CSLF-T-2005-2
Draft

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Discussion Paper from Task Force for Identifying Gaps in CO_2 Capture and Transport

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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 full Technical Group meeting. This draft Discussion Paper is the result of the Task Force's activities.

Action Requested

The Technical Group is requested to review and consider the Discussion Paper presented by 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 meeting of April 30, 2005 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: Identifying Gaps in CO_2 Capture and Transport

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 necessary knowledge improvement 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

This Analysis, according to the instructions of the CSLS Technical Group, handles only the Capture and the Transportation steps in the full chain of capture and storage of CO_2.

Further, 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 read as referring to energy production or in energy-related industrial processes. There are numerous existing industrial processes not discussed here, where CO_2 can be captured in chemical, petrochemical, food, and in the paper and pulp industry, to mention a few.

It was decided at the September meeting of the Technical Group of the CSLF that the analysis should be made by a Task Force. Members of this this Task Force were selected in January 2005, and it consists 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

Later, Germany notified that Jürgen-Friederich Hake at the Forschungszentrum Jülich will also be a Task Force Member.

Capture Technology Overview

The technology can be described several ways. In this paper, three categories of capture technology are discussed.

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 coal on the one hand and gas on the other.

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 processes.

The three technologies in the first category are described in the Technology Roadmap, but are not correct concerning the oxyfuel technology. All three are also well described in the European Power Generators Association's state of the art report from 2004[1]. Here also the other two categories are well described. Another recent overview can be found in the IEA report, *Prospects for CO_2 Capture and Storage from 2004*[2].

Postcombustion Capture

Postcombustion capture is the most well established technology. In principle, this technology exists today. It can be obtained from commercial vendors but needs scaled-up engineering and optimization for 500 MW power plants. Postcombustion capture separates CO_2 from flue gas by a liquid absorber in a rather conventional absorption column at ambient pressure. Regeneration of the absorber is done at relatively low temperature, where the CO_2 separates from the absorber in another column. The criteria for the process are that the flue gas must be cleaned down to a very low level of particulates and sulfur.

The separated CO_2 is then cleaned and processed further, to be compressed to a liquid or supercritical state. The amount of compression required depends on how the CO_2 will be transported. 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.

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[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

Precombustion Capture

Precombustion capture can be adopted both for gas and for coal. For coal, a gasifier is needed to produce a syngas, i.e. CO and H_2. For natural gas, syngas is made by a thermal reforming step involving steam. After that, the processes are similar in principle, though syngas clean-up after a coal gasifier is a necessary first step, as there are impurities in coal that are not found in natural gas. The syngas is transformed into additional H_2 plus CO_2 by a water shift reaction. This gas is then separated in an absorption process, with similar principles as the postcombustion capture. Some differences are that the gas before combustion has higher CO_2 concentrations and higher CO_2 pressure, and that stripping of CO_2 from the gas can partly be done by pressure reductions. These differences simplify the separation. In principle, the power process is a combined cycle or an advanced gas turbine process. At least one vendor claims it can deliver a gas turbine, albeit not of the latest generation, that can operate on a hydrogen-rich gas. However, the development of a gas turbine for hydrogen is generally 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 gas as a fuel, this technology can be considered commercial. However, when using coal, the gasifier cannot yet be considered commercially available. Several large-scale gasifiers with a combined cycle as a power generation process have been built. None of them have proven to be commercially competitive. Thus, present coal gasification power plant technology cannot compete with other modern coal-fired technology, i.e. ultrasupercritical pulverized coal steam cycle.

The inherent ability to produce hydrogen as an intermediate product might give the precombustion technology a boost. No hydrogen market presently exists, but much effort is being put into the development of hydrogen-based energy technology. Since hydrogen is not a natural energy source, it has to be produced. Most likely, the least costly option at present is a coal-based process with carbon capture and storage. Further, electricity can easily be combined with other products, such as syngas for methanol or synthetic liquid fuel. This might form a market-adjusted polygeneration technology, improving profitability when variable load plants are also needed.

In the case of gas, the cost for the precombustion technologies relates to cost for equipment, but also to energy consumption for CO_2 stripping from the adsorber, CO_2 compression and some losses in the reforming and other parts of the process. For coal, the cost is also related to additional investment required for the gasifier, additional energy losses in the gasification to syngas steps, and also for oxygen separation from air for the gasifier.

CO_2/O_2 Recirculation or Oxyfuel Combustion Technology

The principle for oxyfuel combustion is to use oxygen for combustion instead of air. Flue gases then consist in principle 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 vapor is condensed, the remainder is pure CO_2. No separation is then needed. To keep temperature control in the flame, CO_2 might be recycled. In case of coal power, the generation process is a very conventional steam cycle. Thus, a first-generation boiler will be designed similar 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 the air flame i.e., 23% oxygen with the remainder CO_2. The boiler can utilize modern standards with supercritical data and a completely conventional steam turbine process.

This process does not need any energy to recover any sorbent, but does need energy for air separation. The amount of oxygen needed is about seven times higher than for a gasifier. In addition, energy is needed for CO_2 compression just as in the above processes.

All equipment for this process is also commercially available, except that the boiler must be changed slightly to be optimized for CO_2/O_2 combustion instead of air. Another part which also must be adjusted slightly, is the desulfurization equipment, since the gas flows are much smaller and the partial pressure of SO_2 and CO_2 are much higher (since there is no nitrogen ballast). As in the cases above, several of the components are not available in the sizes needed for a very large power plant.

Of course, for coal, the combustion process also can be a fluidized-bed or any other boiler type. 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 recirculation. Future generations are expected to be without external CO_2 recycling for flame temperature control, but will need internal recirculation as in metallurgical furnaces today.

The oxyfuel process can also be adapted to gas firing. However, in this case a new gas turbine design is needed, which could present significant development costs. 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 above.

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 combustion system, which is still to be demonstrated even in a laboratory. 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. Thereby, 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 a laboratory or anywhere else.

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 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 very little or no information on cost for capture.

Chemical Looping

A third alternative is Chemical Looping Combustion (CLC), a special variant of oxyfuel, in which the flue gas is CO_2 and H_2O, plus impurities. The idea is that a solid-state oxygen carrier brings the oxygen for combustion to the combustion zone. This can be a metal oxide or similar designed material. The oxygen is attached to the solid in a separate 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. However, the fuel in that case was 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 in laboratory research.

The simple process as adopted for gas is mechanically very similar to a conventional fluidized-bed boiler, although with two reactors instead of one. This also means that 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.

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 large-scale solutions. They are much less expensive. 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.

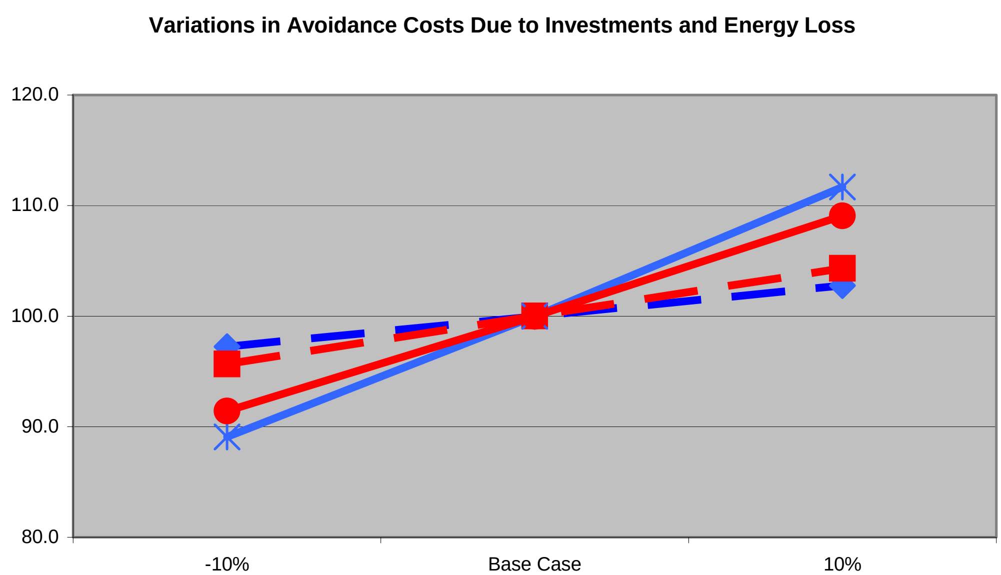
The introduction of carbon capture and storage technologies depends entirely on what extra cost is incurred in comparison to other ways of reducing CO_2 emissions. (In Europe, a trading system for CO_2 emission rights has been introduced. Beginning in February 2005, the market cost was about 7 EUR/ton CO_2. If new technologies can meet future costs, they will be introduced. If not, other cheaper ways of reducing emissions will be used.)

The cost for capture is often calculated in several different ways. It is accepted 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 (e.g. desorber and air separation) shall be accounted for

This results in an increased energy production cost. 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 EUR/ton of CO_2. To make comparison between various possible results, the calculation must give energy penalties, fuel prices, cost estimation basis, expected lifetime, interest rates, load factor, and if taxes etc. are included.

Avoidance costs are sensitive to these factors. The example below illustrates this for variations in capital costs and energy penalties. The production cost is defined as the sum of the capital cost, O&M and the fuel costs. All are calculated for the same operating time per year. In the figure, the capital and fuel costs have been varied +/-10 %.



The dotted lines are for the investments and the solid lines are for energy use. The red lines are for gas (almost double the fuel costs and half the specific investment costs), and the blue are for coal. As can be seen, the avoidance cost varies almost linearly with energy. Thus, if energy consumption is reduced by 10%, the total avoidance cost is also reduced by almost 10%.

This implies that the major goal is to reduce not only the investment cost, but also energy consumption. Present postcombustion and and precombustion technologies have energy penalties in the range of 15-25% of the output, depending on fuel. With these high-energy losses, the capture cost will be sensitive to fuel price. With present fuel prices, it is easier to get 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 USD/ton of CO_2) and by the European Union (20 EUR/ton of CO_2). 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 very large-scale before 2020. Only a few candidate technologies are possible for achieving this, primarily those belonging to the first category, but perhaps also the Chemical Looping.

When examining these technologies, no clear winner can presently be distinguished. Postcombustion technology is the most expensive today, but costs will likely decrease as technologies mature. Precombustion technology is attractive for gas, and possibly advantageous for coal, since it inherently produces hydrogen. At present, oxyfuel is the most cost effective technology for coal and is easily adapted to the power industry since the plants are similar to those operated today. All technologies seem to have potential for considerable cost reductions from present levels.

These developments will be discussed, rather than focusing on new processes that do not even exist in the laboratory. In general terms, the gaps to be covered are reducing energy consumption in the three primary technologies and reducing extra investment costs.

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

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 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 sorbents
- Reduce power consumption by development of amines 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 sorbents

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 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 availability of gasifier island and integration of CO_2 capture equipment
- Development of the catalysts for the water gas shift reaction

- Integration of the air separation unit (ASU)
- Improved solvents for physical absorption
- 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)

CO_2/O_2 Recirculation or Oxyfuel Combustion Technology R&D Needs

The technology for coal is based on conventional processes for coal combustion. What differs is the combustion process, where a CO_2/O_2 mixture is present instead of air (which contains nitrogen). First generation boilers will be very similar to a process using air, while considerable concept development of new generations of boilers and equipment are foreseen. Further, the desulfurization step in flue-gas cleaning is to be validated. All other existing technologies are adapted to this concept. The obvious need is the stepwise development of large plant designs, i.e. pilot plants with all equipment integrated, and demonstration plants given the necessary scale-up for many parts of the process.

The main area for improvement of the oxyfuel power plant concept is found in the ASU. Improving the cost and power requirements of present cryogenic ASUs 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 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 technology 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 without external recirculation

More specifically:

- The boiler has to be developed and optimised for this concept
- Improvement of CFB technology
- Combustion chemistry and kinetics to provide design and scale-up data
- 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
- Dynamic start up and shut down procedures

Chemical Looping Technology R&D Needs

Chemical looping has been shown to be functional in a lab test rig for natural gas. There is no reasonable way to burn coal in a similar process. However, if it could be done, the economic prospects would be very good, since costs for extra energy would be 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 1973. It took 25 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.

The obvious R&D needs are:

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

Transport

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, on shore and off shore. This includes:

- 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

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 than for a line from source to storage.

Further, each alternative is developed for some purpose, e.g. 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 these new technologies. 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 most favourable if the CO_2 is in supercritical form for pipeline transport. On a ship however, CO_2 should be stored as close to its triple point as possible – the larger the vessel, the lower the pressure and temperature.

This means that no actual research is needed to arrive at a solution. Instead, all that is needed is a number of actual cases and a good way of initiating a larger system. Also needed are 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 already exist today, with the potential to capture CO_2 from coal combustion at a cost below 20 EUR/ton - Oxyfuel and IGCC technologies are the most promising. Present postcombustion methods do not seem to reach that goal for retrofitting an existing power plant, but might be achievable for a new plant.

For gas, the situation is a bit different. The cost for capture related to fuel is usually higher. This is mainly due to the lower CO_2 concentration in the flue gas. At the moment, avoidance cost of 20 EUR/ton of CO_2 is just below the economic prospects of the most promising known technologies. However, the focus should not be on the CO_2 avoidance cost alone. The increased electricity production cost should also be evaluated, as this is what the customer sees. In that respect, the situation for gas may be better than for coal.

Much systematic work has been done to find improved technologies for CO_2 capture, especially for gas. These include membrane technologies and solid absorbers. All the "technical gas" companies work seriously with them.

The main challenges are:

- For postcombustion technology:
  - Large scale demo plants improving integration and system efficiency
  - Reduced energy loss for the regeneration of absorber
  - Reduced investment for the separation equipment

- For precombustion technology:
  - Integrate all process steps into a total concept and demonstrate that concept
  - Build, run and later demonstrate optimised gas turbines for hydrogen
  - Improve solvents for physical absorption
  - Develop novel methods for air separation (high temperature ceramic membranes)
  - Verify and test novel methods for CO_2/ H_2 separation in membrane (ceramic and polymer) reformers and water gas shifts

- For oxyfuel combustion:
  - Develop integration and thereby reduce overall energy consumption and investment costs
  - Establish a line of integrated pilot plants and demonstration plants (gas and coal) to validate the designs and scale up data
  - Facilitate inclusion of developed boiler designs, such as CFB and pulverized coal boiler without external recirculation
  - Verify and test at a pilot scale, integrated oxygen transporting membranes with gas turbines
  - Find new integration possibilities for power plants, especially if a new type of ASU is developed

- Search for new process concepts reducing energy penalties:
  - Further process analysis with cost for capture in focus and with an industrial approach
  - Integration of CO_2 capture with the power system
  - Integrated gasification and reforming processes
  - Improved gas separation technologies which are industrially sound and simple
  - More energy efficient sorbents
  - Further development of the solid gas separation technologies, and also the solid absorber technologies
  - Test rigs larger than micro scale, with subsequent pilot-scale testing

One can generally conclude that the three technologies closest to commercial adoption all have in common that rather little research is needed, but they all require an enormous amount of development. In the foreseeable future, these technologies will all see their first large-scale plants. Still needed are:

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

This is by far the most costly part of the development chain.