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TECHNICAL GROUP

**DISCUSSION PAPER BY TASK FORCE TO
IDENTIFY GAPS IN CO₂ CAPTURE AND TRANSPORT**

Note by the Secretariat

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Background

At the meeting of the Technical Group in Melbourne, Australia, on 15 September 2004, a Task Force was created to identify gaps in CO₂ capture and transport. This Task Force consists of the European Commission (lead), China, France, Germany, Italy and Norway. It was instructed to produce a Discussion Paper, which was first presented at the meeting of the Technical Group in Oviedo, Spain, on 30 April 2005, and again, in a finalized version, at the meeting of the Technical Group in Berlin, Germany, on 27 September 2005. At the Berlin meeting, the Task Force was instructed to update its Discussion Paper. This updated paper is a result of the Task Force's activities.

Actions Requested

The Technical Group is requested to consider the Discussion Paper presented by the Task Force for Identifying Gaps in CO₂ Capture and Transport.

Conclusions

The Technical Group is invited to note in the Minutes of its 3 April 2006 meeting that:

“The Technical Group considered the Discussion Paper by the Task Force for Identifying Gaps in CO₂ Capture and Transport.”



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**Developed by a Task Force under the Technical Group
of the Carbon Sequestration Leadership Forum (CSLF)**

General

The basics of CO₂ capture and storage technology, its costs and areas of necessary R&D work are discussed in the CSLF Technology Roadmap. This Roadmap is to be updated regularly. The Gap Analysis was approved by the Technical Group and the present version of the Roadmap was adopted at the meeting of the Technical Group on the 13th of September 2004.

This Gap Analysis shall be seen as additional input to further update and improve this roadmap.

Appointment of the Task Force

It was decided at the September 2005 meeting of the Technical Group of the CSLF that an analysis of the gaps in the knowledge of CO₂ capture and transport should be made by a Task Force. Delegates to this Task Force were selected in January 2005. The Task Force initially consisted of:

- Lars Strömberg, Vattenfall AB Sweden, representing the European Commission (appointed Chairman in January 2005)
- Chen Wenying, Tsinghua University, representing China
- Claudio Zeppi, ENEL S.p.A., representing Italy
- Hubert Höwener, Forschungszentrum Jülich GmbH, representing Germany
- Lars Ingolf Eide, Norsk Hydro ASA, representing Norway
- Jean-Xavier Morin, Alstom, representing France

Germany later announced that Jürgen-Friederich Hake at the Forschungszentrum Jülich would also be a Task Force delegate.

Overview of the Paper

This analysis, according to the instructions of the CSLF Technical Group, handles only the Capture and the Transportation steps in the full chain of capture and storage of CO₂.

This paper describes gaps to be covered in future R&D work to establish a technology knowledge good enough to fulfill the goals set up by several countries, to avoid CO₂ emissions from large scale power plants and other sources, at a cost of 10 – 20 €/ton of CO₂. This is within a time frame up to 2020.

The paper begins with a brief description of the main technology candidates fulfilling the above-mentioned requirements. This means that R&D in processes, principles and technology that might be very important and promising but probably not will give results enabling large-scale applications within this timeframe are not discussed. In addition, only technical ways to capture CO₂ are considered, i.e. reforestation and other system-related ways are not included. Technical options shall also be interpreted as referring to energy production or in energy-related industrial processes. There are also numerous existing industrial processes not discussed here, such as where CO₂ can be captured in chemical, petrochemical, food, and in the paper and pulp industry,.

Capture Technology Overview

Carbon capture technology can be described several ways. Here, three categories of capture technology are considered:

A. Technologies possible to realize within 15 years, based on existing production technology and reasonably well established technologies:

1. Post-combustion Capture
2. Pre-combustion Capture
3. Oxyfuel Processes

Further, one must distinguish between the fuels used, such as different kinds of coal as opposed to natural gas.

B. Technologies tested in technical scale and possible to realize after the three first generation technologies, such as chemical looping.

C. New technologies not yet available that will be based on next-generation physical, chemical or thermodynamic processes, such as processes based on membrane technology, solid adsorbers, or new thermal power processes.

The three technologies in item A are described in the Technology Roadmap. All three technologies are also thoroughly described in the European Power Generators Association's state of the art report from 2004¹ which also describes the technologies in items B and C.. Another recent overview of the technologies can be found in the IEA report, "Prospects for CO₂ Capture and Storage from 2004"². The recently published

¹ CO₂ Capture and Storage. VGB Report on the State of the Art. VGB Power Tech, Essen, Germany 2004. <http://www.vgb.org>

² Prospects for CO₂ Capture and Storage. OECD/IEA 2004. IEA Publications, Paris, France. ISBN 92-64-108-831; 2004

final draft of “IPCC Special Report on Carbon Dioxide Capture and Storage” report also describes the technologies extensively. (A final draft was available per July 25th 2005)

A.1 Post-combustion Capture

Post-combustion capture, or capturing CO₂ from flue gases is a well-established technology that exists today. It can be delivered from commercial vendors but needs scaled-up engineering and optimization to be able to be applied to a 500 MW power plant. Post-combustion capture separates CO₂ from flue gas by a liquid absorber in a conventional absorption column at ambient pressure. Regeneration of the absorber is done at a relatively low temperature, where the CO₂ separates from the absorber in another column. The separated CO₂ is then cleaned and processed further, to be compressed into a liquid or supercritical state. The amount of compression required depends on how the CO₂ will be transported. The criteria for the process are that the flue gas must be cleaned down to a very low level of trace contaminants, such as particulates and sulfur. Furthermore, the regeneration step uses energy taken from the power process.

The cost for the process is related to the extra investment in equipment and the energy use for the desorption and further compression. For coal, the process requirements for cleaning of flue gases before absorption are stringent, which increases investments. For gas combustion, the CO₂ concentration is low, which increases requirements for the absorption tower.

A.2 Pre-combustion Capture

Pre-combustion capture can be adopted both for gas and for coal or any other feedstock that can be converted to syngas (CO and H₂). For coal and other solid fuels, a gasifier is needed to produce a syngas. For natural gas, syngas is usually made by a catalytic reforming step. After that, the processes are similar in principle, although syngas clean-up is a necessary first step after a coal gasifier, as there are impurities in coal that are not found in natural gas. By a water shift reaction, the CO contained in the syngas is converted into additional H₂ plus CO₂. This gas is then separated in an absorption process, with similar principles as for the post-combustion capture. The product gas before combustion has higher CO₂ concentrations and higher CO₂ pressure, and stripping of CO₂ from the gas can partly be done by pressure reductions; these differences simplify the separation. In principle, the ensuing power process is a combined cycle or an advanced gas turbine process. The product stream after separation of CO₂ is a hydrogen-rich gas which is burned in a gas turbine, optimized for this fuel. There currently exist turbines capable of burning hydrogen, although they are not optimized for this. The development of an optimized gas turbine for hydrogen combustion is considered to be a major development task

Most of the process equipment is well established in industry, e.g. in ammonia plants and refineries. The separation technology is not based on liquid chemical absorbers, but on a physical adsorption mechanism. With natural gas as a feedstock, this technology can be considered commercial. However, when using coal, a gasifier system is needed. The

chemical industry has been employing gasifiers for many years that run on many different solid and liquid feedstocks. Several large-scale gasifiers with a combined cycle power generation process have also been built, but without carbon capture. None of these gasifiers have yet proven to be commercially competitive. Thus, present coal gasification power plant technology is not considered competitive by the power industry, and cannot compete with other large-scale modern coal-fired technologies, such as ultra supercritical pulverized coal or fluidized bed units.

The inherent ability to produce hydrogen as an intermediate product might give pre-combustion technologies a boost. Today's hydrogen market is restricted to the internal hydrogen consumption in the chemical and refinery industry and does not play any role as an energy carrier. However, much effort is being put into the development of hydrogen-based energy technology. The least costly option at present to produce hydrogen without CO₂ emissions is a natural gas or coal-based process with carbon capture and storage. Further, electricity can be combined with other products such as syngas for methanol or synthetic liquid fuel production. This might form a market-adjusted polygeneration technology, improving profitability when mid-merit types of plants are also needed.

In the case of gas, the cost for the pre-combustion technologies relates to the cost for equipment, but also to energy consumption for the CO₂ removal step, CO₂ compression and some losses in the reforming and other parts of the process. For coal, the cost is also related to the additional investment required for the gasifier, additional energy losses in the gasification to syngas steps, and also for air separation to produce oxygen for the gasifier.

A.3 CO₂/O₂ Re-circulation or Oxyfuel Combustion Technology

The principle for oxyfuel combustion is to use pure oxygen or a mix of oxygen and carbon dioxide for combustion instead of air. The flue gases will then mainly consist of only CO₂ and H₂O plus impurities related to the fuel. If the flue gas is cleaned of particulates, sulfur, and other undesirable substances, and the water vapor is condensed, the remainder is relatively pure CO₂. No further separation is then needed, except for bleeding off any non-condensable gases. To keep temperature control in the flame, CO₂ is recycled. In the case of coal-fired power facilities, the generation process is a conventional steam cycle. Thus, a first-generation boiler will be designed in a similar fashion to a conventional boiler, but instead of air, CO₂ and O₂ will be used for combustion in a proportion giving similar properties of the flame as a flame with air i.e., 27% oxygen with the remainder CO₂. The boiler can utilize modern standards with supercritical data and a conventional steam turbine process.

This process does not need any energy to recover any absorbent, but does need energy for air separation. The amount of oxygen needed is about seven times higher than what is required for a gasifier. In addition, energy is needed for CO₂ compression, just as in the processes described in items A.1 and A.2 above.

All equipment for this process is commercially available, except that the boiler must be optimized for CO₂/O₂ combustion instead of air. Also, the desulfurization equipment must be adjusted since the gas flows are much smaller and the partial pressure of SO₂ and CO₂ are higher. As in the cases above, several of the components are not available in the sizes needed for a very large power plant, and existing equipment is not optimized for this use.

For coal, the combustion process can also be a fluidized bed or any other type of boiler. For circulating fluidized-beds (CFB), the technology might become more attractive as the bed material can be used for cooling, thus reducing the need for CO₂ re-circulation.

The oxyfuel process can also be adapted to gas firing. However, in this case a new gas turbine process design is needed. As for coal, the air separation is energy-intensive. The cost for the coal-fired oxyfuel process depends on the cost for the CO₂ cleaning equipment and air separation, the energy used for air separation, and for CO₂ compression as described above.

B. Technologies Tested On a Technical Scale

Chemical Looping

Another promising alternative, which might be able to become commercial within the timeframe considered here, is Chemical Looping Combustion (CLC), a special variant of oxyfuel, in which the flue gas is CO₂ and H₂O, plus impurities. The principle is that a solid-state oxygen carrier brings the oxygen for combustion to the combustion zone. This can be a metal oxide or a similarly designed material. The oxygen is attached to the solid in an air blown reactor where the material is oxidized and the metal oxide is subsequently reduced in the combustion reactor.

This process has recently been demonstrated as working well on a laboratory scale, burning natural gas. Due to its impurities, coal cannot be similarly burned as gas because the oxygen carrier becomes mixed with unburned char, degraded by trace elements and difficult to separate from the ash.

The solution is either to use a cheap carrier such as iron ore, which is disposable after short use, or find another way of gasifying the coal that does not produce gas stream impurities. No such process has been demonstrated even on a laboratory scale.

The process is mechanically very similar to a conventional fluidized-bed boiler, although with two reactors instead of one. The power process can be a conventional steam turbine process. This implies that the cost for equipment will be higher than for a conventional fluidized-bed boiler, but there is no longer a cost for energy to separate oxygen from air. However, costs for the oxygen carrier, for CO₂ clean up and for energy for compression must be added.

C. New Technologies

“New technologies”, as used in this paper, means “not based on conventional power generation processes” as described above. The aim of these new technologies is to make gas separation easier, cheaper and more efficient. Numerous variants are possible.

New Gas Separation Technologies

Initially, two gas separation principles can be distinguished. First, for membrane technologies, there exists a family of materials which can be made in the form of a membrane capable of letting some molecules through while others are hindered. Thus, O₂, H₂ and CO₂ separation membranes have been designed. Most of these operate at elevated temperatures, typically about 1,000°C. The driving force is the differences in partial pressure, which can be obtained either by adjusting the concentration of the gas and/or total pressure. Most technologies also need a flushing gas stream to remove the separated molecules from the surface of the membrane. One main challenge facing these technologies is integration with a technically feasible combustion system. However, there exist rather large membranes which are being operated in research laboratories that have the specified requirements established both for O₂ and CO₂ separation. There is ongoing R&D work for hydrogen membranes.

The second principle is to adsorb a gas on a specific material, and cycle this material in alternating surroundings. Therefore, the gas is separated from one stream to another. These technologies also require high temperatures and differential partial pressures, as the membranes do, as well as a flushing stream. Again, the principle works in the laboratory, but no complete power process close to realization has yet been demonstrated.

In addition, numerous new thermodynamic processes have been promoted. They all have in common a need for either a breakthrough in membrane or separation technology. All proposed processes are at the study level and cannot be realized before the others mentioned above. Thus, they are not further described here, and cannot be evaluated at the same level of certainty as the ones above.

The driving motivation for all attempts with new processes is to reduce energy consumption for CO₂ separation, or reduce equipment and operating costs. They all claim better properties in some of these aspects, but most give little or no information on the cost of capture.

Transport of CO₂

Transport of CO₂ is a well-known technology. It is utilized extensively in industry, and also for enhanced oil recovery (EOR) purposes. This means that technologies exist for all types of transports, for small or large volumes, for long and short distances, onshore and offshore. These include:

- Truck transport with standard containers or tanks
- Railroad transport, also with tanks or containers

- Ships (1,000 – 1,500 ton capacity at present; Statoil has performed a study for ships of about 20,000 ton capacity)
- Pipelines

The transport means are established for different purposes, i.e. for the food industry. The requirement there is different than for a power plant, where CO₂ must be disposed as inexpensively as possible. This also indicates a need for adaptation to new requirements. Also, the operational properties of the transport system place requirements on the properties of the CO₂ to be transported. One example is that it is more favorable if the CO₂ is in supercritical form for pipeline transport. Pipelines are the most favorable alternative for large, continuous volumes and long distances. On a ship, also suitable for large volumes, CO₂ should be stored as close to its triple point as possible; the larger the vessel, the lower the pressure and temperature. Truck or tank rail transport can only be adapted to small volumes and short distances. Neither of the latter two are probable for any power plant situation.

What does not exist, and will not, until a market is formed, are larger integrated systems with trunk pipelines, distributed pipelines, ships and trucks forming a system serving several emitters of CO₂ and supplying a system of storage. Several studies have established a cost level for each alternative. These studies have also clearly shown that the system cost per transported ton is much lower for an integrated system than for a line from source to storage.

The Cost Structure

The driving force for all development is to reduce cost. In the process from capture to storage, capture represents the highest costs. Transport cost, as discussed below, depends very much on distance but also on volume, since large volumes allow the use of less expensive large-scale solutions. Again, the storage cost depends on the storage structure, location and depth. However, it is thought that the capture accounts for some two thirds of the total cost.

The introduction of carbon capture and storage technologies depend entirely on what extra cost is incurred in comparison to other ways of reducing CO₂ emissions. In Europe, a trading system for CO₂ emission rights has been introduced. Beginning in February 2005, the market cost was about 7 €/ton CO₂. In July 2005 it was about 22 €/ton. If new technologies can meet future CO₂ costs, they will be introduced. If not, other cheaper ways of reducing emissions will be used.

It must be stressed that the technology choice for new investments is governed by the energy generation costs for the technology in question, including any CO₂ penalty. This implies that a technology with lower generation costs will be preferred over a more expensive technology, even if the calculated CO₂ capture cost is higher. The secondary parameter for the choice is the cost for capture/avoidance.

The cost for capture is calculated in several different ways. The most important issue is to what the comparison is made; a plant of the same kind without carbon capture, or to some other plant. It is common that the calculations shall include:

- Incremental investment costs
- Incremental operational and maintenance costs (O&M)
- Incremental fuel costs
- Energy penalties, i.e. the reduced output or the energy imported to maintain output shall be accounted for

This results in an increased energy production cost, when comparing the same type of plant without and with carbon capture and storage. Dividing the energy production cost by the reduction of CO₂ emitted to the atmosphere yields the unit cost of CO₂ avoided to the atmosphere (not only captured) expressed in €/ton of CO₂. To make a comparison between the different results possible, the calculation must take into account energy penalties, fuel prices, cost estimation basis, expected lifetime, interest rates, load factor, and if taxes etc. are included.

This implies that reducing the cost does not only include reduction of the capital cost, but also energy consumption and unavailability. Present post-combustion and pre-combustion technologies have energy penalties in the range of 15-25% of the output, depending on fuel. This means that the capture cost will be sensitive to reductions in energy loss, but also sensitive to fuel price. With present European fuel prices, it is easier to achieve lower costs for coal than for gas per captured ton of CO₂. In fact, the capture cost for coal is about half that of gas. At the same time, it must be remembered that the present commercial total electricity generation cost for a gas-fired combined cycle power plant is about equal to a modern coal-fired supercritical plant in Europe.

Primary Development Goals

The primary objective is to achieve the avoidance cost goals adopted by the United States (10 USD/ton of CO₂) and by the European Union (20 €/ton of CO₂). Other countries may have similar goals. In addition, a realistic timeframe must be adopted. Most countries have expressed a wish to implement CO₂ capture technology at a large-scale in 2020. Only a few candidate technologies are possible for achieving this, primarily those belonging to the first category, but perhaps also Chemical Looping.

When examining these technologies, no clear winner can presently be distinguished. The calculated costs depend on several factors differing from country to country, but also depend on whether it is an existing process or a future not-yet-realized process, and if the calculation is made by someone with a certain consideration or interest in mind. Therefore widely differing cost estimates exist. Thus post-combustion technology might be the most expensive today, but its costs will likely decrease as technologies mature. Pre-combustion technology is attractive and preferred by many, while others have considered oxyfuel as the most cost effective technology. All technologies seem to have the potential for considerable cost reductions from present levels. This relates to process,

component and material development resulting in investment reductions, but also to the reduction of energy demand for the capture process. The gaps to be covered are in fact those resulting in reaching this potential.

For coal, the target of 20 €/per ton avoidance costs can be achieved from existing knowledge of at least the two processes, oxyfuel and precombustion technology. Thus, the gap then seems to be validation, at a large scale, showing that the studies performed actually hold true. Unfortunately, this is the most costly part in the development chain.

These developments will be discussed below, rather than focusing on new processes that have not reached the technical test scale.

Identifying the Gaps

Post-combustion Technology R&D Needs

One of the advantages of using the post-combustion capture approach with amine absorption is that it can be used for retrofitting existing plants to include CO₂ capture capabilities. The main challenge in parallel with reducing investments is to reduce the heat requirements for regeneration of the solvent.

The general areas to be covered include:

- Process optimization for large-scale plants
- New and less energy-intensive solvents
- Demonstration of long-term operational availability and reliability on a full-scale power plant using relevant fuels

More specifically, the needs are:

- Reduce steam consumption and temperature requirements for regeneration of absorbents
- Reduce power consumption by development of amines or other solvents with higher CO₂ loading that could be applied at a higher concentration to reduce pump requirements and equipment size
- Reduce degradation of sorbents
- Develop other types of absorbents

Pre-combustion Capture Technology R&D Needs

The overall feasibility of the pre-combustion process depends on the total performance of the combination gasifier or reformer, CO₂ capture and the power process. This combination still has to show satisfactory performance, both in terms of efficiency and availability. In existing integrated gasification combined cycle (IGCC) power plants, the coal gasification process has dictated availability. However, the capture of CO₂, which in principle is easier in a gasification concept, will perhaps make IGCC more competitive.

It is anticipated that the present gasification concept, which is optimised to give as high a generating efficiency as possible for the produced gas, can evolve into a concept where syngas is the preferred product. This requires a somewhat different gasification train where the technical solutions are also well established.

The main R&D needs are:

- To integrate all process steps into a total concept and to demonstrate that concept
- To build and run, and later demonstrate optimised gas turbines for hydrogen

More specifically:

- Improved performance, availability and reliability of the gasifier island.
- Integration and optimization of CO₂ capture equipment
- Optimization and integration of the water shift gas reaction, and the catalysts
- Optimization and integration of the air separation unit
- Improved solvents for physical absorption
- Novel methods for air separation (e.g., high temperature ceramic membranes)
- Verify and test novel methods for CO₂/H₂ separation in membrane (ceramic and polymer) reformers and water gas shift
- Development of an optimized hydrogen fuelled gas turbine

In addition:

- Development of “polygeneration” technologies (i.e., hydrogen, methanol and synthetic fuels, in combination with electricity)

CO₂/O₂ Re-circulation or Oxyfuel Combustion Technology R&D Needs

The technology for coal is entirely based on conventional processes. What differs is the combustion process, where a CO₂/O₂ mixture is present instead of air. First generation boilers will be very similar to those using air, while considerable development of new generations of boilers and equipment is foreseen. Furthermore, the de-sulfurization step in flue-gas cleaning is to be validated. The obvious need is a stepwise development of large plant designs, i.e. pilot plants with all equipment integrated, and demonstration plants with the necessary gradual scale-up for the components.

The main area for improvement is the air separation process. Improving the cost and power requirements of present cryogenic air separation units is limited. Development of new large-scale oxygen production concepts is thus essential, e.g. based on ion transport membranes. Its applicability to gas turbine-based processes has been investigated. None of these technologies seems at present successfully applicable to coal combustion due to their dependence on high pressure and temperature

The logical gaps and consequent R&D needs are:

- To better integrate the processes, thereby reducing overall energy consumption and investment costs
- To establish a series of integrated pilot plants and demonstration plants (gas and coal)
- To facilitate inclusion of developed boiler designs, such as CFB and conventional pulverized coal boilers with reduced or no external recirculation

More specifically:

- The boiler has to be developed and optimised for this concept
- Development of CFB technology for this concept
- Combustion chemistry and kinetics to provide design and scale-up data
- Verification of developed flue gas cleaning equipment
- Material selection for new flue gas environment
- The long term operational properties at large scale, such as slagging, fouling and corrosion
- Verification and pilot testing of integrated oxygen transporting membranes with gas turbines
- Finding new integration possibilities within power plants, especially if a new type of ASU is developed

Chemical Looping Technology R&D Needs

Chemical looping has been shown to be functional in a laboratory test rig for natural gas. There exist some reasonable ways to burn coal in a similar process, and these at present have been tested at the laboratory scale. However, if it can be done the economic prospects are very good, since the costs for extra energy are reduced to nil.

This means that the concept may be valid, but it is still at a level of knowledge where even if the development process is going well, there is still a long way to go. A similar situation for fluidized-bed combustion, which today is the leading technology for industrial scale solid fuel boilers, occurred in 1975. It took 20 years to make fluidized-bed combustion fully commercial.

Chemical looping technology depends strongly on finding a suitable oxygen carrier. The requirements are long lifetime and low cost, while maintaining the ability to carry relatively large amounts of oxygen. For coal applications also an ability to handle this specific environment is necessary

The obvious R&D needs are:

- Develop oxygen carriers for gas and coal processes
- Develop a process for coal combustion
- Design and develop a suitable thermal process

Transport technology R&D needs

Transport of CO₂ is a well-known technology. It is utilized extensively in industry. This means that technologies exist for all types of transports, for small or large volumes, for long and short distances, on shore and off shore. However, the needs for an integrated transport system for storage of CO₂ differ from the requirements of present solutions partly in size, but also in gas quality, distances and need for developed infrastructure.

This means that no actual research is needed to arrive at a solution. Instead, what is needed is a number of actual cases and a good way of initiating and expanding a larger system. Also needed is a systematic adjustment from both sides between the storage requirements, the producer's requirements and the transport system's requirements, all with the purpose of reducing total cost. The big step is to establish the first large transport lines in a system, and from there to establish a large integrated system.

Summary and Conclusions

Processes and technologies in principle already exist today, with the potential to capture CO₂ from coal combustion at a cost below 20 €/ton CO₂ under certain circumstances. Oxyfuel and IGCC technologies are the most promising. At present, post-combustion methods do not seem to reach the established goals for retrofitting an existing power plant, but might be able to achieve the goals for a new plant. All technologies have a large development and optimization potential.

For gas, the situation is a bit different. The cost for capture is usually higher. This is mainly due to the lower CO₂ concentration in the flue gas and the higher price of gas, whereby the energy reduction gives a higher cost burden. At the moment, the avoidance cost of 20 €/ton of CO₂ is just below the economic prospects of the most promising known technologies. However, the focus should not be on the CO₂ avoidance cost alone. The cost of electricity is the major factor governing technology choice, as this is what the customer sees. In that respect, the situation for gas may be better than for coal.

Much work has been done to find entirely new improved technologies for CO₂ capture. These often include membrane technologies or solid absorbers. Many attempts with new power processes have also been made, but these are all considered to be commercially available after 2020.

In general, the three technologies closest to commercial adoption all have in common the fact that with regards to R&D, relatively seen, less research is needed, but a large amount of development is required. In the foreseeable future, they will probably all see their first large-scale plants. Common needs for all three are:

- A program for scale-up of these technologies, from pilot plants to several demonstration plants
- Gradually better integration, optimization and improved process layout

- Gradual introduction of improved components, methods and materials

Unfortunately, this is by far the most costly part of the research and development chain.