_2 capture routes are however scarce for installations in non-OECD countries.

In some of the following tables, different power plant and coal types are shown next to each other for the same capture route. While the different types are listed explicitly, this is important to note since coal types can vary widely from the predominantly analysed bituminous coals to the less-common sub-bituminous coals or lignite. In addition, some organisations published several sets of techno-economic data for the same fuel type and capture route. Average data provided in the far right column of the tables are added to guide the reader, but should be interpreted with some care against this background. Additional tables illustrate the influence of the type of the power plant and the specific fuel used for each capture route.

Post-combustion CO_2 capture from coal-fired power generation by amines

Cost and performance data for post-combustion CO_2 capture from coal-fired power generation are shown in Table 3. Techno-economic data for 14 different cases from 7 organisations are analysed, including a case study for an installation in China.

All post-combustion capture cases are using amine-based solvents for CO_2 capture, typically monoethanolamine (MEA). Data for aqueous ammonia-based processes are provided in the Annex. Post-combustion CO_2 capture from SCPC or USCPC boilers that operate on bituminous coals (labelled as “Bit coal”) are analysed most often. Additional data cover sub-critical (Sub-PC) or circulating fluidised bed (CFB) boilers, and plants that operate on sub-bituminous coals, lignite or with 10% co-firing of biomass in addition to bituminous coal.[8]

Average published capacity factors are 83% for the cases shown; CO_2 capture rates are 87%. Net power outputs including CO_2 capture range from 399 MW to 676 MW, at an average net efficiency of 30.9% (LHV) across OECD regions. The cost and performance impact of adding post-combustion CO_2 capture to a coal-fired reference plant without CO_2 capture is given in Figure 2.

Net efficiency penalties between 8.7 and 12.0 percentage points (LHV) are estimated for post-combustion CO_2 capture in OECD regions, which is on average a 25% reduction in efficiency. The net efficiency penalty estimated for an installation in China is 10.8 percentage points.

[7] Another study on CCS performance and cost by the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) is announced for 2011, but was not yet available at the time of this publication.

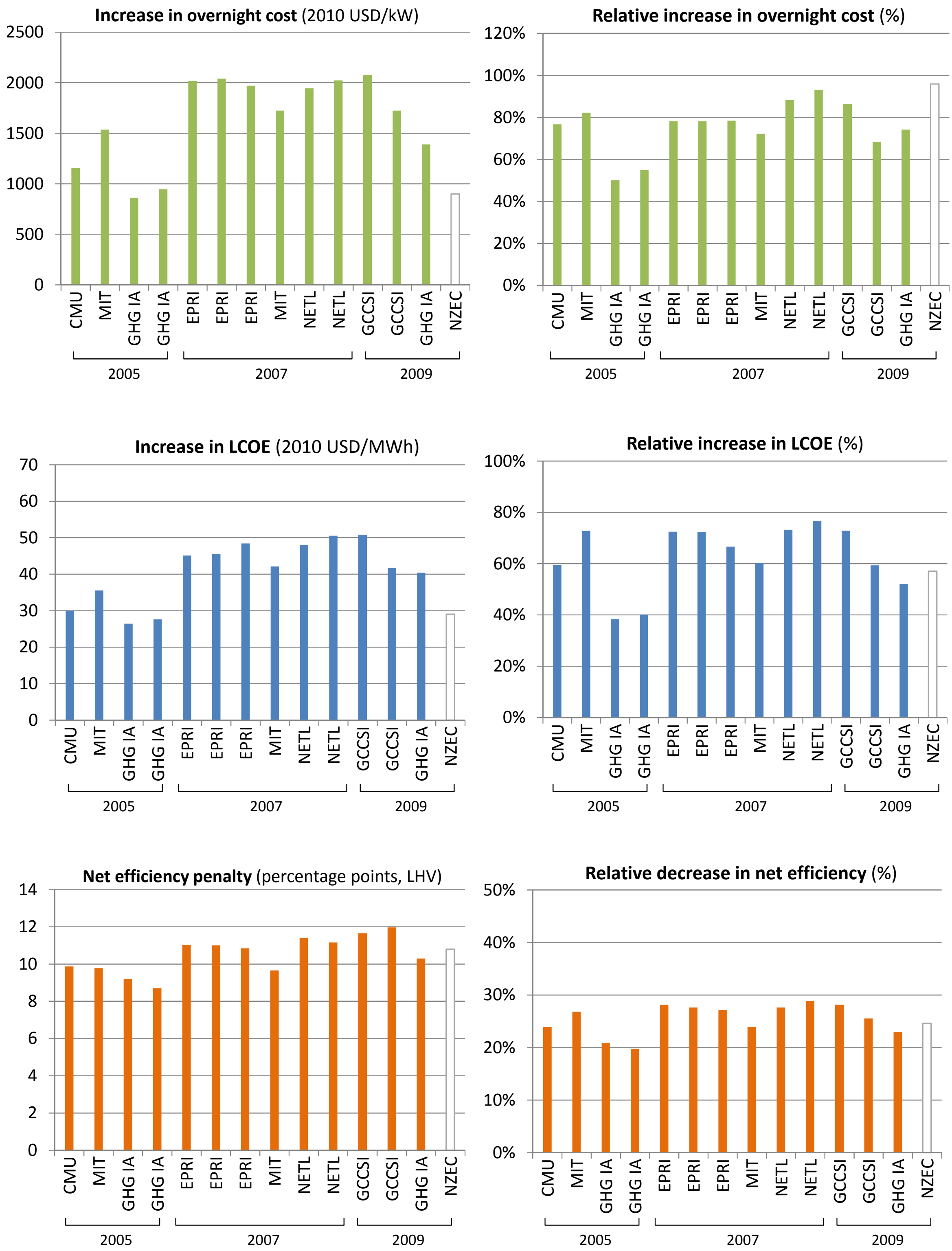
[8] For biomass co-firing, actual CO_2 emissions are stated in Table 3. No price for a green certificate is assumed.

Table 3. Post-combustion capture from coal-fired power generation by amines

Regional focus	OECD													China	*Average (OECD)*
Year of cost data	**2005**	**2005**	**2005**	**2005**	**2007**	**2007**	**2007**	**2007**	**2007**	**2007**	**2009**	**2009**	**2009**	**2009**	
Year of publication	**2007**	**2007**	**2007**	**2007**	**2009**	**2009**	**2009**	**2009**	**2010**	**2010**	**2009**	**2009**	**2009**	**2009**	
Organisation	**CMU**	**MIT**	**GHG IA**	**GHG IA**	**EPRI**	**EPRI**	**EPRI**	**MIT**	**NETL**	**NETL**	**GCCSI**	**GCCSI**	**GHG IA**	**NZEC**	
ORIGINAL DATA AS PUBLISHED (converted to USD)															
Region	US	US	EU	EU	US	US	US	US	US	US	US	US	EU	CHN	
Specific fuel type	Bit coal	Lignite	Bit coal	Bit coal	Sub-bit coal	Sub-bit coal	Bit coal	Bit coal	Bit coal	Bit coal	Bit coal	Bit coal	Bit+10% Biomass	Bit coal	
Power plant type	SCPC	CFB	USCPC	USCPC	SCPC	USCPC	SCPC	SCPC	SCPC	Sub-PC	SCPC	USCPC	SCPC	USCPC	
Net power output w/o capture (MW)	528	500	758	758	600	600	600	500	550	550	550	550	519	824	*582*
Net power output w/ capture (MW)	493	500	666	676	550	550	550	500	550	550	550	550	399	622	*545*
Net efficiency w/o capture, LHV (%)	41.3	36.5	44.0	44.0	39.2	39.8	40.0	40.4	41.2	38.6	41.4	46.8	44.8	43.9	*41.4*
Net efficiency w/ capture, LHV (%)	31.4	26.7	34.8	35.3	28.2	28.8	29.1	30.7	29.9	27.5	29.7	34.9	34.5	33.1	*30.9*
CO_2 emissions w/o capture (kg/MWh)	811	1030	743	743	879	865	836	830	802	856	804	707	754	797	*820*
CO_2 emissions w/ capture (kg/MWh)	107	141	117	92	124	121	126	109	111	121	112	95	73	106	*111*
Capital cost w/o capture (USD/kW)	1 442	1 330	1 408	1 408	2 061	2 089	2 007	1 910	2 024	1 996	2 587	2 716	1 710	856	*1 899*
Capital cost w/ capture (USD/kW)	2 345	2 270	1 979	2 043	3 439	3 485	3 354	3 080	3 570	3 610	4 511	4 279	2 790	1 572	*3 135*
Relative decrease in net efficiency	**24%**	**27%**	**21%**	**20%**	**28%**	**28%**	**27%**	**24%**	**28%**	**29%**	**28%**	**26%**	**23%**	**25%**	***25%***
RE-EVALUATED DATA (2010 USD)															
Overnight cost w/o capture (USD/kW)	1 508	1 868	1 720	1 720	2 580	2 615	2 512	2 391	2 203	2 172	2 409	2 529	1 873	938	*2 162*
Overnight cost w/ capture (USD/kW)	2 664	3 404	2 581	2 664	4 596	4 657	4 482	4 116	4 148	4 195	4 485	4 255	3 263	1 838	*3 808*
LCOE w/o capture (USD/MWh)	50	49	69	69	62	63	73	70	65	66	70	70	78	51	*66*
LCOE w/ capture (USD/MWh)	80	84	95	97	107	109	121	112	113	117	121	112	118	80	*107*
Cost of CO_2 avoided (USD/tCO_2)	**43**	**40**	**42**	**42**	**60**	**61**	**68**	**58**	**69**	**69**	**74**	**68**	**59**	**42**	***58***
Relative increase in overnight cost	**77%**	**82%**	**50%**	**55%**	**78%**	**78%**	**78%**	**72%**	**88%**	**93%**	**86%**	**68%**	**74%**	**96%**	***75%***
Relative increase in LCOE	**59%**	**73%**	**38%**	**40%**	**72%**	**72%**	**67%**	**60%**	**73%**	**77%**	**73%**	**59%**	**52%**	**57%**	***63%***

Notes: Data cover only CO_2 capture and compression but not transportation and storage. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions.

Figure 2. Post-combustion capture from coal-fired power generation by amines: CO_2 capture impact



Notes: Data cover only CO_2 capture and compression but not transportation and storage. Data sorted by year of cost information as published; white bars show data for installations in China. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions.

By adding CO_2 capture, overnight costs updated to 2010 cost levels increase on average by USD 1 647/kW, but vary substantially by a factor of more than two between USD 861/kW and USD 2 076/kW. For China overnight costs are expected to increase by USD 900/kW.

In comparison, the relative (percentage-wise) increase of overnight costs compared to overnight costs of the reference power plant is more stable across studies. Overnight costs increase by on average 75% when adding CO_2 capture. This trend is comparably robust across a wide range of power plant types (SCPC, USCPC, CFB), coals used (bituminous, sub-bituminous and lignite), and to some extent even regions (*e.g.* the United States and the European Union).

In OECD regions, LCOE increases on average by USD 41/MWh, but varies between USD 26/MWh and USD 51/MWh. The relative increase of LCOE compared to LCOE of the reference plant is on average 63%. Costs of CO_2 avoided are on average USD 58/tCO_2 but vary between USD 40/tCO_2 and USD 74/tCO_2 for case studies across OECD regions. Costs of CO_2 avoided for China are estimated USD 42/tCO_2.

Table 4. Post-combustion capture: influence of coals and power plant types (OECD only)

Specific fuel type	**Bit coal**			**Sub-bit & Lignite**			***Overall Average***
Power plant type	**USCPC**	**SCPC**	**Sub-PC**	**USCPC**	**SCPC**	**CFB**	
Number of cases included	3	5	1	1	1	1	
ORIGINAL DATA AS PUBLISHED (converted to USD)							
Net power output w/o capture (MW)	689	581	550	600	600	500	*582*
Net power output w/ capture (MW)	631	553	550	550	550	500	*545*
Net efficiency w/o capture, LHV (%)	44.9	41.4	38.6	39.8	39.2	36.5	*41.4*
Net efficiency w/ capture, LHV (%)	35.0	31.0	27.5	28.8	28.2	26.7	*30.9*
CO_2 emissions w/o capture (kg/MWh)	731	804	856	865	879	1030	*820*
CO_2 emissions w/ capture (kg/MWh)	101	109	121	121	124	141	*111*
Capital cost w/o capture (USD/kW)	1 844	1 896	1 996	2 089	2 061	1 330	*1 899*
Capital cost w/ capture (USD/kW)	2 767	3 151	3 610	3 485	3 439	2 270	*3 135*
Relative decrease in net efficiency	**22%**	**25%**	**29%**	**28%**	**28%**	**27%**	***25%***
RE-EVALUATED DATA (2010 USD)							
Overnight cost w/o capture (USD/kW)	1 990	2 124	2 172	2 615	2 580	1 868	*2 162*
Overnight cost w/ capture (USD/kW)	3 166	3 760	4 195	4 657	4 596	3 404	*3 808*
LCOE w/o capture (USD/MWh)	69	66	66	63	62	49	*66*
LCOE w/ capture (USD/MWh)	101	107	117	109	107	84	*107*
Cost of CO_2 avoided (USD/tCO_2)	**51**	**59**	**69**	**61**	**60**	**40**	***58***
Relative increase in overnight cost	**58%**	**76%**	**93%**	**78%**	**78%**	**82%**	***75%***
Relative increase in LCOE	**46%**	**62%**	**77%**	**72%**	**72%**	**73%**	***63%***

Notes: Data cover only CO_2 capture and compression but not transportation and storage. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions.

The influence of specific power plant and fuel types is shown in Table 4. The number of samples per power plant and fuel combination is limited, however, and results should not be regarded as representative.

Overnight costs for USCPC plants running on bituminous coals are in comparison quite low. It should be noted though that two out of the three underlying data sets are based on updated cost information from a single reference from 2005.

Data for Sub-PC bituminous coal-fired power plants, as well as all sub-bituminous and lignite-fired installations, are each based just on a single publication (Figure 4). They thus should not be interpreted in favour of or against alternative options.

Pre-combustion CO_2 capture from integrated gasification combined cycles

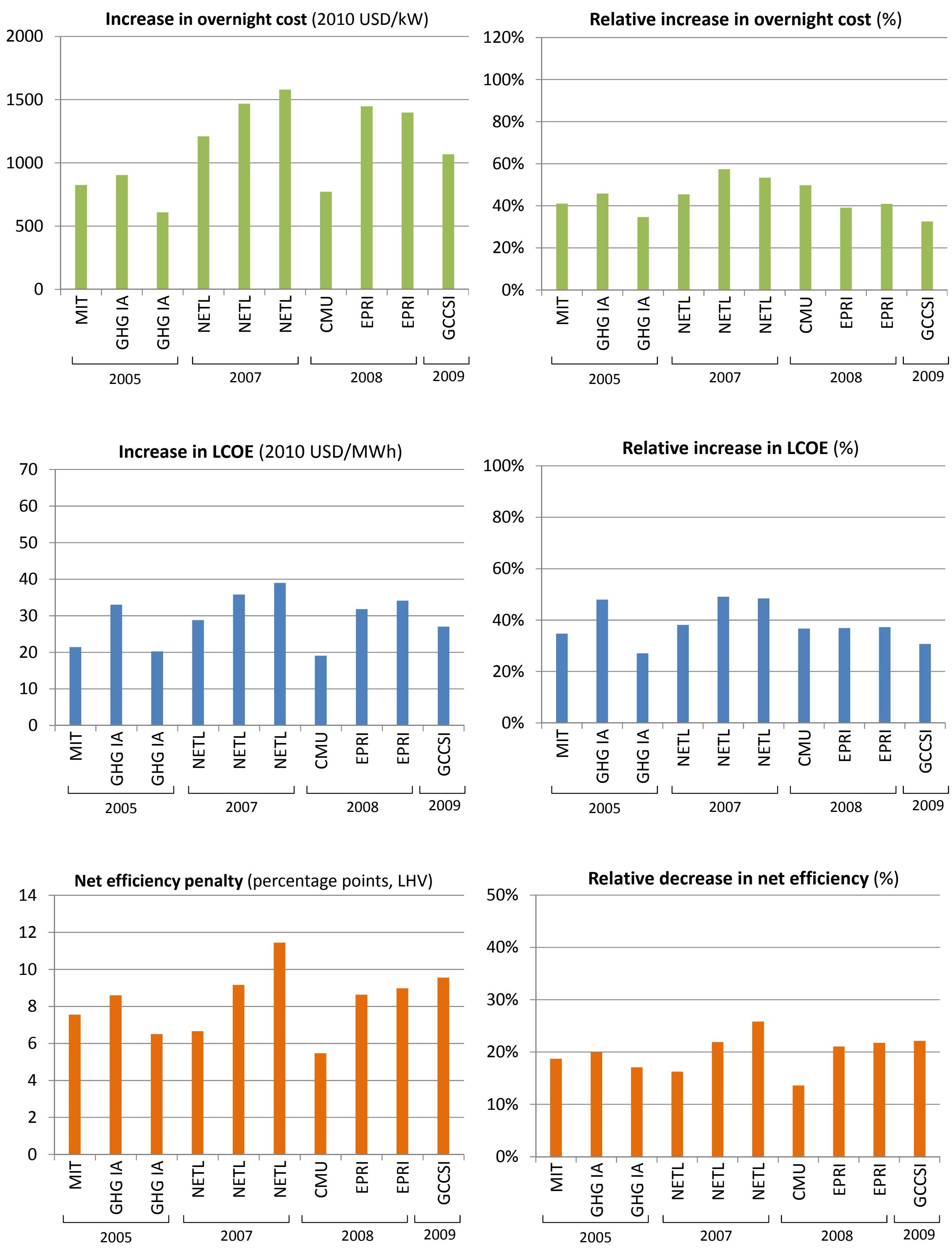
Cost and performance data for pre-combustion CO_2 capture from integrated gasification combined cycles (IGCC) are shown in Table 5. Techno-economic data for 11 different cases from 7 organisations are analysed, including a case study for an installation in China.

Table 5. Pre-combustion capture from integrated gasification combined cycles

Regional focus	**OECD**										**China**	***Average (OECD)***
Year of cost data	**2005**	**2005**	**2005**	**2007**	**2007**	**2007**	**2008**	**2008**	**2008**	**2009**	**2009**	
Year of publication	**2007**	**2007**	**2007**	**2010**	**2010**	**2010**	**2009**	**2009**	**2009**	**2009**	**2009**	
Organisation	**MIT**	**GHG IA**	**GHG IA**	**NETL**	**NETL**	**NETL**	**CMU**	**EPRI**	**EPRI**	**GCCSI**	**NZEC**	
ORIGINAL DATA AS PUBLISHED (converted to USD)												
Region	US	EU	EU	US	US	US	US	US	US	US	CHN	
Specific fuel type	Bit coal	Bit coal	Bit coal	Bit coal	Bit coal	Bit coal	Bit coal	Sub-bit coal	Bit coal	Bit coal	Bit coal	
Power plant type	GE	Shell	GE Quench	GE R+Q	CoP E-Gas FSQ	Shell	GE Quench	(Generic)	(Generic)	Shell IGCC	TPRI	
Net power output w/o capture (MW)	500	776	826	622	625	629	538	573	603	636	-	*633*
Net power output w/ capture (MW)	500	676	730	543	514	497	495	482	507	517	662	*546*
Net efficiency w/o capture, LHV (%)	40.3	43.1	38.0	40.9	41.7	44.2	40.0	41.0	41.2	43.2	-	*41.4*
Net efficiency w/ capture, LHV (%)	32.7	34.5	31.5	34.3	32.6	32.8	34.5	32.3	32.3	33.6	36.8	*33.1*
CO_2 emissions w/o capture (kg/MWh)	832	763	833	782	776	723	819	845	805	753	-	*793*
CO_2 emissions w/ capture (kg/MWh)	102	142	152	93	98	99	94	141	135	90	95	*115*
Capital cost w/o capture (USD/kW)	1 430	1 613	1 439	2 447	2 351	2 716	1 823	3 239	2 984	3 521	-	*2 356*
Capital cost w/ capture (USD/kW)	1 890	2 204	1 815	3 334	3 466	3 904	2 513	4 221	3 940	4 373	1 471	*3 166*
Relative decrease in net efficiency	**19%**	**20%**	**17%**	**16%**	**22%**	**26%**	**14%**	**21%**	**22%**	**22%**	**-**	***20%***
RE-EVALUATED DATA (2010 USD)												
Overnight cost w/o capture (USD/kW)	2 009	1 970	1 758	2 663	2 559	2 956	1 551	3 702	3 410	3 279	-	*2 586*
Overnight cost w/ capture (USD/kW)	2 834	2 874	2 367	3 874	4 027	4 536	2 323	5 150	4 808	4 348	1 721	*3 714*
LCOE w/o capture (USD/MWh)	62	69	75	76	73	81	52	86	92	88	-	*75*
LCOE w/ capture (USD/MWh)	83	102	95	104	109	120	71	118	126	115	73	*104*
Cost of CO_2 avoided (USD/tCO_2)	**29**	**53**	**30**	**42**	**53**	**62**	**26**	**45**	**51**	**41**	**-**	***43***
Cost of CO_2 avoided vs PC baseline (USD/tCO_2)	**18**	**53**	**38**	**57**	**64**	**86**	**28**	**64**	**79**	**64**	**32**	***55***
Relative increase in overnight cost	**41%**	**46%**	**35%**	**45%**	**57%**	**53%**	**50%**	**39%**	**41%**	**33%**	**-**	***44%***
Relative increase in LCOE	**35%**	**48%**	**27%**	**38%**	**49%**	**48%**	**37%**	**37%**	**37%**	**31%**	**-**	***39%***

Notes: Data cover only CO_2 capture and compression but not transportation and storage. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions. Generic data shown for EPRI; further details for individual gasifier designs, including data for Siemens gasifiers are available in EPRI (2009).

Figure 3. Pre-combustion capture from integrated gasification combined cycles: CO_2 capture impact



Notes: Data cover only CO_2 capture and compression but not transportation and storage. Data sorted by year of cost information as published; no full set of data available for installations in China. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions. IGCC reference plant data are not provided in the NZEC (2009) publication.

All reviewed studies apart from one evaluate pre-combustion CO_2 capture from IGCC plants that operate on bituminous coals. Gasifier technologies by ConocoPhillips (CoP), General Electric (GE), Shell and the Chinese Thermal Power Research Institute (TPRI) are analysed.

Average published capacity factors are 81% for the cases shown; CO_2 capture rates are 88%. Net power outputs including CO_2 capture range from 482 MW to 730 MW across OECD regions, at an average net efficiency of 33.1% (LHV). The impact of adding pre-combustion capture to an IGCC reference plant without CO_2 capture is illustrated in Figure 3.

Net efficiency penalties between 5.5 and 11.4 percentage points (LHV) are estimated for pre-combustion CO_2 capture in OECD regions, which is on average a 20% reduction in efficiency. No IGCC reference plant data are provided in the case study on pre-combustion CO_2 capture in China (NZEC, 2009).

By adding CO_2 capture, overnight costs updated to 2010 cost levels increase on average by USD 1 128/kW compared to an IGCC reference case. However, the increase varies substantially by a factor of more than two between USD 609/kW and USD 1 580/kW.[9]

The relative (percentage-wise) increase of overnight costs is more stable across studies. Overnight costs increase by on average 44% compared to an IGCC reference power plant when adding CO_2 capture. This trend appears comparably robust across the range of gasifier technologies and between the United States and the European Union.

LCOE figures follow a similar pattern. In OECD regions LCOE increases on average by USD 29/MWh relative to an IGCC reference plant, but varies between USD 19/MWh and USD 39/MWh. The relative increase of LCOE compared to the LCOE of the reference plant is on average 39%.

Costs of CO_2 avoided are on average USD 43/tCO_2 if an IGCC reference plant is used, but vary between USD 26/tCO_2 and USD 62/tCO_2 for OECD regions across study cases.

If a pulverised coal power plant reference case is used, average costs of CO_2 avoided rise to USD 55/tCO_2. The cost of CO_2 avoided in China is estimated USD 32/tCO_2 relative to a Chinese pulverised coal power plant, or about half of the costs in OECD regions.

Table 6 illustrates the influence of specific fuel types. However, only a single data point is available for sub-bituminous and lignite-fired installations, which is insufficient for drawing conclusions regarding technology competitiveness compared to bituminous coal-fired options.

[9] As stated by the authors in a follow-up publication (MIT, 2009), IGCC cost estimates published in MIT (2007) might have been too optimistic.

Table 6. Pre-combustion capture: influence of coals (OECD only)

Specific fuel type	Bit coal	Sub-bit & Lignite	*Overall Average*
Number of cases included	9	1	
ORIGINAL DATA AS PUBLISHED (converted to USD)			
Net power output w/o capture (MW)	639	573	*633*
Net power output w/ capture (MW)	553	482	*546*
Net efficiency w/o capture, LHV (%)	41.4	41.0	*41.4*
Net efficiency w/ capture, LHV (%)	33.2	32.3	*33.1*
CO_2 emissions w/o capture (kg/MWh)	787	845	*793*
CO_2 emissions w/ capture (kg/MWh)	112	141	*115*
Capital cost w/o capture (USD/kW)	2258	3239	*2356*
Capital cost w/ capture (USD/kW)	3049	4221	*3166*
Relative decrease in net efficiency	**20%**	**21%**	***20%***
RE-EVALUATED DATA (2010 USD)			
Overnight cost w/o capture (USD/kW)	2462	3702	*2586*
Overnight cost w/ capture (USD/kW)	3555	5150	*3714*
LCOE w/o capture (USD/MWh)	74	86	*75*
LCOE w/ capture (USD/MWh)	103	118	*104*
Cost of CO_2 avoided (USD/tCO_2)	**43**	**45**	***43***
Cost of CO_2 avoided vs PC baseline (USD/tCO_2)	**54**	**64**	***55***
Relative increase in overnight cost	**45%**	**39%**	***44%***
Relative increase in LCOE	**39%**	**37%**	***39%***

Notes: Data cover only CO_2 capture and compression but not transportation and storage. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions.

Oxy-combustion CO_2 capture from coal-fired power generation

Cost and performance data for oxy-combustion CO_2 capture from coal-fired power generation are shown in Table 7. Techno-economic data for 11 different cases from 5 organisations are analysed, including a case study for an installation in China. It should be noted a particularly large number of data stem from a single recent US Department of Energy assessment (NETL, 2010e).

Oxy-combustion capture from SCPC and USCPC boilers that operate on bituminous coals are most often evaluated in the reviewed studies. Additional data cover CFB boilers, and plants operating on sub-bituminous coals or lignite.

Average published capacity factors are 85% for the cases shown; CO_2 capture rates are 92%. Net power outputs including CO_2 capture range from 500 MW to 550 MW in OECD countries, at an average net efficiency of 31.9% (LHV).

Table 7. Oxy-combustion capture from coal-fired power generation

Regional focus	OECD										China	*Average (OECD)*
Year of cost data	**2005**	**2005**	**2007**	**2007**	**2007**	**2007**	**2007**	**2007**	**2009**	**2009**	**2009**	
Year of publication	**2007**	**2007**	**2008**	**2010**	**2010**	**2010**	**2010**	**2010**	**2009**	**2009**	**2009**	
Organisation	**GHG IA**	**MIT**	**NETL**	**NETL**	**NETL**	**NETL**	**NETL**	**NETL**	**GCCSI**	**GCCSI**	**NZEC**	
ORIGINAL DATA AS PUBLISHED (converted to USD)												
Region	EU	US	US	US	US	US	US	US	US	US	CHN	
Specific fuel type	Bit coal	Bit coal	Bit coal	Sub-bit coal	Sub-bit coal	Lignite	Sub-bit coal	Lignite	Bit coal	Bit coal	Bit coal	
Power plant type	USCPC	SCPC	SCPC	SCPC	SCPC	SCPC	CFB	CFB	SCPC	USCPC	USCPC	
Net power output w/o capture (MW)	758	500	550	550	550	550	550	550	550	550	824	*566*
Net power output w/ capture (MW)	532	500	550	550	550	550	549	550	550	550	673	*543*
Net efficiency w/o capture, LHV (%)	44.0	40.4	41.4	40.6	40.6	39.4	40.9	40.2	41.4	46.8	43.9	*41.6*
Net efficiency w/ capture, LHV (%)	35.4	32.1	30.7	32.5	29.5	31.4	31.6	30.7	30.8	34.7	35.6	*31.9*
CO_2 emissions w/o capture (kg/MWh)	743	830	800	859	859	925	846	884	800	707	797	*825*
CO_2 emissions w/ capture (kg/MWh)	84	104	0	98	0	103	99	105	0	0	98	*59*
Capital cost w/o capture (USD/kW)	1 408	1 330	1 579	1 851	1 851	2 003	1 938	2 048	2 587	2 716	856	*1 931*
Capital cost w/ capture (USD/kW)	2 205	1 900	2 660	3 093	3 086	3 163	3 491	3 821	4 121	3 985	1 266	*3 153*
Relative decrease in net efficiency	**20%**	**21%**	**26%**	**20%**	**27%**	**20%**	**23%**	**24%**	**26%**	**26%**	**19%**	***23%***
RE-EVALUATED DATA (2010 USD)												
Overnight cost w/o capture (USD/kW)	1 720	1 868	1 976	2 317	2 317	2 507	2 426	2 563	2 409	2 529	938	*2 263*
Overnight cost w/ capture (USD/kW)	2 875	2 849	3 555	4 133	4 124	4 227	4 665	5 106	4 098	3 962	1 481	*3 959*
LCOE w/o capture (USD/MWh)	69	59	61	56	56	62	59	63	70	70	51	*62*
LCOE w/ capture (USD/MWh)	101	84	100	96	97	100	108	119	112	106	69	*102*
Cost of CO_2 avoided (USD/tCO_2)	**49**	**35**	**49**	**52**	**47**	**46**	**66**	**72**	**52**	**50**	**27**	***52***
Relative increase in overnight cost	**67%**	**53%**	**80%**	**78%**	**78%**	**69%**	**92%**	**99%**	**70%**	**57%**	**58%**	***74%***
Relative increase in LCOE	**47%**	**43%**	**65%**	**71%**	**72%**	**62%**	**84%**	**89%**	**60%**	**51%**	**36%**	***64%***

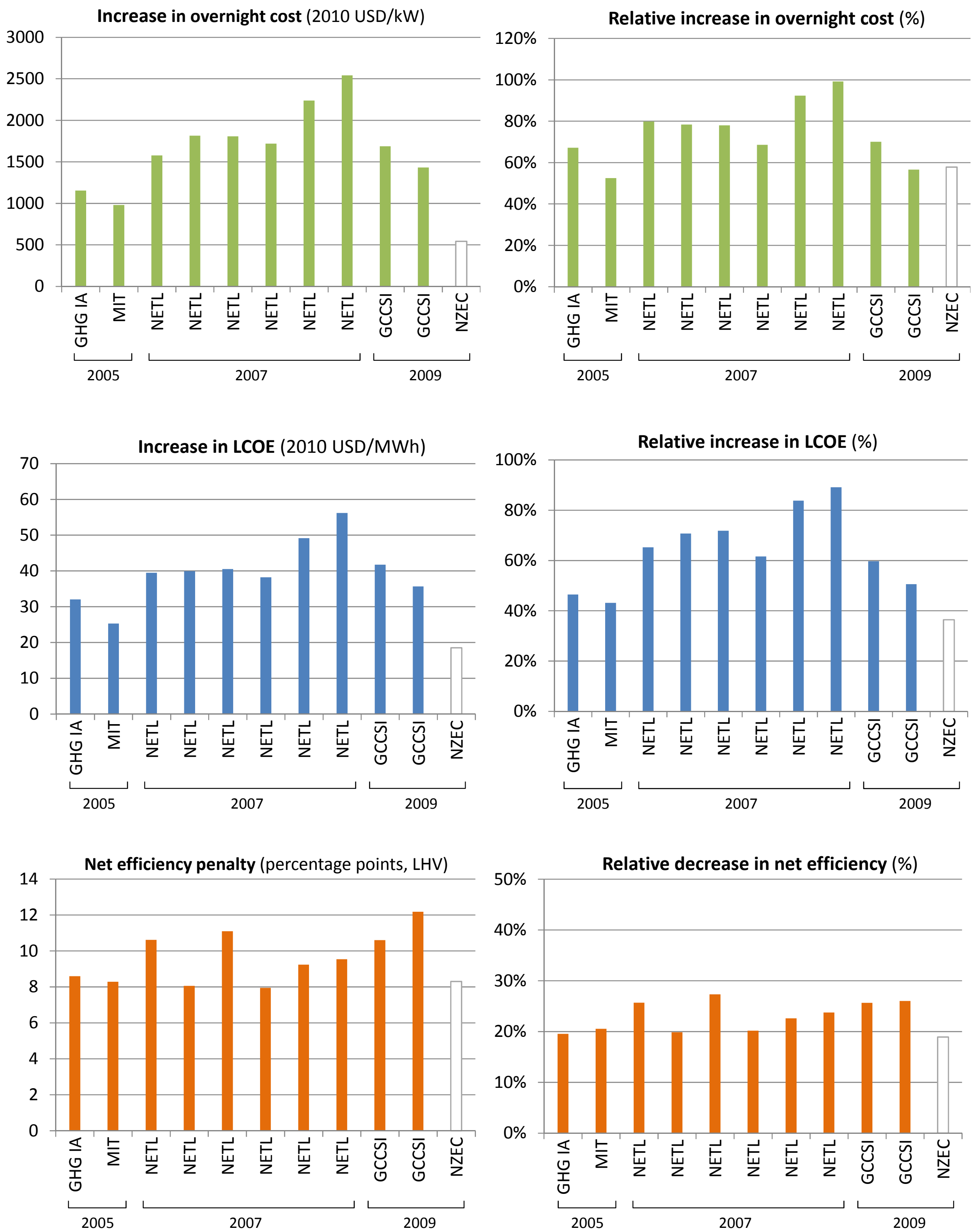
Notes: Data cover only CO_2 capture and compression but not transportation and storage. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions. CO_2 purities >99.9% apart from GHG IA (96%), GCCSI (83%) and NETL case with 29.5% (LHV) efficiency (83%).

The impact of adding oxy-combustion CO_2 capture relative to a coal-fired reference plant without CO_2 capture is illustrated in Figure 4.

Net efficiency penalties between 7.9 and 12.2 percentage points (LHV) are estimated for oxy-combustion CO_2 capture in OECD regions, which is on average a 23% reduction in efficiency. The net efficiency penalty estimated for an installation in China is 8.3 percentage points.

By adding CO_2 capture, overnight costs updated to 2010 cost levels increase on average by USD 1 696/kW but vary substantially by a factor of more than two between USD 981/kW and USD 2 543/kW. For China overnight costs are expected to increase by USD 542/kW. The relative (percentage-wise) increase of overnight costs is on average 74% compared to overnight costs of the reference power plant.

Figure 4. Oxy-combustion capture from coal-fired power generation: CO_2 capture impact



Notes: Data cover only CO_2 capture and compression but not transportation and storage. Data sorted by year of cost information as published; white bars show data for installations in China. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions.

In OECD regions, LCOE increases on average by USD 40/MWh, but varies between USD 25/MWh and USD 56/MWh. The relative increase of LCOE compared to LCOE of the reference plant is on average 64%. Costs of CO_2 avoided are on average USD 52/tCO_2 but vary between USD 35/tCO_2 and USD 72/tCO_2 for OECD regions across study cases. Costs of CO_2 avoided for China are estimated to be USD 27/tCO_2, or about half of average costs in OECD regions.

Table 8 illustrates the influence of the specific power plant and fuel type. Sample sizes are quite similar across power plant and fuel variations but still limited; hence results should not be considered representative. Total plant overnight costs of power plants including CO_2 capture tend to be lower for bituminous coals compared to sub-bituminous or lignite coals. Costs of CO_2 avoided are similar though, apart from oxy-combustion capture from CFB boilers.

Table 8. Oxy-combustion capture: influence of coals and power plant types (OECD only)

Specific fuel type	Bit coal		Sub-bit & Lignite		*Overall Average*
Power plant type	**USCPC**	**SCPC**	**SCPC**	**CFB**	
Number of cases included	2	3	3	2	
ORIGINAL DATA AS PUBLISHED (converted to USD)					
Net power output w/o capture (MW)	654	533	550	550	*566*
Net power output w/ capture (MW)	541	533	550	549	*543*
Net efficiency w/o capture, LHV (%)	45.4	41.0	40.2	40.5	*41.6*
Net efficiency w/ capture, LHV (%)	35.0	31.2	31.2	31.2	*31.9*
CO_2 emissions w/o capture (kg/MWh)	725	810	881	865	*825*
CO_2 emissions w/ capture (kg/MWh)	42	35	67	102	*59*
Capital cost w/o capture (USD/kW)	2 062	1 832	1 902	1 993	*1 931*
Capital cost w/ capture (USD/kW)	3 095	2 894	3 114	3 656	*3 153*
Relative decrease in net efficiency	**23%**	**24%**	**22%**	**23%**	***23%***
RE-EVALUATED DATA (2010 USD)					
Overnight cost w/o capture (USD/kW)	2 125	2 085	2 380	2 495	*2 263*
Overnight cost w/ capture (USD/kW)	3 419	3 500	4 161	4 885	*3 959*
LCOE w/o capture (USD/MWh)	70	63	58	61	*62*
LCOE w/ capture (USD/MWh)	103	99	98	114	*102*
Cost of CO_2 avoided (USD/tCO_2)	**50**	**45**	**49**	**69**	***52***
Relative increase in overnight cost	**62%**	**67%**	**75%**	**96%**	***74%***
Relative increase in LCOE	**49%**	**56%**	**68%**	**86%**	***64%***

Notes: Data cover only CO_2 capture and compression but not transportation and storage. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions.

Post-combustion CO_2 capture from natural gas combined cycles

Cost and performance data for post-combustion CO_2 capture from natural gas combined cycles by amines are shown in Table 9. Techno-economic data for 9 different cases from 5 organisations are analysed.

Table 9. Post-combustion capture from natural gas-fired power generation (OECD only)

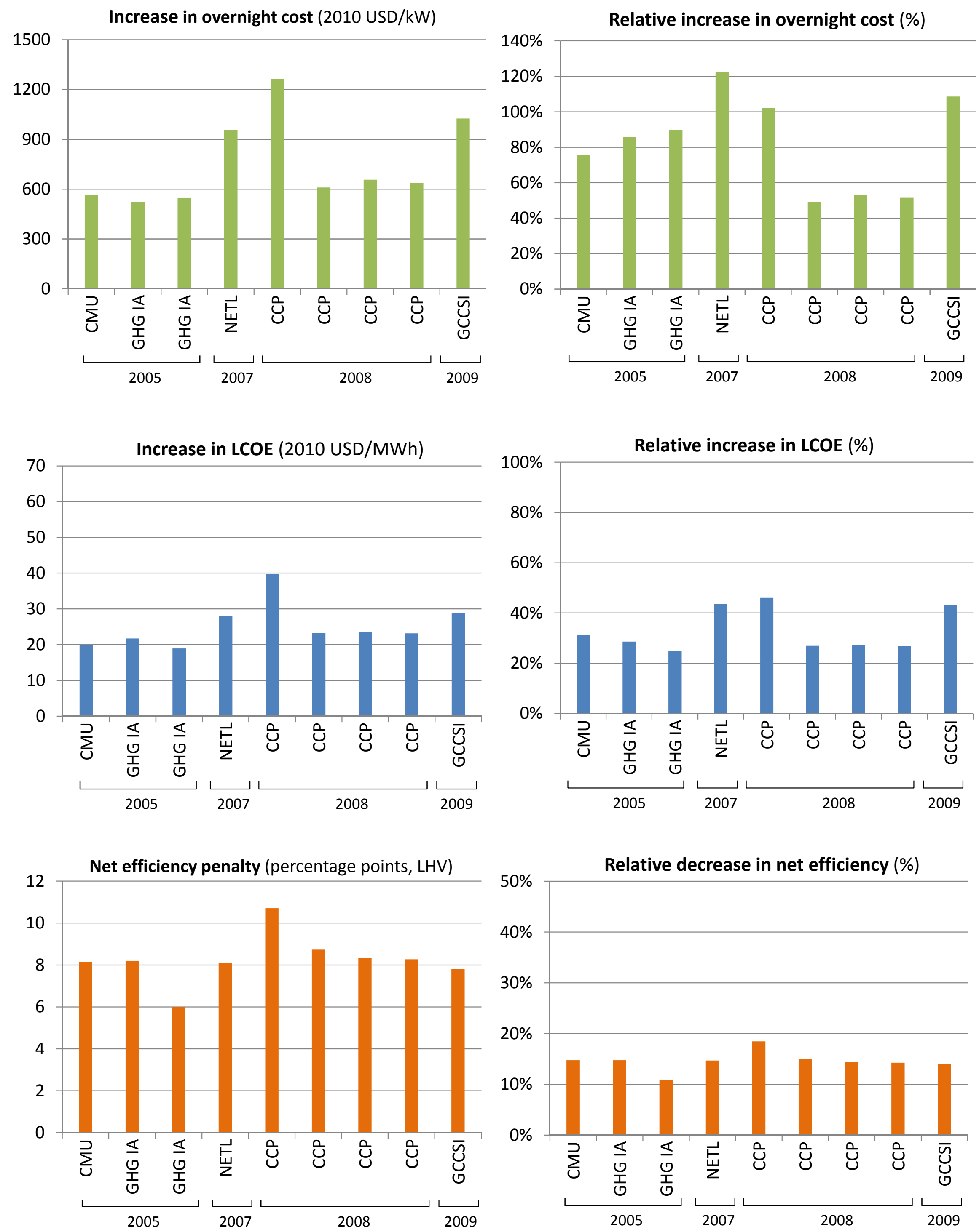
Regional focus	**OECD**									***Average***
Year of cost data	**2005**	**2005**	**2005**	**2007**	**2008**	**2008**	**2008**	**2008**	**2009**	
Year of publication	**2007**	**2007**	**2007**	**2010**	**2009**	**2009**	**2009**	**2009**	**2009**	
Organisation	**CMU**	**GHG IA**	**GHG IA**	**NETL**	**CCP**	**CCP**	**CCP**	**CCP**	**GCCSI**	
ORIGINAL DATA AS PUBLISHED (converted to USD)										
Region	US	EU	EU	US	EU	EU	EU	EU	US	
Specific fuel type	NG	NG	NG	NG	NG	NG	NG	NG	NG	
Power plant type	F-class	F-class	F-class	F-class	F-class	F-class	F-class	F-class	F-class	
Net power output w/o capture (MW)	507	776	776	555	395	395	395	395	560	*528*
Net power output w/ capture (MW)	432	662	692	474	322	367	360	361	482	*461*
Net efficiency w/o capture, LHV (%)	55.2	55.6	55.6	55.2	58.0	58.0	58.0	58.0	55.9	*56.6*
Net efficiency w/ capture, LHV (%)	47.1	47.4	49.6	47.1	47.3	49.3	49.7	49.7	48.1	*48.4*
CO_2 emissions w/o capture (kg/MWh)	367	379	379	365	370	370	370	370	362	*370*
CO_2 emissions w/ capture (kg/MWh)	43	66	63	43	60	60	60	60	42	*55*
Capital cost w/o capture (USD/kW)	671	499	499	718	1 245	1 245	1 245	1 245	957	*925*
Capital cost w/ capture (USD/kW)	1 091	869	887	1 497	2 358	1 741	1 786	1 767	1 870	*1 541*
Relative decrease in net efficiency	**15%**	**15%**	**11%**	**15%**	**18%**	**15%**	**14%**	**14%**	**14%**	***15%***
RE-EVALUATED DATA (2010 USD)										
Overnight cost w/o capture (USD/kW)	749	609	609	781	1 237	1 237	1 237	1 237	944	*960*
Overnight cost w/ capture (USD/kW)	1 313	1 133	1 157	1 740	2 502	1 847	1 895	1 875	1 969	*1 715*
LCOE w/o capture (USD/MWh)	64	76	76	64	86	86	86	86	67	*77*
LCOE w/ capture (USD/MWh)	84	98	95	92	126	110	110	110	96	*102*
Cost of CO_2 avoided (USD/tCO_2)	**62**	**69**	**60**	**87**	**128**	**75**	**76**	**75**	**90**	***80***
Relative increase in overnight cost	**75%**	**86%**	**90%**	**123%**	**102%**	**49%**	**53%**	**52%**	**109%**	***82%***
Relative increase in LCOE	**31%**	**29%**	**25%**	**44%**	**46%**	**27%**	**27%**	**27%**	**43%**	***33%***

Notes: Data cover only CO_2 capture and compression but not transportation and storage. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions. The GHG IA case with the lower efficiency penalty assumes KS-1 as a solvent. Two CCP cases (with 360 MW and 361 MW power output) make use of exhaust gas recirculation and/or advanced heat integration, which are as of today not yet commercially available technologies.

Average published capacity factors are 88% for the cases shown; CO_2 capture rates are 87%. Net power outputs including capture range from 322 MW to 692 MW, at an average net efficiency of 48.4% (LHV) across OECD regions.

The impact of adding post-combustion CO_2 capture to a natural gas combined cycle compared to an NGCC reference plant without CO_2 capture is illustrated in Figure 5.

Figure 5. Post-combustion capture from natural gas-fired power generation: CO_2 capture impact



Notes: Data cover only CO_2 capture and compression but not transportation and storage. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions

Net efficiency penalties between 6.0 and 10.7 percentage points (LHV) are estimated for post-combustion CO_2 capture in OECD regions, which is on average a 15% reduction in efficiency.

By adding CO_2 capture, overnight costs updated to 2010 cost levels increase on average by USD 754/kW but vary substantially by a factor of more than two between USD 524/kW and USD 1 264/kW.

The relative (percentage-wise) increase of overnight costs compared to overnight costs of the reference power plant is less stable than the trend observed for data for coal-fired power generation. Overnight costs increase by on average 82% when adding CO_2 capture. In contrast to coal-fired power generation, using the relative increase of overnight costs as a key metric appears to offer a less clear benefit over using absolute cost increases, given the large variation of data across studies.

In OECD regions LCOE increases on average by USD 25/MWh, but varies between USD 19/MWh and USD 40/MWh. The relative increase of LCOE compared to LCOE of the reference plant is on average 33%.

Costs of CO_2 avoided are on average USD 80/tCO_2, but vary between USD 60/tCO_2 and USD 128/tCO_2 for OECD regions across study cases.

Summary of results

Published cost and performance data vary significantly over time, across studies and sometimes even within countries or regions. This spread also reflects current macro-economic uncertainties that result from the recent global financial crisis, during which energy and supplier prices reached historical levels. As a consequence, costs for CO_2 capture processes and costs for reference plants without CO_2 capture fluctuate significantly across studies.

Cost and performance figures for the United States and the European Union, which represent the bulk of the analysed data, are summarised in Table 10. These data are average figures across a very diverse set of CO_2 capture applications and references. They nonetheless provide a snapshot of current estimates for generic costs and performance related to CO_2 capture from power generation.

Taking into account the level of uncertainty across case studies, the following general cost and performance trends can be identified for early commercial CO_2 capture from power generation:

- *For coal-fired power plants (average figures):*

  Net efficiency penalties of around 10 percentage points are estimated for post- and oxy-combustion CO_2 capture compared to a pulverised coal plant without CO_2 capture. Penalties for pre-combustion are about eight percentage points relative to an integrated gasification combined cycle without CO_2 capture.

  Overnight costs with CO_2 capture on average are USD 3 800/kW in OECD regions. Average figures vary very little across capture routes. Within single CO_2 capture routes however, variation between different power plant and fuel types can be substantial. Average LCOE estimates are USD 105/MWh.

  Costs of CO_2 avoided are on average USD 55/tCO_2 across CO_2 capture routes, provided a pulverised coal power plant without CO_2 capture is used as a reference case.

- *For natural gas-fired power plants (average figures):*

  Net efficiency penalties of about eight percentage points are estimated for post-combustion CO_2 capture from natural gas combined cycles.

  Overnight costs for power plants with post-combustion CO_2 capture are on average USD 1 700/kW, while the LCOE is USD 102/MWh.

  Costs of CO_2 avoided are on average USD 80/tCO_2 for power plants with post-combustion CO_2 capture.

For comparison, average overnight costs for SCPC and USCPC plants with CO_2 capture in the OECD *PCGE 2010* analysis are USD 3 804/kW at 2010 cost levels, or 86% above the average overnight costs of SCPC and USCPC plants without CO_2 capture. The results of the OECD PCGE 2010 analysis are thus similar to the findings of this study, although the OECD study is not based on a review of engineering studies but instead on data submissions by OECD member countries and industry associations.[10]

[10] CCS data of the *PCGE 2010* study include in total eight data points for USCPC and SCPC power plants that were submitted by the Czech Republic, Germany and the United States, as well as the industry associations Eurelectric and the Energy Supply Association of Australia.

Table 10. Average cost and performance data by CO_2 capture route (OECD only)

Fuel type	COAL			NG
Capture route	**Post-combustion**	**Pre-combustion**	**Oxy-combustion**	**Post-combustion**
Reference plant w/o capture	**PC**	**IGCC (PC)**	**PC**	**NGCC**
Net efficiency w/ capture (LHV, %)	30.9	33.1	31.9	48.4
Net efficiency penalty (LHV, percentage points)	10.5	7.5	9.6	8.3
Relative net efficiency penalty	**25%**	**20%**	**23%**	**15%**
Overnight cost w/ capture (USD/kW)	3 808	3 714	3 959	1 715
Overnight cost increase (USD/kW)	1 647	1128 (1566)	1 696	754
Relative overnight cost increase	**75%**	**44% (71%)**	**74%**	**82%**
LCOE w/ capture (USD/MWh)	107	104	102	102
LCOE increase (USD/MWh)	41	29 (37)	40	25
Relative LCOE increase	**63%**	**39% (55%)**	**64%**	**33%**
Cost of CO_2 avoided (USD/tCO_2)	**58**	**43 (55)**	**52**	**80**

Notes: Data cover only CO_2 capture and compression but not transportation and storage. The accuracy of feasibility study capital cost estimates is on average ±30%, hence for coal the variation in average overnight costs, LCOE and cost of CO_2 avoided between capture routes is within the uncertainty of the study. Underlying oxy-combustion data include some cases with CO_2 purities <97%. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions.

The IEA plans to regularly update findings, and include additional techno-economic data for other CO_2 capture applications from power generation, including bioenergy with CCS (BECCS). In many global climate scenarios, BECCS plays a crucial role for reducing CO_2 emissions in the atmosphere. Commercial attractiveness of BECCS is currently limited since no specific mechanisms are in place that would incentivise the potential of BECCS to generate negative CO_2 emissions.

Future cost and performance potential

Cost and performance estimates for near-term CO_2 capture from power generation are typically based on currently available technologies. Characteristics of future CO_2 capture installations deployed in the longer term will likely differ in comparison to near-term designs. Though a rise in cost is not uncommon for technologies in early phases of demonstration, cost reduction and performance improvement are typically expected over time and with increasing deployment.

Potential cost and performance improvement can be assessed based on bottom-up techno-economic engineering models of advanced capture approaches. An alternative approach is to apply the concept of historical learning curves by using data for already established technologies that are extrapolated to CO_2 capture processes.

Experience curves are used to describe cost reduction as a function of cumulative deployment, which for CO_2 capture technologies derives from energy scenarios. Studies have analysed the historical deployment and cost development of power generation-related technologies – such as flue gas desulphurisation, selective catalytic reduction, gas turbine combined cycles, pulverised coal boilers, oxygen production plants and steam methane reforming – as a basis for estimating similar learning effects for CO_2 capture processes. It should be noted that cost estimates initially often increase rather than decrease when novel technologies move into first use.

Based on a scenario that assumes 100 GW of CCS have been deployed the improvement potential through learning effects was analysed (Rubin, 2007). For different power plants with CO_2 capture, reductions are estimated at between 9.1% and 17.8% in capital costs, and between 9.7% and 17.6% in cost of electricity. Reference power plants without CCS could also benefit from further improvement, but net reductions of overall CO_2 mitigation costs are identified. Further information on the underlying methodology and work that extends this approach to also include potential improvement of power plant performance data can be found in the literature (van den Broek, 2009).

Uncertainty and sensitivity of results

Given their generic nature or early stage of development, most of the published data evaluated in this report should be considered as feasibility study estimates. Typical accuracy ranges of feasibility study cost estimates are -15% to -30% on the low side, and +20% to +50% on the high side (AACE, 2005). This uncertainty applies to capital cost estimates, but extends also to corresponding LCOE figures, in particular for coal power plants that are traditionally capital-intensive. Considering the uncertainty level of cost estimates, differences in overnight costs and LCOE across different CO_2 capture routes for coal-fired power generation cannot be interpreted as a competitive advantage of one technology route over the alternative routes.

Total capital requirement of a real-life project will be significantly different from generic estimates. Important considerations for a specific project include (among others) financing structures and conditions, company- and site-specific requirements, geographic cost differences or costs related to permitting, site and technology approval.

Project- and site-specific costs should not be underestimated. This report assumes new-build power plants with integrated CO_2 capture that can use existing utility systems on a brown-field industrial site. If this is not the case, project- and site-specific costs may add significantly to the total project costs. Gassnova made a cost estimate for a retrofit of post-combustion capture to a natural gas power plant in a rural area in Norway, and found that project- and site-specific costs added 30% to the EPC-contract costs for the CO_2 capture plant. The project- and site-specific costs included site preparation, connections for flue gas and other utilities, sea water cooling system, power supply, fire water supply, training of personnel and miscellaneous other costs in the construction phase.[11]

Across the reviewed studies, it is often not fully transparent which sources and methodologies are used for estimating cost. When interpreting results, readers should keep in mind that often estimates will not be based on original source data from plant suppliers but might be derived from other published sources, or have been provided by the same engineering contractor. As an example, the study by GCCSI uses NETL capital cost data as a starting point for further analysis and re-evaluation.

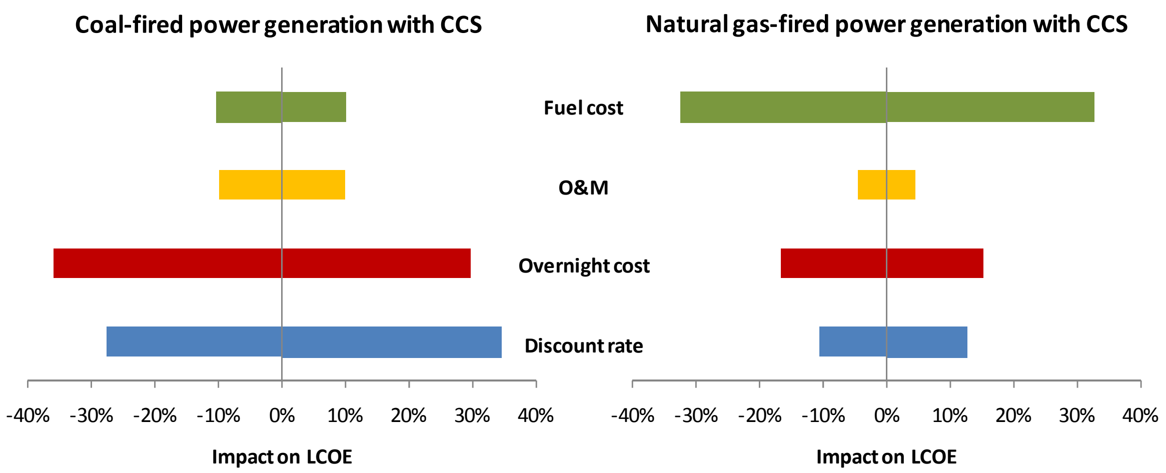
The tools and methodologies used for this study are based on the *PCGE 2010* analysis, which also discusses in detail sensitivities of results to variations of key input parameters. For example, this analysis uses assumptions on capacity factors that are representative of baseline operation of

[11] Personal communication with Tore Hatlen, Gassnova, 2011.

power plants. It is important to note that in future scenarios with substantial electricity supply by variable renewable energy, other power generation options – including those with CO_2 capture – might have to operate at load factors that are significantly lower. Given the sensitivity of LCOE to the capacity factor, this would lead to higher LCOE figures than those provided in the results section of this working paper. In addition, once installed, the marginal operating costs of power plants will play an important role for determining the capacity factor of a specific power plant. Due to higher fuel costs, marginal operating costs of natural gas-fired power plants are often higher than those for coal-fired plans, which could result in lower capacity factors. The sensitivity of LCOE to variations in the capacity factor and other key parameter is discussed in the *PCGE 2010* publication.

In addition, sensitivities of LCOE results from this study are illustrated in Figure 6. The vertical axis denotes the average baseline LCOE result for coal- and natural gas-fired power generation with CCS. The horizontal bars indicate the percentage increase or decrease of this value caused by a ±50% variation in the assumptions for fuel cost, O&M, overnight costs and discount rate. The graphs quantify the generally known strong sensitivity of LCOE to capital cost related factors such as overnight costs and the discount rate for coal-fired power generation, and fuel cost for natural gas-fired power generation.

Figure 6. Impact of a ±50% variation in key assumptions on LCOE



In general, CO_2 capture cost estimates published before 2007 are comparably low. While this coincides with low cost indices for power and chemical installations at that time, costs remain lower than more recent estimates even after updating them to current levels. Hence, simple recalibration of older cost figures often cannot fully close the gap between older and latest cost estimates for CO_2 capture. Reasons for this difference might include:

- Fundamental differences in prices of individual core equipment, for example for gas turbines or other key cost components that are not fully reflected by generalised cost indices used in this study;
- Increased and more detailed knowledge about processes and required auxiliary installations leading to higher cost; and
- Changes in pricing strategies by technology providers and engineering companies.

Conclusions and recommendations

This study discusses cost and performance trends for CO_2 capture from power generation. Estimates for about 50 different CO_2 capture installations at power plants are included in the analysis, with a focus on generic, new-build CO_2 capture processes that would be located in the United States, Europe and China. Techno-economic data published over the last five years are re-calibrated and updated to current cost levels.

Most cost and performance estimates are available for post-, pre- and oxy-combustion CO_2 capture from coal-fired power generation, and for post-combustion CO_2 capture from natural gas-fired power generation.

Based on the re-evaluated cost and performance estimates, the following observations and recommendations can be summarised for early commercial CO_2 capture from power generation:

- **Considering uncertainties of current cost and performance data, no single technology for CO_2 capture from coal-fired power generation clearly outperforms the available alternative capture routes.** This applies in particular to average overnight costs and levelised cost of electricity but also includes cost of CO_2 avoided, provided the same plant without capture is chosen as a reference. This conclusion is also reflected by current CCS demonstration activities, which cover all capture routes.

- **While absolute CO_2 capture cost estimates for coal-fired power generation vary over years, figures that describe the relative increase of cost compared to a reference plant without CO_2 capture are often more stable across studies.** For providing initial generic cost estimates of coal-fired power plants with CO_2 capture, especially for regions with limited available data, relative cost increases compared to actual reference plant cost thus should be considered a primary option. If no detailed site-specific data are available, this approach appears more appropriate than using constant absolute cost increments.

- **For natural gas-fired power plants, post-combustion CO_2 capture is the option most predominantly considered across studies.** Based on data provided in the reviewed studies, post-combustion appears the most attractive option for near-term CO_2 capture from natural gas combined cycles. Variation across data, however, is particularly high for natural gas-fired power plants. Since this trend includes latest publications, additional analysis is required to secure a better understanding of related costs.

- **Harmonisation of costing methodologies and formats of reporting data is desirable in order to increase transparency, and further simplify comparisons of data across studies.** Though many studies use a conceptually similar approach in estimating CO_2 capture cost and performance, specific methodologies, terminologies and underlying assumptions are not consistently used across all studies. In support of energy scenario modelling, overnight costs is the preferable metric for capital costs, since it minimises the impact of project-specific financing structures.

- **Additional analysis is needed across capture routes to further quantify differences between generic cost estimates (as presented in this report) and project- and site-specific costs of CO_2 capture projects.** Generic cost estimates provide a first orientation regarding likely average costs that can be expected for early commercial CO_2 capture systems. Further work is required to better understand the cost spreads that could be expected due to project- and site-specific conditions.

- **Additional cost and performance estimates are desirable for bioenergy with CCS (BECCS).** Though BECCS is playing an important role in several global climate models, engineering-level techno-economic data comparable with those for coal- or natural gas-fired power generation are still scarce in the literature. In this context, mechanisms need to be evaluated that could incentivise negative CO_2 emissions generated by BECCS.

- **Availability of data for CO_2 capture from power generation in non-OECD countries is very limited, though global energy scenarios foresee that deployment of CCS in these countries might have to exceed levels in OECD countries.** It remains challenging to find broader assessments on CO_2 capture from power generation that stem from domestic organisations in developing countries. Given the potential importance of CCS technology in non-OECD countries, additional techno-economic studies are needed, including case studies that analyse the retrofit of CCS. In this context, appropriate capacity building in non-OECD countries is important. High quality information is required for global energy scenario models. Moreover, domestic know-how will be critical for developing countries in order to evaluate the potential role of CCS in their national energy contexts.
- **In addition to CO_2 capture data, accurate information on CO_2 transport and storage is crucial for evaluating the viability of CCS globally and in specific regions.** It is important to further validate the practically achievable and economically affordable storage capacities and related costs based on internationally standardised assessment methodologies. Though CO_2 transportation and storage are not covered by this working paper, the IEA is addressing this subject in other work streams.

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Annex: Study cases with limited available data

Post-combustion CO_2 capture from coal-fired power generation by ammonia

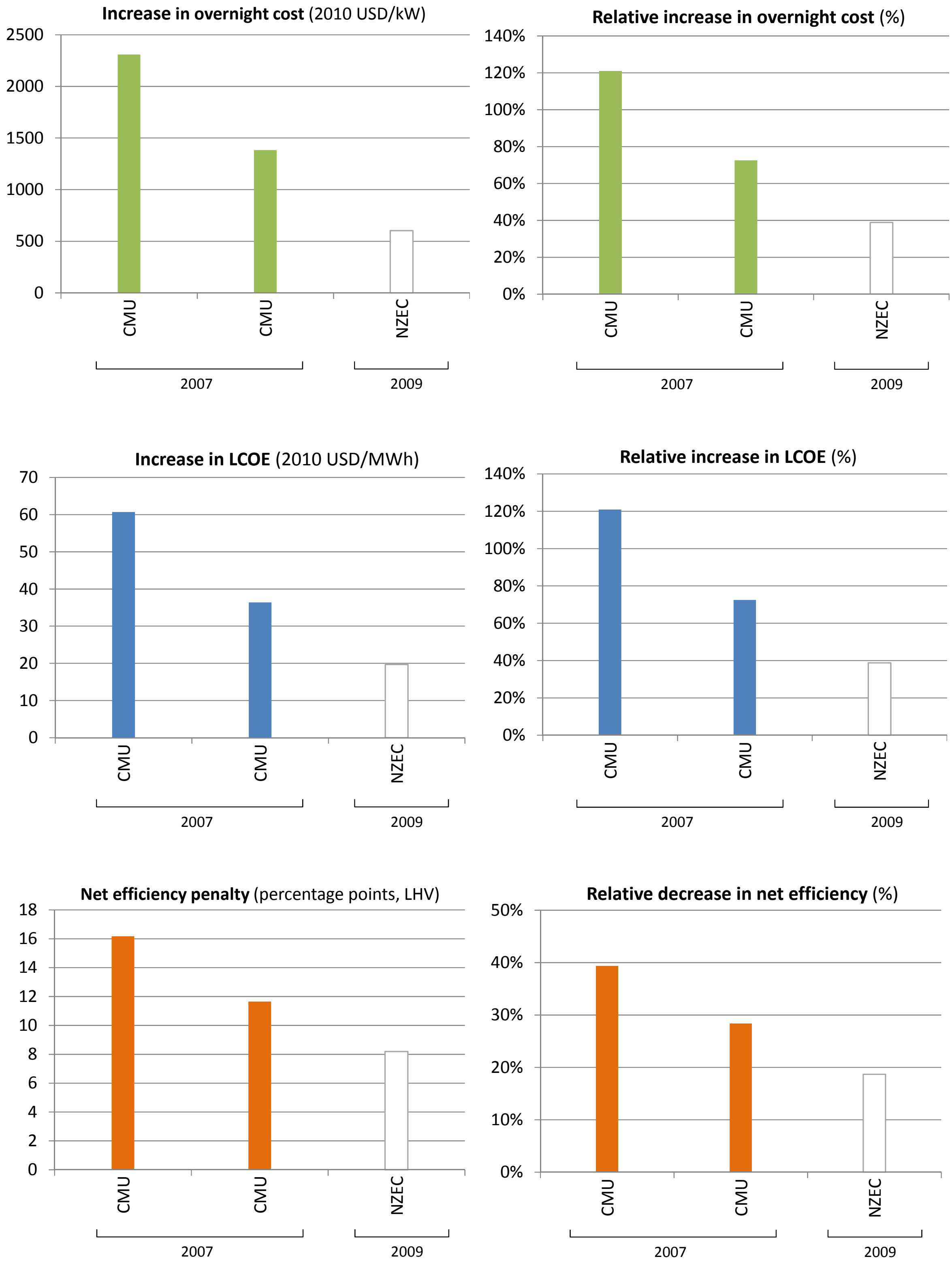
While amine-based today is the most mature technology for post-combustion CO_2 capture, ammonia-based solvents are considered a potentially attractive alternative. Only two of the reviewed studies evaluate ammonia-based CO_2 capture in detail. In contrast to amine-based capture, which is known for decades from industrial processes, assessing cost and performance of ammonia-based CO_2 capture remains challenging due to limited available data and simulation tools. Data for ammonia capture systems that are summarised should be thus considered preliminary and more uncertain. They are nonetheless shown in Table 11 for reference.

Table 11. Post-combustion capture from coal-fired power generation by ammonia

Regional focus	OECD		China	*Average (OECD)*
Year of cost data	**2007**	**2007**	**2009**	
Year of publication	**2010**	**2010**	**2009**	
Organisation	**CMU**	**CMU**	**NZEC**	
ORIGINAL DATA AS PUBLISHED (converted to USD)				
Region	US	US	CHN	
Specific fuel type	Bit coal	Bit coal	Bit coal	
Power plant type	SCPC	SCPC	USCPC	
Net power output w/o capture (MW)	550	550	824	*550*
Net power output w/ capture (MW)	475	561	670	*518*
Net efficiency w/o capture, LHV (%)	41.1	41.1	43.9	*41*
Net efficiency w/ capture, LHV (%)	24.9	29.4	35.7	*27*
CO_2 emissions w/o capture (kg/MWh)	811	811	797	*811*
CO_2 emissions w/ capture (kg/MWh)	107	107	98	*107*
Capital cost w/o capture (USD/kW)	1 601	1 601	856	*1 601*
Capital cost w/ capture (USD/kW)	3 753	2 841	1 318	*3 297*
Relative decrease in net efficiency	**39%**	**28%**	**19%**	***34%***
RE-EVALUATED DATA (2010 USD)				
Overnight cost w/o capture (USD/kW)	1 491	1 491	938	*1 491*
Overnight cost w/ capture (USD/kW)	3 799	2 875	1 541	*3 337*
LCOE w/o capture (USD/MWh)	50	50	51	*50*
LCOE w/ capture (USD/MWh)	111	87	71	*99*
Cost of CO_2 avoided (USD/tCO_2)	**86**	**52**	**28**	***69***
Relative increase in overnight cost	**155%**	**93%**	**64%**	***124%***
Relative increase in LCOE	**121%**	**73%**	**39%**	***97%***

Notes: Data cover only CO_2 capture and compression but not transportation and storage. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions. CMU data include a low (left column) and high (right colum) concentration ammonia system operating w/o and w/ solids.

Figure 7. Post-combustion capture from coal-fired power generation by ammonia: CO_2 capture impact



Notes: Data cover only CO_2 capture and compression but not transportation and storage. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions. CMU data include a low (left column) and high (right colum) concentration ammonia system operating w/o and w/ solids.

Acronyms, abbreviations and units of measure

Acronyms and abbreviations

AACE	Association for the Advancement of Cost Engineering
Bio	biomass
Bit	bituminous
CCP	CO_2 Capture Project
CCS	carbon capture and storage
CEPCI	Chemical Engineering Plant Cost Index
CFB	circulating fluidised bed
CHN	China
CMU	Carnegie Mellon University
CNY	Yuan Renminbi (China currency)
CO_2	carbon dioxide
COE	cost of electricity
CoP	ConocoPhillips
EPC	engineering, procurement and construction
EPRI	Electric Power Research Institute
EU	European Union
FEED	front-end engineering and design
GCCSI	Global CCS Institute
GE	General Electric Company
GHG	Greenhouse-Gas
GHG IA	Greenhouse-Gas Implementing Agreement
HHV	higher heating value
IDC	interest during construction
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCOE	levelised cost of electricity
LHV	lower heating value
MEA	monoethanolamine
MIT	Massachusetts Institute of Technology
NEA	Nuclear Energy Agency
NETL	National Energy Technology Laboratory
NG	natural gas
NGCC	natural gas combined cycle
NZEC	Near Zero Emissions Coal Initiative
OECD	Organisation for Economic Co-operation and Development
O&M	operation and maintenance
PC	pulverised coal
PCGE	*Projected Costs of Generating Electricity 2010* (OECD publication)
SCPC	supercritical pulverised coal
Sub-PC	subcritical pulverised coal
TPRI	Thermal Power Research Institute
UNIDO	United Nations Industrial Development Organization
US	United States
USCPC	ultra-supercritical pulverised coal
USD	United States Dollar
w/	with
w/o	without

Units of measure

GJ	Gigajoule
kW	Kilowatt
MBtu	million British thermal units
MW	Megawatt
t	tonne (metric)

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