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# CO<sub>2</sub> Capture Process Principles and Costs

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**Résumé — Les différents procédés de capture du CO<sub>2</sub> et leurs coûts** — De grandes quantités de CO<sub>2</sub> sont émises à pression atmosphérique par la production thermique d'électricité en particulier. Le principe de capture-stockage du CO<sub>2</sub> offre des perspectives intéressantes pour limiter les émissions de gaz à effet de serre de cette filière. Le CO<sub>2</sub> capturé doit ensuite être compressé avant les étapes de transport et de stockage.

Il y a trois catégories de procédés de capture du CO<sub>2</sub> :

- les procédés postcombustion ;
- les procédés précombustion ;
- les procédés en oxycombustion.

Ces catégories sont toutes applicables aux combustibles fossiles et à la biomasse, moyennant des spécificités techniques en fonction de la nature du combustible. Elles mettent en œuvre plusieurs méthodes physicochimiques de séparation des gaz.

La capture du CO<sub>2</sub> est l'étape la plus coûteuse de la chaîne capture-séquestration. Le bilan de cette chaîne est ici présenté pour différentes technologies de production de l'énergie, de capture et de transport du CO<sub>2</sub>. Huit étapes sont prises en compte, de l'extraction des combustibles fossiles à la séquestration du CO<sub>2</sub>.

**Abstract — CO<sub>2</sub> Capture Process Principles and Costs** — Carbon dioxide capture and storage (CCS) is an important concept to reduce greenhouse gas emissions, in particular from power plants. After CO<sub>2</sub>-capture the CO<sub>2</sub> needs to be compressed to achieve the right transport and storage conditions.

CO<sub>2</sub> capture processes can be divided into three main categories:

- postcombustion processes;
- precombustion processes;
- oxy-combustion/denitrogenation processes.

These process categories are applicable to both fossil fuel and biomass. Several different physical-chemical gas separation methods used CO<sub>2</sub>-capture will be described.

The capture of CO<sub>2</sub> is the most expensive step in the CCS-chain. A systematic approach to costs and emission of the chain capture-transport-sequestration of CO<sub>2</sub> is presented, for different power generation technologies, capture and transport technologies. This involves eight steps, incorporating the complete chain from fossil fuel extraction to the production of the energy carrier and the storage of CO<sub>2</sub>.

## 1 INTRODUCTION TO CO<sub>2</sub> CAPTURE

### 1.1 Relevance of CO<sub>2</sub> Capture

Carbon dioxide capture and storage (CCS) is gradually becoming an important concept to reduce greenhouse gas emissions, next to other options, such as, the use of renewable energy, the use of nuclear energy, energy efficiency improvements and switching from coal to gas firing. In CCS, CO<sub>2</sub> is extracted at some point in the energy conversion train, depending on the type of energy technology used. It is then prepared for transport and stored in a suitable geological sink, where it is kept for a sufficiently long period. As such, CCS limits or altogether avoids the release of CO<sub>2</sub> into the atmosphere as a result of combustion processes. It is thereby possible to sustain the use of fossil fuels (coal, gas and oil), while drastically reducing the CO<sub>2</sub>-emissions. In case of biomass based fuels the capture and storage of CO<sub>2</sub> will result in a net decrease of CO<sub>2</sub> in the atmosphere.

The overall, general CCS concept involves three steps:

- Capture of CO<sub>2</sub>. Large amounts of CO<sub>2</sub> are emitted in diluted streams at atmospheric pressure, for instance, in flue gases from power stations, as the fuel is usually burned in air. To simplify the ensuing steps of transport and storage this needs to be concentrated. In general a near pure CO<sub>2</sub> product at an absolute pressure of 100 bar needs to be produced by the capture process. Therefore also a compression step is needed to achieve the right transport/storage conditions.
- Transport of CO<sub>2</sub>. Transport of CO<sub>2</sub> is needed as the emissions of CO<sub>2</sub> will not necessarily be, at the same location as the storage site. A transport system is therefore needed to link the CO<sub>2</sub>-sources to the CO<sub>2</sub>-sinks.
- Storage of CO<sub>2</sub>. Storage of CO<sub>2</sub> should be such that it remains isolated from the atmosphere for a suitably long period. The options for this are mainly in the underground, *i.e.* exhausted oil and gas fields, deep coal beds and aquifers. CO<sub>2</sub> might also be chemically bound to certain rock materials, which is the means of CO<sub>2</sub>-control over geological time scales.

Various aspects and components of the CCS process chain have been researched over the past 15 years, both practically and theoretically. This has revealed that CCS can be a valuable part in the portfolio of technologies to reduce CO<sub>2</sub>-emissions. Both capture and transport of CO<sub>2</sub> can be done using technologies which are commercially available. For instance, CO<sub>2</sub>-separation technologies are commonplace in the oil and gas industry. There is a need to adapt and optimise these separation technologies for CCS. As regards transport: various modes of CO<sub>2</sub> transport are possible: pipeline, ship, tanker and the focus is on the infra-structural requirements. CO<sub>2</sub>-storage can be done in exhausted oil and gas fields, coal beds and aquifers. These technologies are at

various stages of development. Injection of CO<sub>2</sub> into oil fields is practiced already in the United States, under commercial conditions. The first commercial application of CO<sub>2</sub> storage in an of-shore aquifer has been successfully been running since 1996 at the Sleipner gas field in Norway. An experimental study into the storage of CO<sub>2</sub> in a coal bed, supported by the EC, is currently underway in Poland. A major challenge is to achieve societal acceptance of the concept of underground CO<sub>2</sub>-storage, for which several demonstration projects are currently underway.

As will be shown later on, capture of CO<sub>2</sub> will determine the costs of the CCS-route. The contribution of capture to the overall cost will be around 75%. It will also be shown that the production costs of electricity will increase by over 50%. This shows that cutting the costs of capture is one of the most important issues in making the option acceptable to the energy industry.

CO<sub>2</sub>-capture processes or decarbonisation technologies can be divided into three main categories or general process routes:

- Postcombustion processes. Carbon dioxide is captured from a flue gas at low pressure (1 bar) and low CO<sub>2</sub>-content (3-20%), in general. The separation task is to remove CO<sub>2</sub> from a mixture of mainly nitrogen and oxygen, but also the impact of flue gas impurities (SO<sub>x</sub>, NO<sub>x</sub>, particulates) needs to be taken into account.
- Precombustion processes. Carbon dioxide is captured from a gas mixture with predominantly H<sub>2</sub> gas at high pressure (15-40 bar) and medium CO<sub>2</sub>-content (15-40%) or carbon is produced directly from fossil fuels. Apart from the CO<sub>2</sub>/H<sub>2</sub> separation, the feed gases also contain CO, H<sub>2</sub>S and sometimes other sulphur components.
- Denitrogenation processes. A concentrated stream of carbon dioxide can be produced by the exclusion of nitrogen before or during the combustion/conversion process. The difference with the previous process routes is that here the separation is targeted to produce oxygen from air (*i.e.* separation of oxygen from mainly nitrogen), thereby avoiding the need for CO<sub>2</sub> separation. An additional advantage might be that in the same process all impurities are captured, as the process is essentially free of flue gas.

These process categories are applicable to both fossil fuel and biomass based energy conversion processes (power plants and industrial plants). The process details will however be different for each type of fuels, and each type of energy conversion process. In addition to this, for coal based energy conversion processes the sulphur content of coal is an item, which impacts on the design, operation and costs of decarbonisation processes. This also applies for situations where bottom fuels, such as petcoke or asphalt are used. CO<sub>2</sub> emissions from power production are around 30% of overall emissions. Power plants are the largest point sources of diluted CO<sub>2</sub> and hence CO<sub>2</sub>-capture from power plant can have a large impact. Other large single point sources of

diluted CO<sub>2</sub> are furnaces and industrial boilers, and calcining processes. Power plants provide a convenient framework for comparison of options, but capture processes or decarbonisation technologies might be applied to any CO<sub>2</sub> emission source.

## 1.2 Postcombustion Decarbonisation

The power station is a conventional one in which the fuel is mixed with air and burnt. Power is produced by gas turbines and/or steam turbines. The challenge here is to develop a CO<sub>2</sub> separation process able to recover CO<sub>2</sub> from the flue gas at an acceptable energy penalty and costs. The leading option is an absorption process using amine based solvents.

The general post-combustion process scheme is shown in Figure 1.

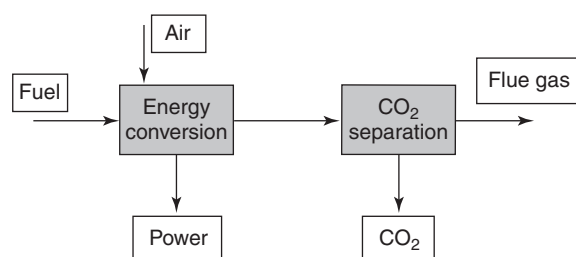


Figure 1

Postcombustion decarbonisation.

Postcombustion decarbonisation consists of two main process steps: an energy conversion step during which power is produced, followed by a CO<sub>2</sub> separation process in which a concentrated stream of CO<sub>2</sub> is produced.

## 1.3 Precombustion Decarbonisation

The fuel is first converted in a reformer or gasification process and the subsequent shift-reaction into a mixture of

CO<sub>2</sub> and H<sub>2</sub>. The high pressure of this product gas stream facilitates the removal of CO<sub>2</sub>. The H<sub>2</sub>-product can then be burnt in a gas turbine, followed by a heat recovery and steam generation process or can be used in fuels cells. Although the pre-combustion technology results generally in relatively low parasitic power losses, a major issue here is the H<sub>2</sub> combustion for a gas turbine. In the leading option is an absorption process is used for CO<sub>2</sub>-separation, in which the solvent can be a chemical one of physical one.

An alternative pathway is direct carbonisation giving solid carbon and H<sub>2</sub>. In this route the chemical energy content of carbon is not used. Hence the overall conversion efficiencies are expected to be lower.

Overall the precombustion decarbonisation may also contribute to (an accelerated) introduction of H<sub>2</sub> as an energy carrier for stationary and mobile applications. As such it provides a link to an energy infrastructure based on H<sub>2</sub> produced from renewable energy sources.

The general precombustion process scheme is shown in Figure 2.

Precombustion decarbonisation consists of three consecutive process steps: a fuel conversion step which produces a gas mixture from which CO<sub>2</sub> can be removed as the second step and the final energy conversion process in which the power is produced.

## 1.4 Denitrogenation

In the route of denitrogenation the nitrogen present in the combustion air is kept separated from the carbon dioxide formed by the conversion process. In the leading option O<sub>2</sub> is obtained in an air separation unit and combustion is carried out in an O<sub>2</sub>/CO<sub>2</sub> atmosphere, obtained by the partial recycling of the nitrogen free flue gas. This is also referred as the oxy-fuel process.

The general denitrogenation process scheme is shown in Figure 3.

Denitrogenation consists of two consecutive process steps: an air separation step which results in an oxygen stream which is then used instead of air in the energy

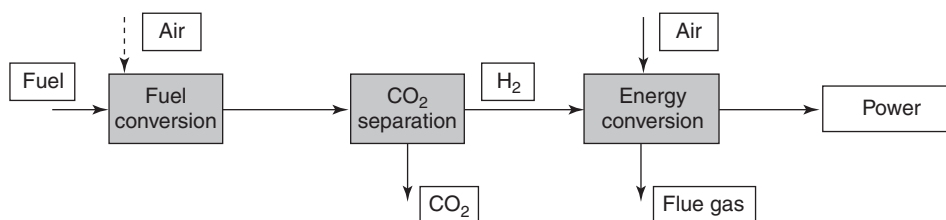


Figure 2

Precombustion decarbonisation.

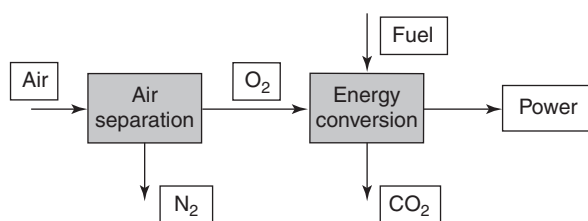


Figure 3

Denitrogenation.

conversion process. The resulting flue gas is then a high purity CO<sub>2</sub> stream.

## 2 CLASSIFICATION OF CO<sub>2</sub>-CAPTURE TECHNOLOGIES

Capture of CO<sub>2</sub> from energy conversion process generally means that at some point in the process CO<sub>2</sub> will need to be separated, which is the case for post- and precombustion decarbonisation. Alternatively, the energy conversion process

can produce a concentrated CO<sub>2</sub>-stream, provided nitrogen is not present during the CO<sub>2</sub>-formation. This is the principle of a denitrogenation process. In any case it is clear that overall CO<sub>2</sub> capture or decarbonisation process will in general consist of a combination of energy or fuel conversion steps and separation steps.

Decarbonisation processes can involve several physical-chemical separation methods. These methods are:

- membranes, using selective barriers to separate gases;
- solvents, using absorption liquids to separate gases;
- sorbents, using selective particles to separate gases;
- cryogenic, using difference in points of condensation to separate gases.

In addition to these separation methods, fuels can also directly decarbonated and converted to inert carbon and hydrogen, avoiding the use of carbon in the combustion process. Also biological processes can be used to convert CO<sub>2</sub> into biomass, which can then be used as a fuel. Finally, there is a number of enabling energy conversion technologies which are part of a decarbonisation process. It is particularly important to integrate the energy conversion technologies with the separation technologies for CO<sub>2</sub> and O<sub>2</sub> to achieve low cost and high efficiency capture routes.

TABLE 1  
CO<sub>2</sub>-capture toolbox

Capture method	Postcombustion decarbonisation	Precombustion decarbonisation	Denitrogenated conversion
<b>Principle of separation</b>			
Membranes	<ul style="list-style-type: none"> <li>• Membrane gas absorption</li> <li>• Polymeric membranes</li> <li>• Ceramic membranes</li> <li>• Facilitated transport membranes</li> <li>• Carbon molecular sieve membranes</li> </ul>	CO <sub>2</sub> /H <sub>2</sub> separation based on: <ul style="list-style-type: none"> <li>• Ceramic membranes</li> <li>• Polymeric membranes</li> <li>• Palladium membranes</li> <li>• Membrane gas absorption</li> </ul>	<ul style="list-style-type: none"> <li>• O<sub>2</sub>-conducting membranes</li> <li>• Facilitated transport membranes</li> </ul>
Adsorption	<ul style="list-style-type: none"> <li>• Lime carbonation/calcinations</li> <li>• Carbon based sorbents</li> </ul>	<ul style="list-style-type: none"> <li>• Dolomite, hydrotalcites and other carbonates</li> <li>• Zirconates</li> </ul>	<ul style="list-style-type: none"> <li>• Adsorbents for O<sub>2</sub>/N<sub>2</sub> separation</li> <li>• High temperature O<sub>2</sub> adsorbent eg., perovskites</li> </ul>
Absorption	<ul style="list-style-type: none"> <li>• Improved absorption liquids</li> <li>• Novel contacting equipment</li> <li>• Improved design of processes</li> </ul>	<ul style="list-style-type: none"> <li>• Improved absorption liquids</li> <li>• Improved design of processes</li> </ul>	<ul style="list-style-type: none"> <li>• Absorbents for O<sub>2</sub>/N<sub>2</sub> separation</li> </ul>
Cryogenic	<ul style="list-style-type: none"> <li>• Improved liquefaction</li> </ul>	<ul style="list-style-type: none"> <li>• CO<sub>2</sub>/H<sub>2</sub> separations</li> </ul>	<ul style="list-style-type: none"> <li>• Improved distillation for air separation</li> </ul>
Carbon extraction	Not applicable	<ul style="list-style-type: none"> <li>• Direct decarbonisation</li> </ul>	Not applicable
Biotechnology	<ul style="list-style-type: none"> <li>• Algae production</li> </ul>	<ul style="list-style-type: none"> <li>• High pressure applications</li> </ul>	<ul style="list-style-type: none"> <li>• Biomimetic approaches</li> </ul>
Energy conversion	<ul style="list-style-type: none"> <li>• Power cycles</li> <li>• Combustion processes</li> <li>• Gas turbine cycles</li> <li>• Steam cycles</li> </ul>	<ul style="list-style-type: none"> <li>• Hydrogen in gas turbine combustors</li> </ul>	<ul style="list-style-type: none"> <li>• Combustion in O<sub>2</sub>/CO<sub>2</sub>/H<sub>2</sub>O atmosphere</li> </ul>

A technology matrix can be built up, linking the three capture process routes with the different technological platforms. The matrix is filled with different technologies part of the overall CO<sub>2</sub> capture process. The resulting CO<sub>2</sub>-capture toolbox is shown in Table 1. It is a useful instrument for both mapping the relevant separation technologies and guiding future research initiatives in this area.

### 3 COSTS AND EMISSIONS OF CO<sub>2</sub> CAPTURE, TRANSPORT AND STORAGE

The variety in technologies for CO<sub>2</sub> capture as demonstrated in the previous sections can be quite large. In principle any kind of carbon containing fuel can be used in CCS systems. This may result in countless CCS systems by linking up the various chain elements. Each CCS chain will have its own emission factor and specific energy production costs. In this chapter a systematic approach to costs and emission of CCS systems is presented and the results of some relevant pre-defined CCS chains are compared. The technologies considered in the CCS system are all commercially available, but for the capture technologies in particular the scale of current applications is smaller than is needed for large scale power plants. The operation of these plants is governed by the existing regulations on health, safety and environment. There is no need to develop new regulations. Aspects such as the safety related to the handling of CO<sub>2</sub> and the treatment of waste products are all dealt with through existing regulations. As regards the technology implementation the existing planning procedures can be followed. An environmental impact report will need to be included in these procedures, but this will be according to existing practices, as a capture plants not different from any other chemical plant.

#### 3.1 CO<sub>2</sub> Emitted – Avoided, Captured

The purpose of capture and storage of carbon dioxide is to reduce carbon dioxide emissions to the atmosphere. According to that view it is not the amount of carbon dioxide *captured* per unit of production (e.g. per kWh electricity) that is important, but it is the amount of carbon dioxide emission *avoided*. Due to the capture, transport and storage of CO<sub>2</sub> additional energy input is required per unit of output. Because the plant with carbon dioxide capture produces the same output, but generates more carbon dioxide, the amount of carbon dioxide produced per unit of production will increase. As a result, the amount of carbon dioxide avoided is less than the amount of carbon dioxide captured. Figure 4 shows a graphical representation of these properties. As an example a coal-fired power plant is taken with 90% capture of the total generated carbon dioxide. In this example 0.86 kg CO<sub>2</sub>/kWh is captured and 0.70 kg CO<sub>2</sub>/kWh is avoided. The lower amount of avoidance compared to captured also

implies that the costs per tonne of carbon dioxide avoided will be higher than the costs per tonne of carbon dioxide captured.

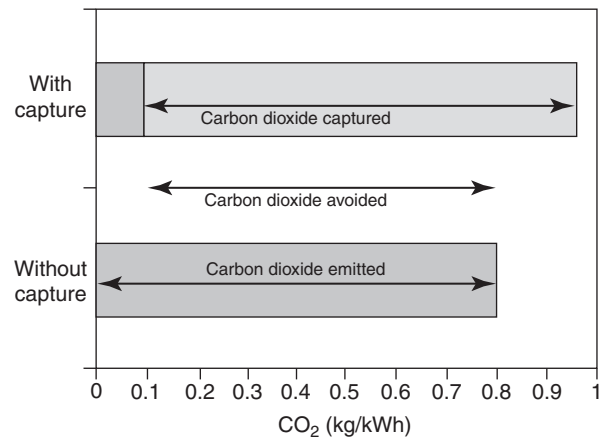


Figure 4

Graphical representation of the properties carbon dioxide emitted, carbon dioxide generated, and carbon dioxide avoided (example given for a coal-fired power plant).

#### 3.2 The Concept of the Production Chain

Eight chain elements can be distinguished in the production chain of an energy conversion system with carbon dioxide capture and storage. This includes the four steps within the definition of the CCS system and three additional steps which are not directly belonging to the CCS activity but might be influenced by the application of the technology.

The eight chain elements and their mutual dependence are displayed in Figure 5. The production chain includes:

- *Extraction and production of the fossil energy carrier.* This means the extraction of coal, natural gas or oil.
- *Transport of the fossil energy carrier.* This means the transport of coal, natural gas or oil.
- *Production of two products: the energy carrier (e.g. hydrogen or electricity) and the CO<sub>2</sub>.* In a few concepts carbon instead of carbon dioxide is produced. A variety of production technologies can be used to produce these two products simultaneously. For instance:
  - producing electricity with a coal-fired power plant and scrubbing the CO<sub>2</sub> from the flue gases;
  - firing natural gas with pure oxygen in a gas turbine producing electricity and a pure CO<sub>2</sub> stream or reforming natural gas, and scrubbing the flue gas from a electricity or hydrogen production unit.
- *Compression of the CO<sub>2</sub>.* In practice in all cases carbon dioxide needs to be transported and is required at high pressure. Ship transport requires liquefaction. The CO<sub>2</sub> is



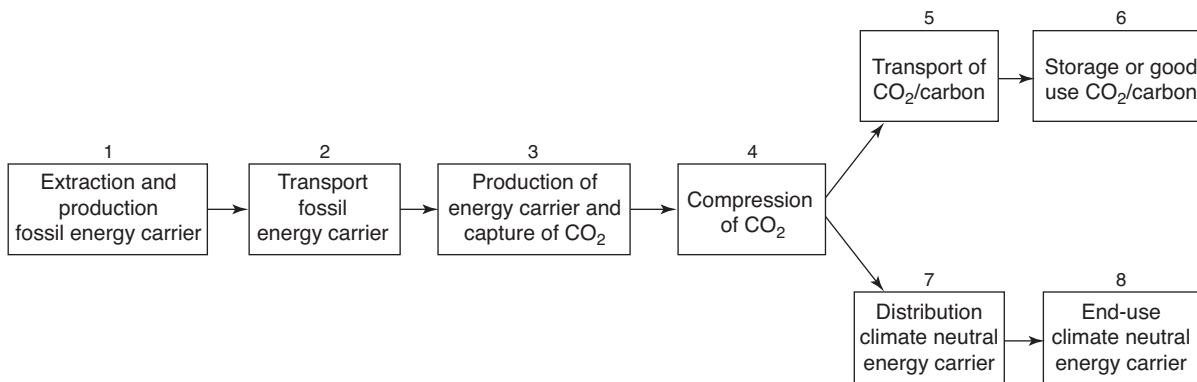


Figure 5

Chain elements in a CCS-system chain.

only at moderate pressure, *e.g.* 0.6 MPa (although it has to be compressed as part of the liquefaction process).

- *Transport* and/or distribution of the CO<sub>2</sub> or carbon.
- *Storage of the CO<sub>2</sub> or carbon.* In this step the CO<sub>2</sub> is stored. Examples are the use of CO<sub>2</sub> to extract methane from coal layers not economically accessible for coal mining through Enhanced Coal Bed Methane (ECBM), storage of CO<sub>2</sub> in aquifers and empty gas fields.
- *Transport and distribution of the produced energy carrier.*
- *End-use of the produced energy carrier.* This means the use of the energy carrier by the end-user.

### 3.3 Electricity Production Technologies

In this chapter we evaluate a number of electricity production technologies without and with carbon dioxide capture

regarding their emission and cost performance. Information on emission and costs presented in this chapter is obtained from Audus (2001), Bolland *et al.* (1992, 2001), Chiesa *et al.* (1999), Clemens and Wit (2001), Condorelli *et al.* (1991), Dave *et al.* (2001), Foster and Wheeler (2000), Hendriks (1994), Hendriks *et al.* (2002), Hendriks *et al.* (2003), Mariz (1995, 1999), Parsons (1996), Pruschek and Gottlicher (1996), Simbeck (1999), and Stork (2000).

The production technologies are either based on coal or on natural gas. The evaluation is based on the total electricity production chain, thus including the extraction and transportation of fossil fuels, the capture of the carbon dioxide from the energy conversion processes, and the compression, transport and storage of the captured carbon dioxide. Table 2 shows the list of electricity production technologies that are evaluated. In the table also the abbreviations are given which will be used throughout the

TABLE 2

List of electricity production technologies  
that are evaluated in this study on emission and cost performance

Production technology	Abbreviation
Natural gas-fired combined cycle	NGCC-none
....including postcombustion CO <sub>2</sub> capture technology	NGCC-postcomb
....including precombustion CO <sub>2</sub> capture technology	NGCC-precomb
Natural gas-fired conventional (boiler) power plant	NG conv-none
....including postcombustion CO <sub>2</sub> capture technology	NG conv-postcomb
Coal-fired conventional (boiler) power plant	Coal conv-none
....including postcombustion CO <sub>2</sub> capture technology	Coal conv-postcomb
Integrated coal gasifier combined cycle	IGCC-none
....including precombustion CO <sub>2</sub> capture technology	IGCC-precomb

text. Table 3 presents the (financial) conditions under which the electricity production chain is evaluated.

TABLE 3

Standardised electricity production chain conditions

Capture rate	90%
Outlet pressure compressor	12 MPa
Compression energy	416 kJ/kg
Transport distance to CO <sub>2</sub> storage	100 km
Depreciation factor	11% (discount rate 10%, lifetime 25 y)
Storage location	Depleted natural gas field
Coal price	1.5 €/GJ
Natural gas price	3.0 €/GJ

### 3.4 Emission of Greenhouse Gases in the Electricity Production Chain

For the electricity production technologies shown in Table 2, the total emissions and emission per chain element are determined. The results of the calculation are shown in Figure 6. It can be seen that the actual energy conversion step represents the largest contributor to the emission of the total electricity production chain. When coal is used, also

substantial amounts of greenhouse emissions (methane) occur during the extraction of the fuel. The indirect emissions from the power consumed during the compression of the captured carbon dioxide also contribute to the total emissions.

### 3.5 Cost of Electricity and Cost of Avoidance

The production costs for the energy carrier can be split into three parts:

- investments: once-only costs for the production facility, the CO<sub>2</sub> storage facility and the infrastructure;
- operation and maintenance costs (O&M);
- fuel costs.

By choosing the appropriate technical lifetime and discount rate the costs for the production of one unit electricity is determined by:

$$cost = \frac{(annuity\ factor \times investments) + O\&M + fuel\ cost}{delivered\ energy} \left[ \frac{euro}{GJ} \text{ or } \frac{euro}{kWh} \right]$$

NB: The discount rate and the depreciation period determine annuity factor.

The investments are depreciated over the lifetime of the investments. It is assumed that installations will be depreciated in 25 years at a discount rate of 10%.

The emission reduction costs may also be expressed in avoidance costs, *i.e.* the costs to avoid the emission of 1 t

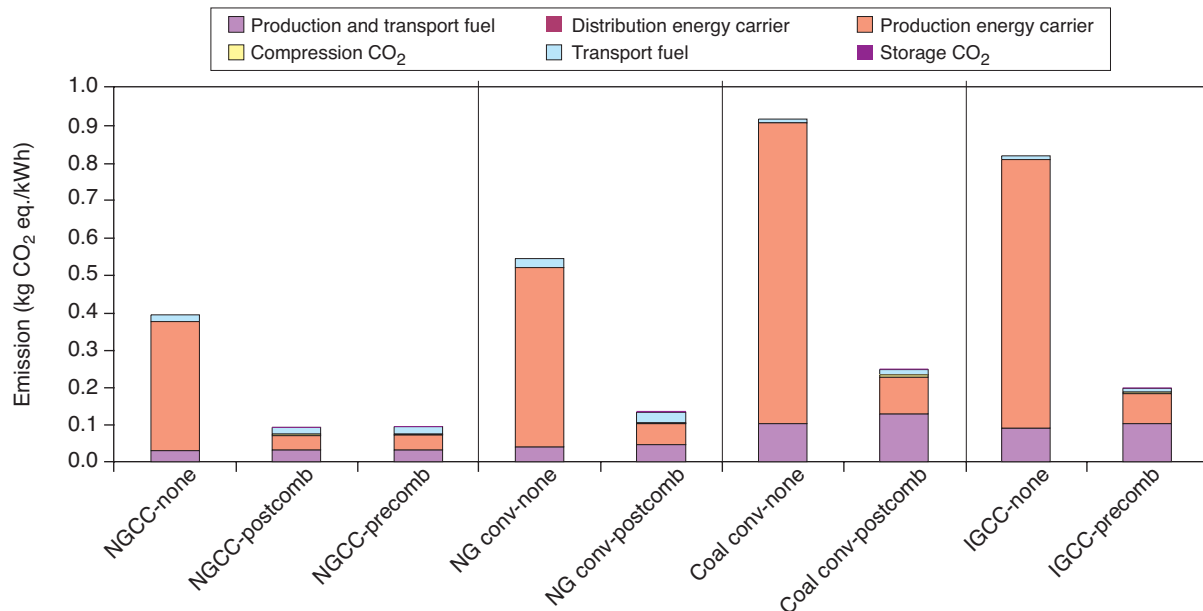


Figure 6

Emission breakdown of greenhouse gases for various electricity production routes. The emissions are given in CO<sub>2</sub>-equivalent using 100-year GWP. Assumed is that the power requirements for compression is obtained from the power plant with capture facilities.



CO<sub>2</sub>-eq. The costs of CO<sub>2</sub> avoidance (relative to a reference plant with no CO<sub>2</sub> capture) is the economic parameter most widely presented. The avoidance costs are calculated as:

$$\text{cost CO}_2 \text{ avoided} = \frac{\text{cost}_{\text{CCS}} - \text{cost}_{\text{reference}}}{\text{emission factor}_{\text{reference}} - \text{emission factor}_{\text{CCS}}} \left[ \frac{\text{euro}}{\text{tCO}_2} \right]$$

Figure 7 shows the electricity production costs for the technologies listed in Table 2. The production costs for natural gas-based technologies are dominated by the fuel price, whereas the costs for coal-based technologies are

dominated by the investment costs for the power production facilities. The cost increase for technologies with carbon dioxide capture is mainly subject to the costs associated with the capture of carbon dioxide. Costs for transport, compression and storage of the captured carbon dioxide are less relevant. If carbon dioxide capture and storage is applied to electricity production the costs increase by 0.015 to 0.030 euro/kWh.

Figure 8 depicts the avoidance costs for the technologies listed in Table 2. The costs are relative to the same electricity production technology without a capture facility (light bars)

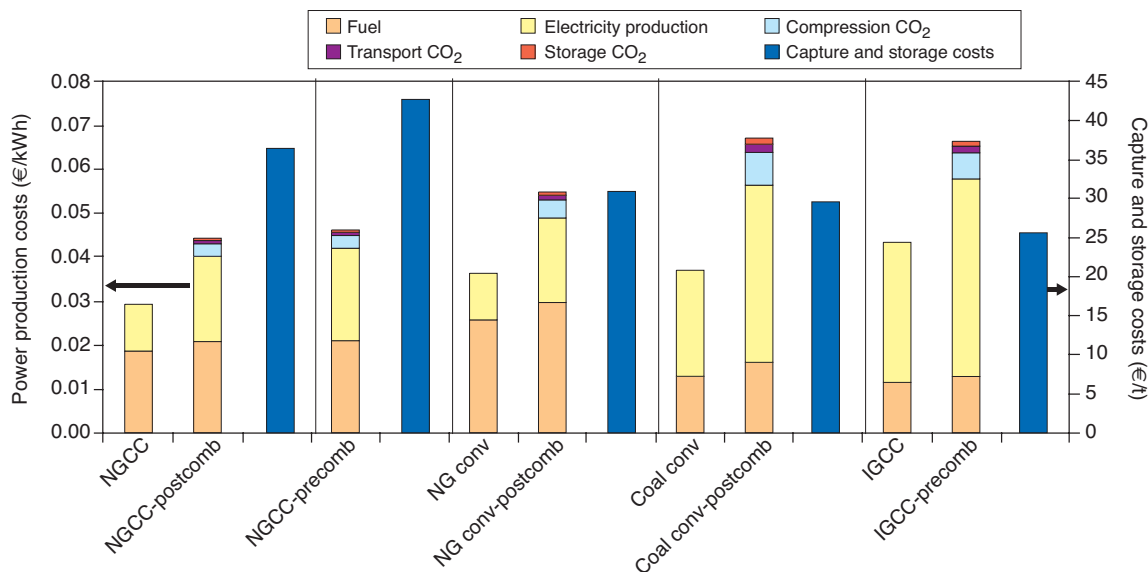


Figure 7

Electricity production costs for various electricity production technologies.

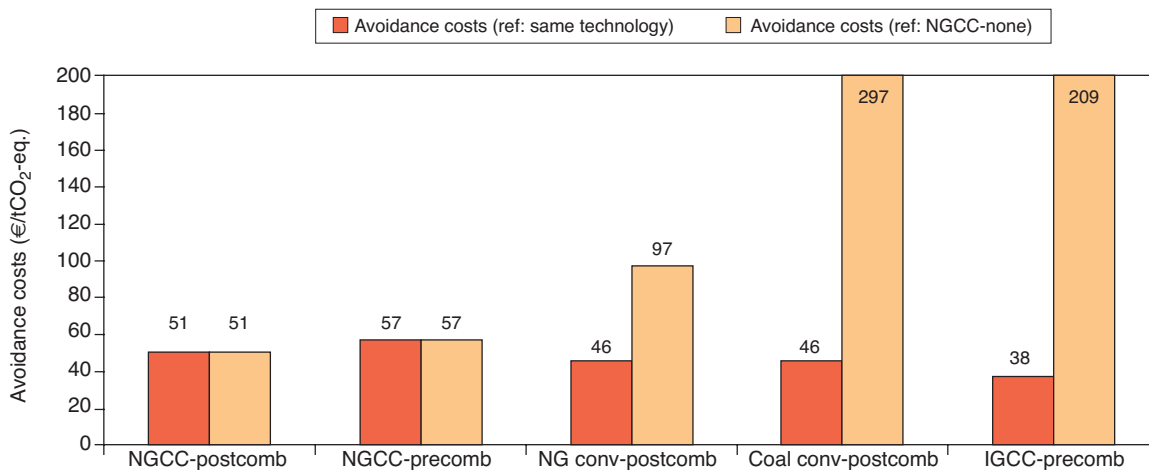


Figure 8

The greenhouse gas emission reduction costs for the various electricity production technologies. The references are the same electricity production technology (dark bar) and the NGCC-none (light bar).

and relative to an NGCC-none (dark bars). The costs range from about 40 to 60 €/t CO<sub>2</sub>-eq. avoided when the same technology (but without capture of carbon dioxide) is the reference. In the figure it can be seen that the avoidance costs for coal-fired power plants is less than for the natural gas-based systems. However, the avoidance costs for coal-based systems increase substantially (to 200 €/t CO<sub>2</sub>-eq. avoided or more) when the NGCC technology is chosen as the reference technology.

## ACKNOWLEDGEMENTS

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