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TECHNICAL GROUP

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Discussion Paper from Task Force for Identifying Gaps in CO_2 Capture and Transport (Final Version)

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Note by the Secretariat

Background

At the meeting of the Technical Group in Melbourne, Australia on September 15, 2004, a Task Force was created to identify gaps in CO_2 capture and transport. This Task Force consists of the European Commission (lead), China, Italy, Germany, and Norway. It was instructed to produce a Discussion Paper that would then undergo review and be presented at a Technical Group meeting. A first version of this discussion paper was presented at the meeting of the Technical Group in Oviedo, Spain, on April 30, 2005 and a revised version was presented at the meeting of the Technical Group in Berlin, Germany, on September 28, 2005. This final version of the Discussion Paper represents the conclusion of the Task Force's activities.

Action Requested

The Technical Group is requested to review and consider the final version of the Discussion Paper from the Task Force for Identifying Gaps in CO_2 Capture and Transport.

Conclusions

The Technical Group is invited to note in the Minutes of its next meeting that:

"The Technical Group reviewed and considered the Discussion Paper presented by the Task Force for Identifying Gaps in CO_2 Capture and Transport."

Discussion Paper:
Gaps Existing in Knowledge of CO_2 Capture and Transport
(Final Version)

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

General

The CO_2 capture and storage technology, its basics, costs and areas of knowledge improvements necessary are discussed in the CSLF Technology Roadmap. This Roadmap is to be updated regularly. The present version 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 meeting of the Technical Group of the CSLF that an analysis of the gaps in the knowledge of CO_2 capture and transport should be made by a Task Force. Delegates to this Task Force were selected in January 2005, and 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

Subsequently, Germany notified that Jürgen-Friederich Hake from Forschungszentrum Jülich was also a Task Force delegate. Also, in 2006, Volker Breme from Forschungszentrum Jülich replaced Hubert Höwener as one of Germany's Task Force delegates.

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 CO_2. The 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 CO_2 emissions from large scale power plants and other sources, at a cost of 10-20 € per ton of CO_2. 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 will not give results enabling large-scale applications within this timeframe is not discussed. In addition, only technical ways to capture CO_2 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 CO_2 can be captured in chemical, petrochemical, food, and in the paper and pulp industry.

Capture Technology Overview

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

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

    a. Postcombustion capture
    b. Precombustion capture
    c. Oxyfuel processes

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

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

3. 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 the first category are described in the CSLF Technology Roadmap. All three are also well described in the European Power Generators Association's state of the art report from 2004[1] which also describes the technologies in the second and third categories. Another recent overview can be found in the IEA report, "Prospects for CO_2 Capture and Storage from 2004[2]". The "IPCC Special Report on Carbon Dioxide Capture and Storage[3]" also describes the technologies extensively.

1-a) Postcombustion Capture

Postcombustion capture, or capturing CO_2 from flue gases, is an established technology that exists today. It can be delivered from commercial vendors but needs scaled-up engineering by a factor of about 10 and optimization to be able to be applied to a 500 MW power plant. Postcombustion capture separates CO_2 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

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[1] CO_2 Capture and Storage. VGB Report on the State of the Art. VGB Power Tech, Essen, Germany 2004. http://www.vgb.org

[2] Prospects for CO_2 Capture and Storage. OECD/IEA 2004. IEA Publications, Paris, France. ISBN 92-64-108-831; 2004

[3] Available at www.ipcc.ch

CO_2 separates from the absorber in another column. The separated CO_2 is then cleaned and processed further, to be compressed into a liquid or supercritical state. The amount of compression required depends on how the CO_2 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 CO_2 concentration is low, which increases requirements for the absorption tower.

1-b) Precombustion Capture

Precombustion capture can be adopted both for gas and for coal or any other feedstock that can be converted to syngas (i.e., CO and H_2). 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, though 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. Using a water shift reaction, the CO contained in the syngas is converted into additional H_2 plus CO_2. This gas is then separated in an absorption process, with similar principles as the postcombustion capture. The product gas before combustion has higher CO_2 concentrations and higher CO_2 pressure, and stripping of CO_2 from the sorbent can partly be done by pressure reductions; these differences simplify the separation. In principle, the following power process is a combined cycle or an advanced gas turbine process. The product stream after separation of CO_2 is a hydrogen-rich gas which is burned in a gas turbine that has been 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 is considered 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 as a power generation process have also been built. However, without CO_2 capture, this technology is approximately 10-20% more expensive than current technology. Nevertheless, studies suggest that precombustion technology may be the most favourable and technically appropriate for cases where CO2 capture is required[4].

The inherent ability to produce hydrogen as an intermediate product might give precombustion 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 CO_2 emissions is a natural gas or coal-based process with carbon capture and storage. Further, electricity can be combined with other products such as

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[4] for example, COORETEC Report, Research and Development Concept for Zero-Emission Fossil-Fuelled Power Plants, Federal Ministry of Economics and Labour, Germany

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.

The cost for the pre-combustion technologies relates to the cost for equipment, energy consumption for the CO_2 removal step, CO_2 compression and some energy losses other parts of the process, such as the water-gas shift.

1-c) CO_2/O_2 Recirculation 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 CO_2 and H_2O plus impurities related to the fuel. If the flue gas is cleaned of particulates, sulfur, and other undesirable substances, and the water vapour is condensed, the remainder is relatively pure CO_2. Further separation is then needed to remove non-condensable gases. To keep temperature control in the flame, CO_2 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, CO_2 and O_2 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 CO_2. The boiler must also be built air-tight to avoid nitrogen in-leakage. 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 CO_2 compression, just as in the two processes described in 1-a and 1-b above.

All equipment for this process is also commercially available, except that the boiler must be optimized for CO_2/O_2 combustion instead of air. Also the desulfurization equipment must be adjusted, since the gas flows are much smaller and the partial pressure of SO_2 and CO_2 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 bed (CFB), the technology might become more attractive as the bed material can be used for cooling, thus reducing the need for CO_2 recirculation.

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 CO_2 cleaning equipment and air separation, the energy used for air separation, and for CO_2 compression as described in 1-a and 1-b above.

2) Technologies Tested On a Technical Scale

Chemical Looping
Another promising alternative, which might be able to become almost commercial within the time frame considered here, is Chemical Looping Combustion (CLC), a special variant of oxyfuel, in

which the flue gas is CO_2 and H_2O, 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 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 in a laboratory scale, burning natural gas. Due to its impurities, coal cannot be similarly burned in as simple a way 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 more delicate 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 CO_2 clean up, and for energy for compression must be added.

3) 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 generally 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 exist 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, O_2, H_2 and CO_2 separation membranes have been designed. Most of these operate at elevated temperatures, typically about 1,000°C. The driving force is 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 laboratory surroundings that have these specified requirements established both for O_2 and CO_2 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 gas 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 described above.

The driving force for all attempts with new processes is to reduce energy consumption for CO_2 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 CO_2

Transport of CO_2 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 CO_2 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 CO_2 to be transported. One example is that it is more favourable if the CO_2 is in supercritical form for pipeline transport. Pipelines are the most favourable alternative for large, continuous volumes and long distances. On a ship, also suitable for large volumes, CO_2 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 CO_2 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 considered 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 CO_2 emissions. In Europe, a trading system for CO_2 emission rights has been introduced. Beginning in February 2005, the market cost was about 7 € per ton CO_2. In July 2005 it was about 22 € per ton. If new technologies can meet future CO_2 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 CO_2 penalty. This implies that a technology with lower generation costs will be preferred over a more expensive technology, even if the calculated CO_2 capture cost is higher. 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 CO_2 emitted to the atmosphere yields the unit cost of CO_2 avoided to the atmosphere (not only captured) expressed in € per ton of CO_2. To make comparison between 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 cost does not only include reduction of the capital cost, but also energy consumption and unavailability. Present postcombustion and precombustion 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 reduction 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 CO_2. 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% rise in cost of electricity) and by the European Union (20 € per ton of CO_2 avoided). Other countries may have similar goals. In addition, a realistic timeframe must be adopted. Most countries have expressed a wish to implement CO_2 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.

When examining these technologies, no clear winner can presently be distinguished. The calculated costs depend on several factors differing from location to location, assumptions about future not-yet-realized processes and technological change, feedstock characteristics, economic parameters used, etc. Therefore, widely differing cost estimates exist. Thus, postcombustion technology might be the most expensive today, but its costs will likely decrease as technologies advance. But it should be noted that the other technologies will advance and improve their economic situation as well. Precombustion 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 studies performed actually hold true. Unfortunately, this is the most costly part of the development chain.

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

Identifying the Gaps

Postcombustion Technology R&D Needs

One of the advantages of using the postcombustion capture approach with amine absorption is that it can be used for retrofitting existing plants to include CO_2 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 optimisation 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 CO_2 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

Precombustion Capture Technology R&D Needs

The overall feasibility of the precombustion process depends on the total performance of the combination gasifier or reformer, CO_2 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 CO_2, 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 optimisation of CO_2 capture equipment
- Optimization and integration of the water shift gas reaction, and the catalysts
- Optimisation and integration of the air separation unit
- Improved solvents for physical absorption
- Development of an optimized hydrogen-fuelled gas turbine

Long-term options:

- Novel methods for air separation (e.g., high temperature ceramic membranes)
- Verify and test novel methods for CO_2/ H_2 separation in membrane (ceramic and polymer) reformers and water gas shift

In addition:

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

A 70 MW (electricity) IGCC with 360 ton Methanol production and 180 MW (thermal) district heat is operating in Germany since 1995.

CO_2/O_2 Recirculation 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 CO_2/O_2 mixture is present instead of air. First generation boilers will be very similar to a process using air, while considerable development of new generations of boilers and equipment is foreseen. Further, the desulfurization 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 given 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
- Optimization and integration of the air separation unit
- 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 lab 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 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, an ability to handle this specific environment is also 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 CO_2 is a well-known technology. It is utilized extensively in industry. Thousands of kilometers of pipelines are in use today to transport pressurized CO_2. 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 CO_2 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 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

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, demonstration and optimisation is required. In the foreseeable future, they will probably all see their first large-scale plants. Common needs for all three in case of CO_2 capture and storage 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.