

# TNO Built Environment and Geosciences

**Process Industry**  
Schoemakerstraat 97  
P.O. Box 6005  
2600 JA Delft  
The Netherlands

## TNO report

**CATO-D2.1.08/2.1.13**

## Overview of post combustion capture technology

[www.tno.nl](http://www.tno.nl)

T +31 15 269 69 00  
F +31 15 262 07 66  
[info-lenT@tno.nl](mailto:info-lenT@tno.nl)

Date	31 December 2008
Author(s)	Earl Goetheer, Mohammad Abu-Zahra
Assignor	CATO
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# 1 Public summary

In this report the latest news of post combustion capture is reported. Next to that also analysis has been made on the topics which need to be addressed to make CO<sub>2</sub> capture more economically attractive. It is clear that a significant progress has to be made. However, looking from a retrospective point of view, it can be concluded there are already substantial improvements made.

The topics to be addressed for further research are:

## Solvent development

- Stable solvents
- Low energy consuming
- Fast kinetics
- No emissions to the environment

## Process intensification

- Compact absorbers
- Heat integration with the power plant
- Intensified strippers (eg heat integration within the stripper)

At this moment there are several potential breakthrough technologies under investigation (eg chilled ammonia). However, at this moment it is early day to report the performance of these novel capture systems.

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## 2 Introduction

*The atmospheric concentration of greenhouse gases GHGs (e.g. carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons) has increased gradually in the last century. The Intergovernmental Panel on Climate Changes (IPCC) has evaluated the size and impact of this increase. One of the conclusions is that the reasons behind the increased concentration of the greenhouse gases in the atmosphere are the human activities [1]. As a result, the global atmospheric concentration of CO<sub>2</sub> increased from a pre-industrial value of about 280 ppmv to 384 ppmv in 2007(see Figure 1) [2]. Moreover, the GHGs concentration is expected to increase to about 600 ppmv by 2050 if no mitigation and emissions reduction options are applied [3].*

*The emissions of the different greenhouse gases have been monitored and measured all around the globe. It is evident that carbon dioxide is the most important anthropogenic GHG. Its annual emissions have grown between 1970 and 2004 by about 80%, from 21 to 38 gigatonnes, and represented 77% of total GHGs emissions in 2004 (Figure 2) [3]. There is a consensus between most scientists that CO<sub>2</sub> emissions need to be reduced worldwide by 30 to 60 % in 2050 compared to 2000 in order to keep CO<sub>2</sub> concentration in the atmosphere below 450 parts per million by volume. This would keep the temperature raise between 2.4 °C and 2.8 °C compared to the pre-industrialised levels [1].*

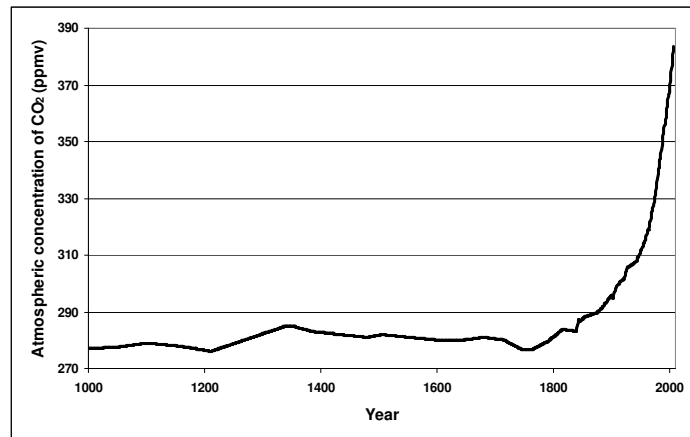
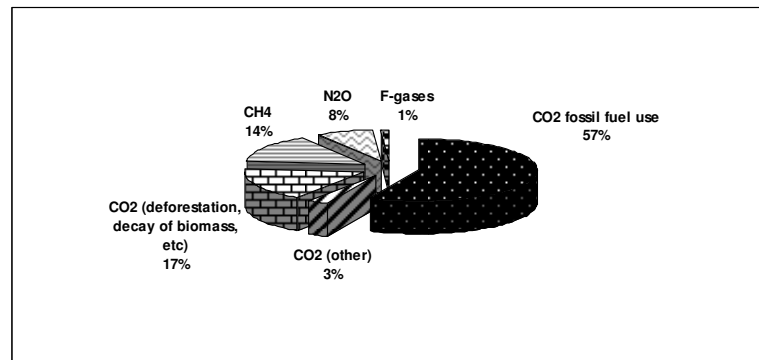
Figure 1: CO<sub>2</sub> global concentration [2]

Figure 2: Share of different Greenhouse gases in total global emissions in 2004 [3]

In order to achieve the Kyoto protocol targets, the European Union (EU) emphasizes the necessity to reduce CO<sub>2</sub> emissions by developed countries by 30% in 2020 compared to 1990 levels [3] and [4]. In addition, the EU is committed to achieve a 20% reduction of its greenhouse gas emissions by 2020 compared to 1990 [5]. To reach this ambitious goal, the focus is on the power generation sector. The fossil fuels that are used for electricity generation are responsible for 41% of the global CO<sub>2</sub> emission in 2004 [6] (see Figure 3). In addition, there is attention towards the transport sector, which is the second largest CO<sub>2</sub> emitter, for reducing CO<sub>2</sub> emissions (e.g. by the development of more efficient engines and by switching to more environmental friendly fuel like hydrogen).

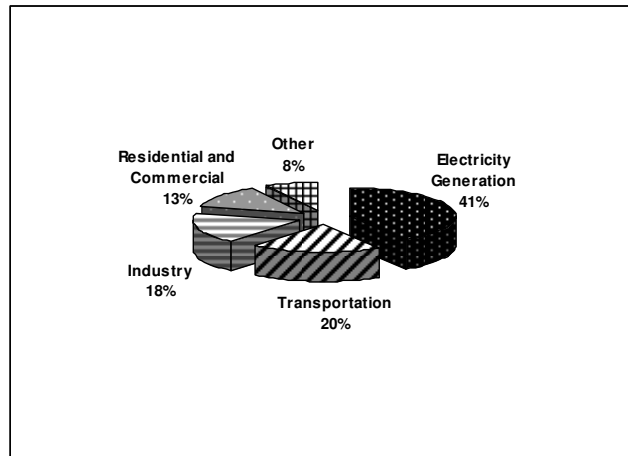


Figure 3: The global CO<sub>2</sub> emissions shares per sector 2004 [6]

Currently, fossil fuels provide around 80% of the world's total energy demand. Coal is playing a major role as the main source of electrical power (38% of the total electricity generation) [7]. The large dependency on fossil fuels makes it difficult to switch to other energy sources. Moreover, the world energy demand is expected to increase by over 50% between now and 2030. The prognoses indicate that fossil fuel will still be the main and most effective source of energy (see Figure 4) [8].

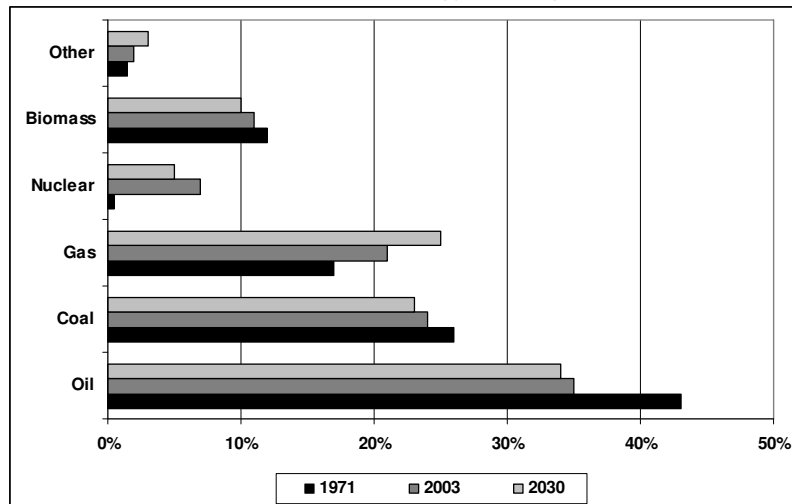


Figure 4: Fuel shares in global primary energy demand. *Other includes amongst others solar and wind energy* [8]

### 3 Options to reduce CO<sub>2</sub> emissions from the power generation sector

A reduction of CO<sub>2</sub> emission to the atmosphere from the power generation sector (main CO<sub>2</sub> emitters) would require a combination of several solutions (see Figure 5) [1] and [3]:

- Reduction of energy consumption
- Improve power supply and distribution efficiency
- Massive switching from coal to natural gas
- Widespread use of renewable or nuclear energy
- CO<sub>2</sub> capture and storage (CCS)

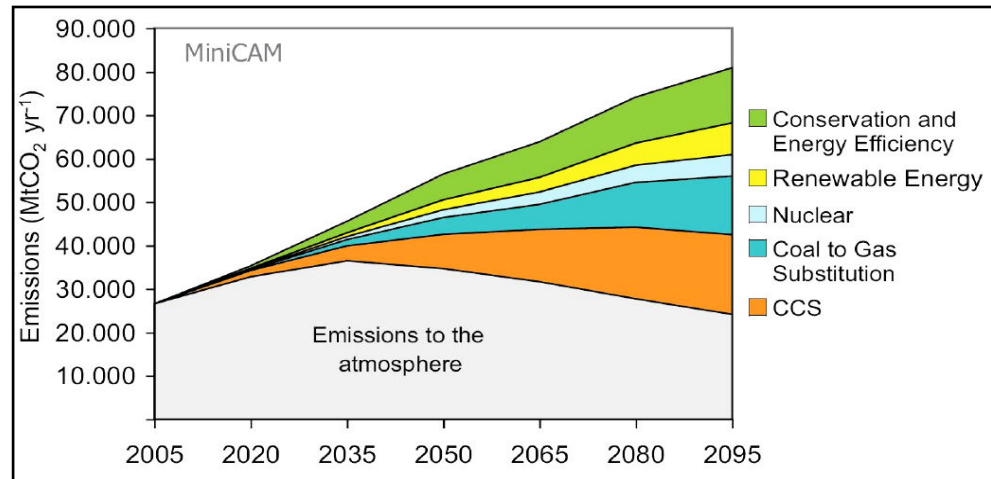


Figure 5: Option to reduce CO<sub>2</sub> emissions [1]

CCS is a promising method considering the ever-increasing worldwide energy demand and the possibility of retrofitting existing plants with capture, transport, and storage of CO<sub>2</sub>. The captured CO<sub>2</sub> can be used for enhanced oil recovery, in the chemical and food industries, or can be stored underground instead of being emitted to the atmosphere. There are three basic systems for capturing the emitted CO<sub>2</sub> from the power sector, which are shown in simplified form in Figure 6 [1].

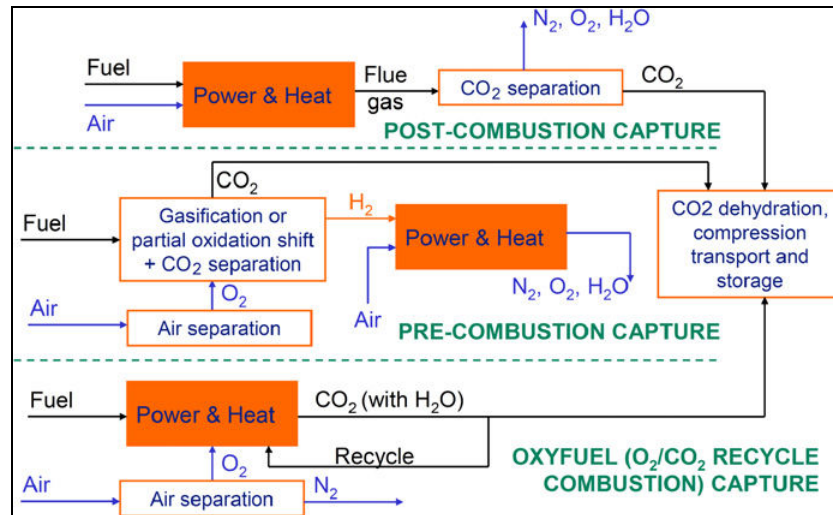


Figure 6: Overview of CO<sub>2</sub> capture systems for the power sector [1]

### 3.1 Post-combustion capture

Capture of CO<sub>2</sub> from flue gases produced by combustion of fossil fuels is referred to as post-combustion capture. Post-combustion capture typically uses a solvent to capture the CO<sub>2</sub> from the flue gases after the combustion process. The main line of research is on the development of reactive solvents for the capture of CO<sub>2</sub>. Reactive solvents are the preferred choice due to the low partial pressure of CO<sub>2</sub> (between 3-15 kPa) in the flue gas with nitrogen to be considered as the main component (see Table 1) [10]. Nevertheless, other techniques, such as membranes, adsorption) are under development [9], [11].

### 3.2 Pre-combustion capture

In this concept, a fuel is reacted with air or oxygen and/or steam to give a syngas (mixture of carbon monoxide and hydrogen). This process is known as the gasification step. In the second step, the carbon monoxide is reacted with steam in a catalytic reactor (water-gas shift reactor) to produce CO<sub>2</sub> and more hydrogen. A physical or chemical absorption process then separates the highly concentrated CO<sub>2</sub> from the hydrogen (see Table 1). The hydrogen rich stream can be used as a fuel in a gas turbine combined cycle plant. Another option is to distribute the hydrogen for use in fuel cells or in the future to provide vehicle fuel [1], [10].

### 3.3 Oxy-fuel combustion

In oxy-fuel combustion, nearly pure oxygen mixed with recycled flue gas is used for combustion instead of air. This will result in a flue gas that is mainly CO<sub>2</sub> saturated with water vapour [12], [13]. Having water vapour as the main component in the CO<sub>2</sub> stream makes it possible to purify and store CO<sub>2</sub> with less downstream processing (see Table 1). If fuel is burnt in pure oxygen, the flame temperature is excessively high. However, by recycling the CO<sub>2</sub> rich flue gas the flame temperature will be similar to that of a normal air-blown combustor. Oxygen is usually produced by cryogenic air separation. Novel techniques with lower energy consumption and cost are being developed [1], [10].



### 3.4 Capture routes and technologies evaluation

Significant effort is directed towards the comparison of the three different technological routes for the CO<sub>2</sub> capture from fossil fuel power plants [14]-[17]. The majority of these studies came out with the conclusion that the net efficiency of the power plant, the overall cost of electricity, and cost of CO<sub>2</sub> avoided for the different technologies are almost comparable. In Figure 7, the efficiencies of the power plant reference cases without capture are compared with the overall power plant net efficiency after implementing the capture process. It is clear that the overall efficiency of the three CO<sub>2</sub> capture routes (post, pre and oxy-fuel combustions) are very similar. This supports the conclusion that the selection of one of the capture routes based on the overall efficiency is not sufficient.

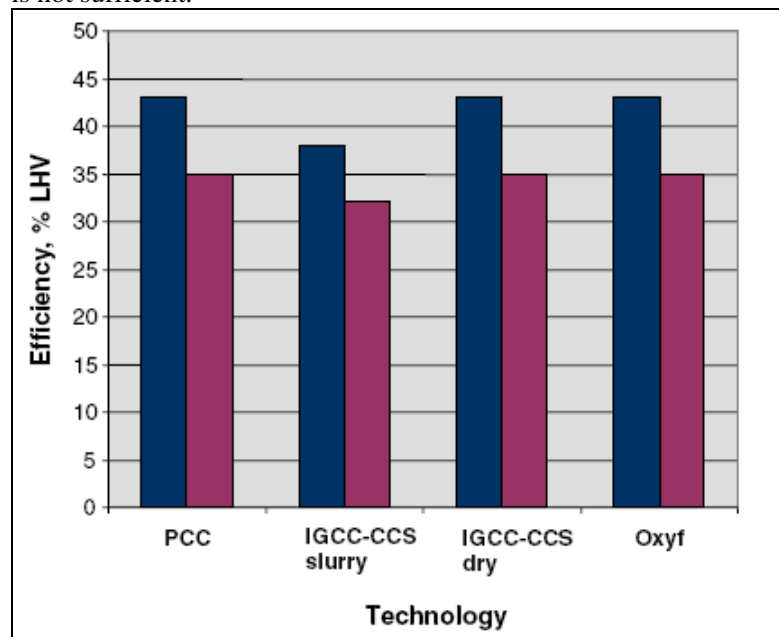


Figure 7: The efficiency for different power plant technologies before and after adding the capture process [14]. *PCC: Pulverised coal power plant (with and without post-combustion capture), IGCC: integrated gasification combined cycle (pre-combustion capture), CCS: CO<sub>2</sub> capture, transport and storage, Oxyf: Oxy-fuel combustion power plant and LHV: low heating value.*

By evaluating the effect of the different CO<sub>2</sub> capture routes on the overall estimated cost of electricity, it was found that the difference between these different routes using the same type of fuel is very limited and could not be used to select a preferred capture route, see Figure 8.

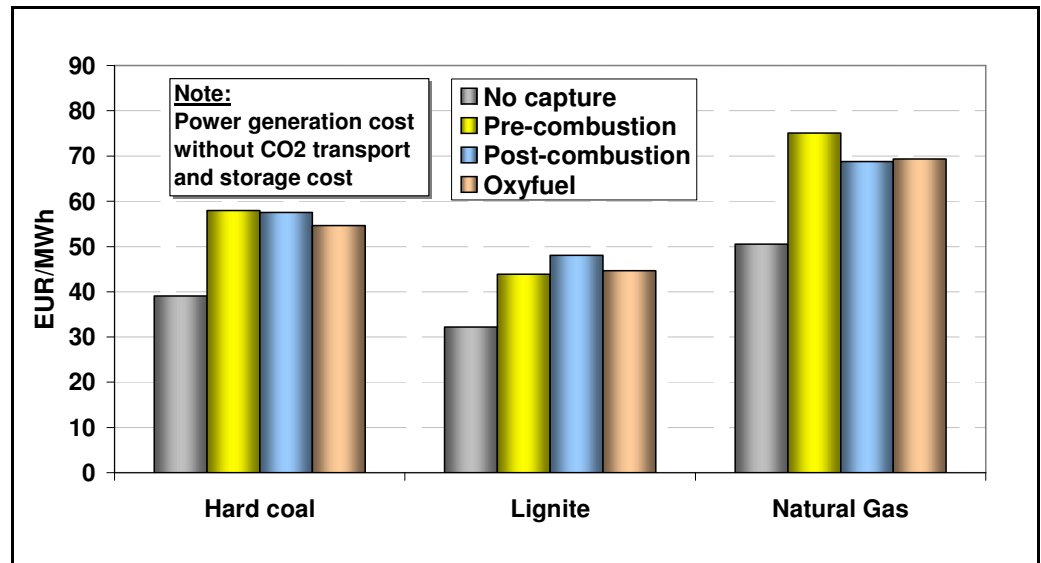


Figure 8: Estimated cost of electricity in 2020 after applying different CO<sub>2</sub> capture routes [18]

However, the advantage of one technology route over the others could be related to the technology availability, the level of maturity of the technology, the possibility of capture process retrofitting to the existing power plants, the experience, and repetition in commercial and large-scale applications and the most important factor is the period needed for the technology implementation.

In this thesis, the focus is on CO<sub>2</sub> post-combustion capture route. Post combustion capture has been selected because it has the following advantages over the other technologies [19]:

- The possibility of add-on to existing power plants (retrofit possibility).
- Capture technologies are considered available and the solvent technologies are proven on a smaller scale.
- Capture readiness makes the post-combustion capture relatively easy to incorporate into power plant tackling issue with infrastructure inertia.
- It has more operational flexibility in switching between capture – no capture options.
- Learning by doing will lead to cost reductions similar to experience with SO<sub>2</sub> capture process development.

Currently, a wide range of technologies for separation and capture of CO<sub>2</sub> from gas streams exist. They are based on different physical and chemical processes including absorption, adsorption, membranes and cryogenics (see Figure 9) [9], [11].

The choice of a suitable technology depends on the characteristics of the CO<sub>2</sub>-gas streams, which depend mainly on the power plant. As it can be seen from Table 1, for the different CO<sub>2</sub> capture routes different types of gases need to be separated. In addition, the pressure and the CO<sub>2</sub> content in the gas streams, which are important parameters in selecting the most suited technology for CO<sub>2</sub> removal, are different from one route to another.

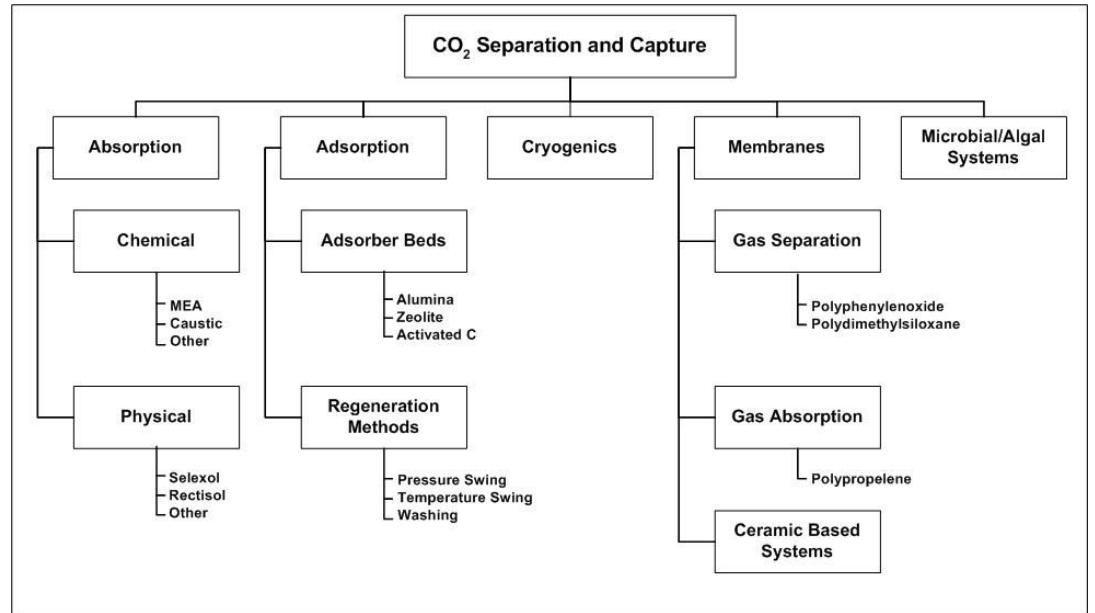


Figure 9: Different technological routes for CO<sub>2</sub> capture [11]

Table 1: CO<sub>2</sub> capture routes classifications

	<i>Post-combustion (flue gas)</i>	<i>Pre-combustion (shifted syngas)</i>	<i>Oxy-fuel combustion (exhaust)</i>
Gases to separate	CO <sub>2</sub> /N <sub>2</sub>	CO <sub>2</sub> /H <sub>2</sub>	O <sub>2</sub> /N <sub>2</sub>
p (bar)	~1	10-80	~1
[CO <sub>2</sub> ] (%)	3-15	20-40	75-95

In case of post-combustion, the CO<sub>2</sub> is diluted and available at low pressure that makes chemical absorption one of the most efficient options for CO<sub>2</sub> removal. However, in the pre-combustion route, the CO<sub>2</sub> has higher partial pressure that makes physical absorption or adsorption a good technology candidate for CO<sub>2</sub> removal. The relevance and potential of these separation technologies to CO<sub>2</sub> capture is subject of research and development efforts worldwide.

## 4 CO<sub>2</sub> post-combustion capture

Carbon dioxide post-combustion capture is considered one of the most mature capture technologies, since there is a good experience and reputation of this technology within many industrial applications [11].

### 4.1 Oerview

Rao and Rubin 2002 [11] shows that for many reasons amine based CO<sub>2</sub> absorption systems are the most suitable for combustion based power plants: for example, they can be used for dilute systems and low CO<sub>2</sub> concentrations, the technology is commercially available, it is easy to use and can be retrofitted to existing power plants. Typically, absorption processes are based on a thermally regenerable solvent, which have a strong affinity for CO<sub>2</sub>. The process thus requires thermal energy for the solvent regeneration. The benchmark absorption process is based on an aqueous solution with 30% by weight Monoethanolamine (MEA) as the active ingredient. This amine-based process is considered the state-of-the-art technology [20].

Fluor Daniel markets the 30% aqueous MEA solution based process under the name Econamine FG<sup>SM</sup> [20] and [24]. The solution also contains proprietary additives to prevent corrosion and solvent degradation. The presence of these additives is expected to have a negligible effect on the major performance parameters. Fluor Daniel has improved its process performance by various means, including a modification of the solvents and process under the name Econamine FG Plus<sup>SM</sup>. However, none of these novel improvements have been validated on a large-scale process. Some of the proposed improvements are based on modelling studies and lab-scale development. It is acknowledged that the solvent developments for post-combustion CO<sub>2</sub> capture are accelerating with the expectation of future CO<sub>2</sub> emissions constraints. Apart from Mitsubishi Heavy Industries marketing their KS-1 solvent [25], [26] and [27], also the CBI-Lummus [21], Cansolv and Praxair are amongst the new suppliers.

#### 4.1.1 Process short description

The general process flow diagram for amine absorption is shown in

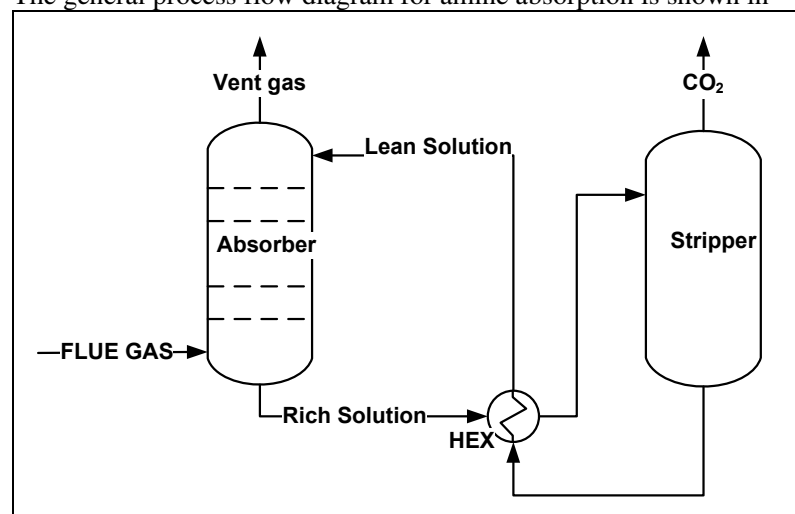


Figure 10. This is the typical conventional MEA-CO<sub>2</sub> capture flow sheet, which has been described and discussed in a large number of commercial, industrial and research activities [9], [11], [19]-[24] and [28]. The underlying fundamental principle is the

exothermic, reversible reaction between a weak acid (e.g. CO<sub>2</sub>) and a weak base (e.g. MEA) to form a soluble salt. The inlet gas is contacted counter-currently with lean solvent in the absorber. The acid gases are preferentially absorbed by the solution. The solution, enriched with CO<sub>2</sub>, is pre-heated before entering the stripper where, through the addition of heat, the reaction is reversed. The lean solvent leaves the stripper and is lowered in temperature by exchanging heat with the rich solvent. The lean solvent is recycled back to the absorber. From the top of the stripper, a high-purity (dry-basis) CO<sub>2</sub> is produced. For the regeneration of the rich solvent large quantities of heat is required. An important aspect is the source of the heat and electricity. One approach is to produce the required heat and electrical power using auxiliary equipment. The other alternative is to extract the required heat from the existing power plant.

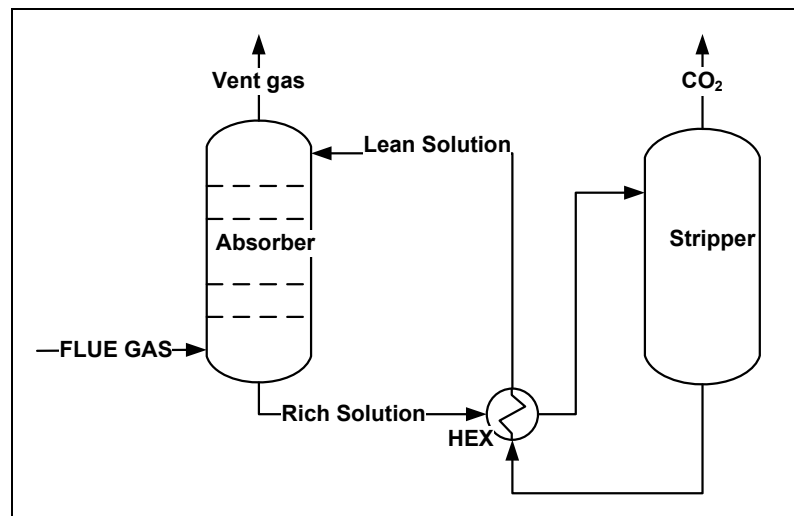
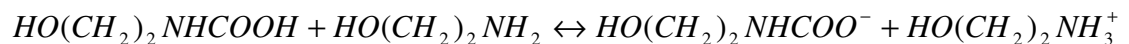
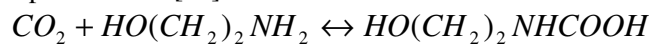


Figure 10: General chemical absorption CO<sub>2</sub> capture process flow sheet

#### 4.1.2 CO<sub>2</sub>-Monoethanolamine chemical reactions and thermodynamics

Since the first applications of this system were in early in 1960's, a large number of studies on the reaction mechanism of CO<sub>2</sub>-H<sub>2</sub>O-MEA system have been reported [29]-[36]. As a general conclusion of these studies, the absorption of CO<sub>2</sub> by aqueous MEA solution is based on a complex system of parallel and consecutive reactions in liquid phase. With the overall forward reaction between CO<sub>2</sub> and MEA has usually been represented as [34]:



The first step is second-order and rate determining. The second step is considered an instantaneous reaction. However, this scheme is a substantial simplification for the reaction mechanism that actually occurs.

The CO<sub>2</sub>-H<sub>2</sub>O-MEA system is considered non-ideal, which could be described in the gas phase using the Soave-Redlich-Kwong equation of state [36]. For the liquid phase, electrolyte-NRTL model is considered as a good representation of this system. The required data and parameters for this system have been developed and presented by Austgen 1989 [37].

In addition, of the main physical properties of this system (density, viscosity, thermal conductivity, and specific heat) have been measured as a function of MEA concentration and operating temperature by Cheng 1996 [38]. Moreover, the solubility and the diffusivity of CO<sub>2</sub> into the aqueous MEA solution have been measured and estimated by different studies, which are reviewed and summarized by Versteeg 1996 [31].

#### 4.2 Post-combustion capture process challenges

Several researchers have studied and evaluated the MEA absorption process [11], [14], [20]-[24], [28] and [39]. Most of their conclusions focused on reducing the thermal energy requirement to reduce the overall process expenses. The literature results show different estimations for the regeneration energy requirement for the MEA process. Chapel et al. 1999 estimated the Econamine FG<sup>SM</sup> energy requirement of 4.2 GJ/tonne CO<sub>2</sub>, which is around 36% of the overall operating cost [20]. Singh et al. 2003 [23] found by modelling the MEA process for 400 MWe coal fired power plant a specific thermal energy requirement equal to 3.8 GJ/tonne CO<sub>2</sub>. Alie et al. 2005 [22] found that an energy requirement of 176 kJ/mol CO<sub>2</sub> (4 GJ/tonne CO<sub>2</sub>). Recently, Fluor claims a process development based on the MEA technology leading to a significant reduction of the energy requirement down to around 2.9 GJ/tonne CO<sub>2</sub>. The improvements are based on process integration and solvent improvements [40].

In conclusion, the high-energy requirement makes the capture process energy-intensive and costly. Therefore, it is important to study the conventional MEA process to have a better understanding of the process to work on reducing the energy requirement. Moreover, the general conclusion of all the studies is that by applying the current state-of-art capture process the overall power plant net efficiency will decrease with 8 to 12 percentage points ([1] and [41]). This means, for the conventional hard coal power plant that the overall electricity output will be decreased by almost 20 %. Furthermore, the CO<sub>2</sub> capture overall economic evaluation shows that the cost of CO<sub>2</sub> capture is currently very high. This implies that for realizing the potential of CCS there is a strong need for breakthrough technology.

As a result of the different CCS projects, evaluation and studies, a general conclusion can be made that the current CO<sub>2</sub> capture technologies have the following disadvantages:

- Significant efficiency reduction
- Increase of the power generation costs
- Huge capture plant components and equipment, which requires further development and modification
- Lack of experience in CO<sub>2</sub> capture process at a full power plant scale
- No global political and social decision to apply the technology and to subsidize it
- Very limited public awareness of the importance of CCS technology as one of the solutions to reduce the global warming problem

## 5 CO<sub>2</sub> capture activities and development lines

The importance of carbon dioxide capture, transport, and storage (CCS) for the reduction of the overall CO<sub>2</sub> emission can be considered as a fact. In addition, the understanding of the challenges facing the large-scale CCS application, encourage different governments, nongovernmental organizations, research institutes, universities and many other commercial companies to invest in the CCS chain to make it ready for application in the near future.

The CCS research and development takes a significant funding and attention from all related parties. Different projects and activities, which cover most of the aspects in the CCS chain, have been started since the early 1990's.

The focus of the international institutes and organizations like the intergovernmental panel on climate change (IPCC) and the international energy association (IEA) is on the overall CCS chain definition, evaluation, legislation, international cooperation, and activities organization. However, many technical oriented projects have been carried out or planned for the future with EU or national funds. Figure 11 shows an overview of the completed, ongoing or planned CCS projects. The focus in these projects is varied from one project to another. Part of these projects focus on the development of one capture route like the European CESAR project, which focuses on CO<sub>2</sub> post-combustion capture. On the other hand, other projects evaluate the complete carbon capture, transport and storage chain like in the Dutch CO<sub>2</sub> capture and storage programme (CATO project).

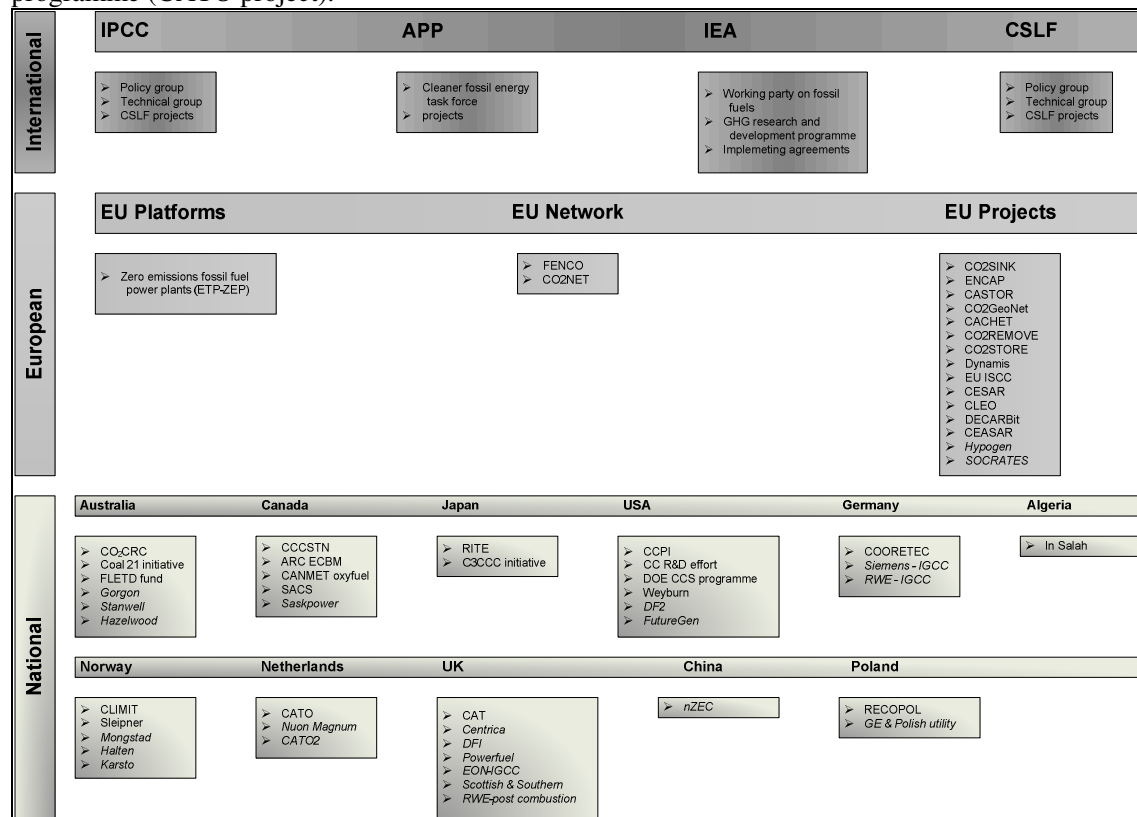


Figure 11: CCS projects and activities [42] - [45] *Projects with italic font are planned for the future*

## 6 Research questions for CO<sub>2</sub> post-combustion capture

As has been discussed in the previous sections, CO<sub>2</sub> post-combustion capture is becoming an important option for CO<sub>2</sub> emission reduction. However, applying this technology on large-scale will not be a reality before tackling different legal, economic, social, political and technical challenges related to the current technologies. There are many questions, which need to be answered before applying large-scale CO<sub>2</sub> post-combustion capture:

1. How to reduce the additional power consumption, which results from applying the capture process?
2. How to reduce the overall footprint of the capture process and to make the equipments more compact?
3. What are the main parameters and factors that contribute in the overall cost of the capture process and how to reduce this cost?
4. What are the main technological areas of focus for the future development to achieve the CO<sub>2</sub> emission reduction with an acceptable cost?
5. Is there still a room for improvement on the current state-of-art CO<sub>2</sub> post-combustion capture process?
6. How reliable the capture process techno-economic evaluation tools that have been used for process evaluation?
7. How the CO<sub>2</sub> capture processes can be made reliable in power generation environment?
8. How to encourage the decision makers to adopt the CCS development politically and economically?
9. What are the methods and routes that should be followed to increase public awareness?

Most of these questions and many more need to be solved in order to apply the capture technology for large-scale applications and achieve the targeted CO<sub>2</sub> emission reduction.



## 7 State of the art

At this moment there are several vendors working on the development of post combustion capture. In this chapter a short overview of some of the more important vendors of technology are given.

### 7.1 Mass transfer technology

Equipment for gas absorption processes are well known in the industry. Especially, the chemical industrial sector have a vast amount of experience for this type of operation. Companies like Sulzer have been designing and erecting this kind of equipment for decades (see Figure 16). The typical sizes which are now available are on the order of a diameter between 0.3 and 16 meter, with a tower height of 2 to 80 meter.

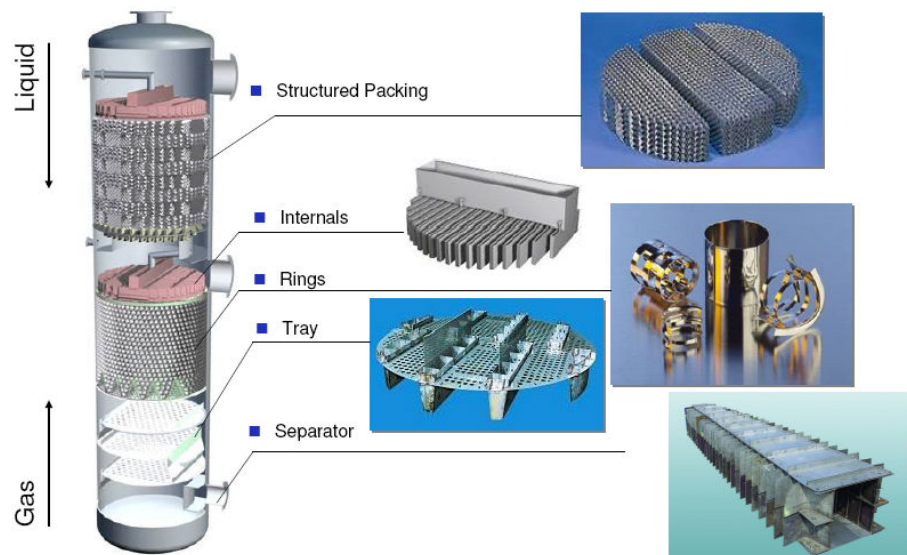


Figure 12: mass transfer equipment<sup>1</sup>

The focus is now among the vendors of mass transfer equipment to intensify the process by enhancing and further optimisation process and equipment performance, leading to savings on CAPEX and OPEX. An example is the continuous improvement of packing material. The main aim is to have packing material with low pressure drop (OPEX reduction) but with high interfacial area (CAPEX reduction). Trends are to examine non-metallic packings and absorber towers. For instance concrete constructions can lead to significant cost reduction (up to 40%). However, robustness over a time period of 20 to 30 years needs to be established.

<sup>1</sup> [www.sulzer.com](http://www.sulzer.com)

## 7.2 Absorption systems

### 7.2.1 Alstom<sup>2</sup>

Alstom decided a decade ago to invest in technology for amongst others post combustion capture. Three routes were selected and are still continued:

- chilled ammonia
- enhance amines (together with DOW Chemicals)
- antisublimation

In Figure 17, the vision of Alstom is depicted. The aim is clearly to reduce OPEX by reducing energy costs from 4 MJ/kg to 2 MJ/kg. This should lead to a significant reduction in cost of CO<sub>2</sub> captured. Alstom thinks it is possible to reach a goal of 15 to

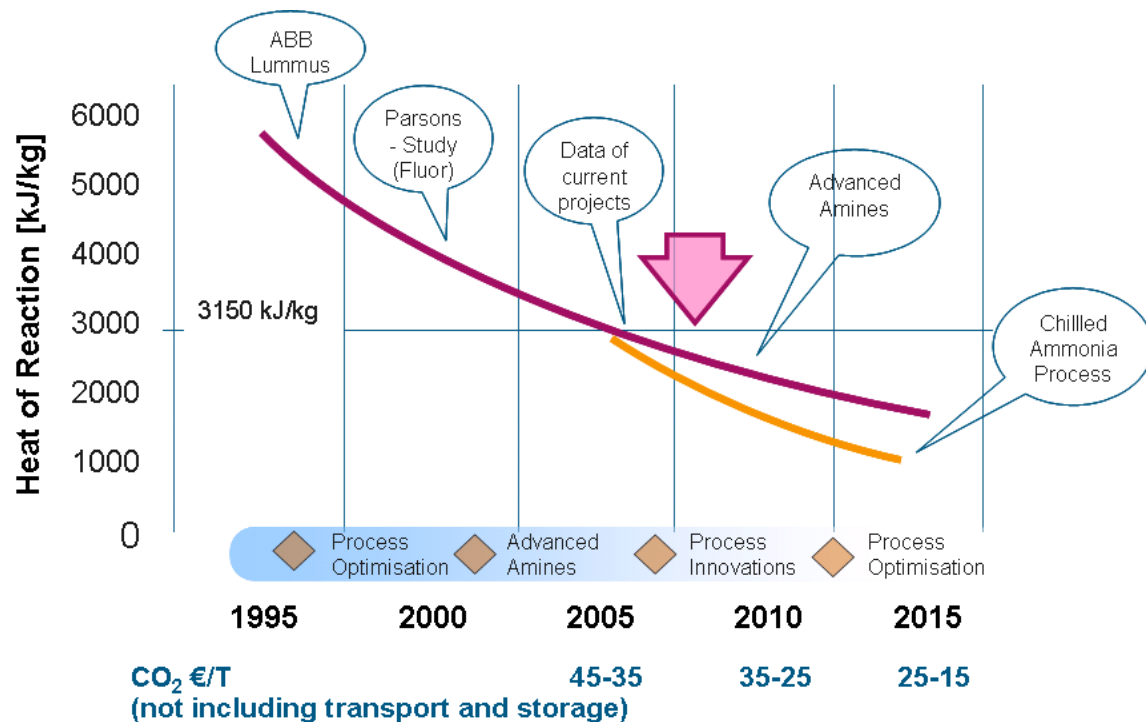


Figure 17: Alstom vision on post combustion capture

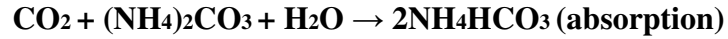
#### 7.2.1.1 chilled ammonia

In the overview reports in the CATO project (eg written by TNO and KEMA) chilled ammonia has been discussed. In Figure 18, the process is schematic depicted. The principle for this process is based on:

- Ammonia (NH<sub>3</sub>) reacts with CO<sub>2</sub> and water. It forms ammonia carbonate or bicarbonate
- Moderately raising the temperatures reverses the above reactions – releasing CO<sub>2</sub>

<sup>2</sup> www.alstom.com

This technology seems to be very promising. However, major challenges are the volatility of ammonia, the low reaction kinetics and the slurry handling. The basic reaction are given below:



It is of importance to note that there are more competing reactions during absorption, which can lead to higher energy consumption during regeneration.

The advantages are the claimed lower energy consumption and the desorption at higher pressure leading to lower cost for compression. Alstom has together with the American Electric Power (AEP) designed and build a pilot plant at AEP's Mountaineer Plant, located in New Haven, on a 30 MWth slipstream. In total 100 ktons of CO<sub>2</sub> will be captured annually. The second phase would be a 200 MW demonstration on a 450 MW unit at the Northeastern Station, located in Oologah (USA).

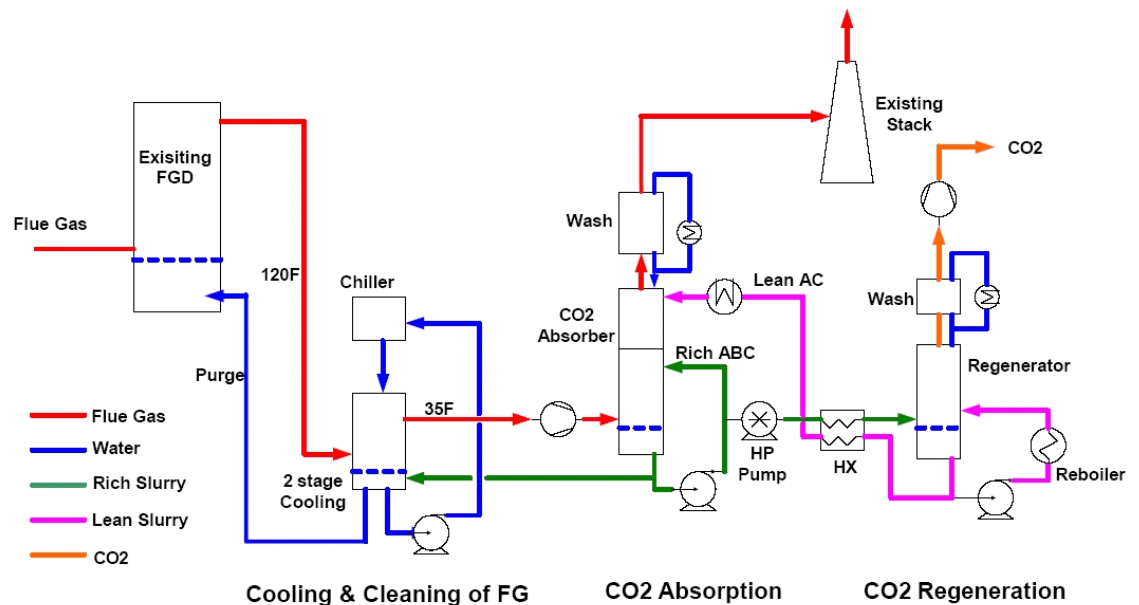


Figure 18: schematic design chilled ammonia plant

In Figure 19 the envisaged timelines are given for this technology.

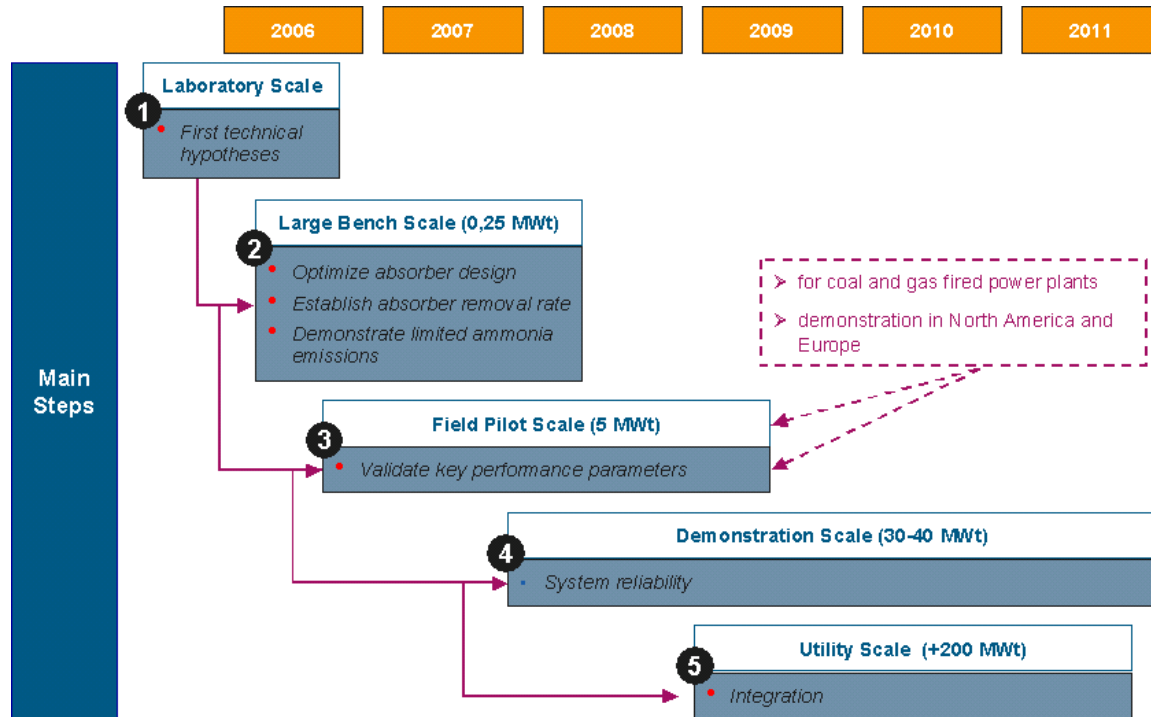


Figure 19: timeline chilled ammonia

At this moment there is no news available in the open literature about the performance of the pilot plants. The data is expected reported in this year.

#### 7.2.1.2 Other techniques

No real data is available in public literature. However, it is expected that the development of the enhanced amines should lead to a mixture of two different type of amines. This lead to a predominantly carbonate forming system enhanced by a carbamate forming promoter.

### 7.2.2 *Fluor*

Fluor is a well know company involved in amongst others technology development and building of installations. The Fluor process Econamine has been discussed prior in this report. Here a short factsheet is given.

- World-wide licenses to date 24 plants
- Plants/Licenses on order: 10
- CO<sub>2</sub> concentrations from 3% to 20% v/v
- O<sub>2</sub> Concentrations from 1 to 15% v/v
- Only process that has 14 years commercial operation recovering
- CO<sub>2</sub> from a gas turbine exhaust (13 to 15% v/v O<sub>2</sub>)
- Demonstrated on heavy fuel-oil boiler
- Several installed on boilers and steam reformers in Ammonia and Methanol plants

The largest plant is located in Bellingham (USA). This plant has the capacity of treating 330 tons/day (40MW). This is also the largest absorber (6,1 m diameter). Here below some facts are given:

- CO<sub>2</sub> Concentration: 3.5% v/v
- O<sub>2</sub> Concentration: 13 to 14% v/v
- 100% air cooled, zero water import or export
- Product Usage: Food-grade CO<sub>2</sub>
- Status: Continuous operation since 1991 with a 98.5% on-stream factor in 2004.

Here below some pictures are given for this installation.



Figure 20: Bellingham location

Compared with a standard flowsheet the econamine process has the following modifications:

- Enhanced solvent formulation
- Absorber Intercooling
- Lean vapor compression configuration
- Advanced reclaiming technologies
- Heat integration with the power plant

Next to that Fluor is focused on strategies to minimize the number of trains. One methodology is to enlarge the diameter of the absorber to 20 m. This would lead to a 1000 MW coal based power plant a requirement of 2 absorber trains.

### 7.2.3 *Mitsubishi*

Next to Fluor Mitsubishi is the other vendor of the so called proven technology. Based on the solvents KS-1 and KS-2 several small size plants have been erected. The solvents which have been used are based on the same ideas as described at the solvent development section of Alstom. In several CATO-reports this technology is discussed.



Figure 21a: This plant employs a chemical absorption process to separate 0.2 MtCO<sub>2</sub> per year from the flue gas stream of a gas-fired power plant for urea production (Malaysia, Courtesy of Mitsubishi Heavy Industries). (b) CO<sub>2</sub> precombustion capture at a coal gasification plant in North Dakota, USA. This plant employs a physical solvent



process to separate 3.3 MtCO<sub>2</sub> per year from a gas stream to produce synthetic natural gas.

#### 7.2.4 *Siemens*

Siemens is currently working on post combustion using an amino acid based system. The solvent will be tested in a pilot plant connected to a powerplant of E.ON in Germany. The use of a salt of an amino acid should lead to a stable, low energy consuming process. The main advantage is the low amount of chemicals consumed due to chemical and thermal stability of amino acids. The system of Siemens is comparable to the development at TNO (CORAL family of absorption solvents).

In Figure 22 a view is given how a post combustion plant looks like according to Siemens.

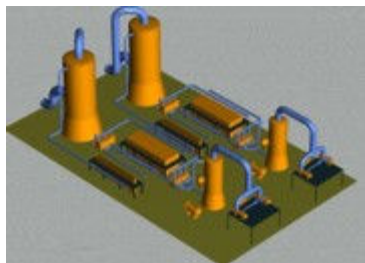


Figure 22: PCC according to Siemens

#### 7.2.5 *HTC<sup>3</sup>*

HTC is a Canadian firm located at Regina. This firm has connection with the International Test Centre . They have developed an amine based process. This process should be low energy consuming. In the figure below some typical pictures are given.

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<sup>3</sup> [www.htcenergy.com](http://www.htcenergy.com)

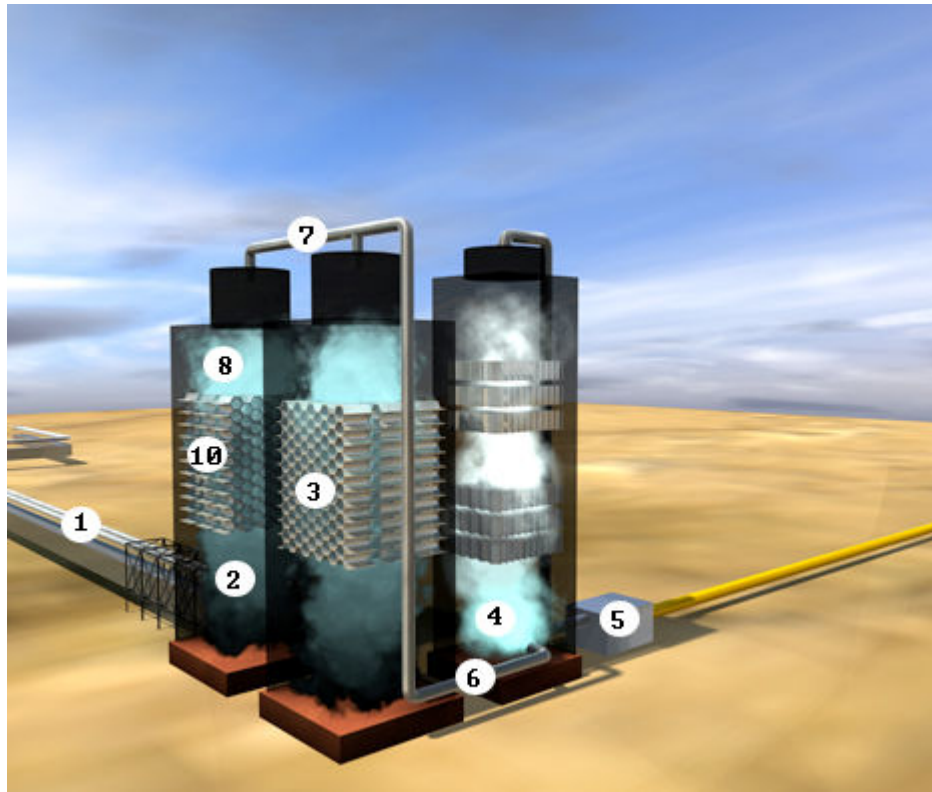


Figure 23: modular design of a PCC unit

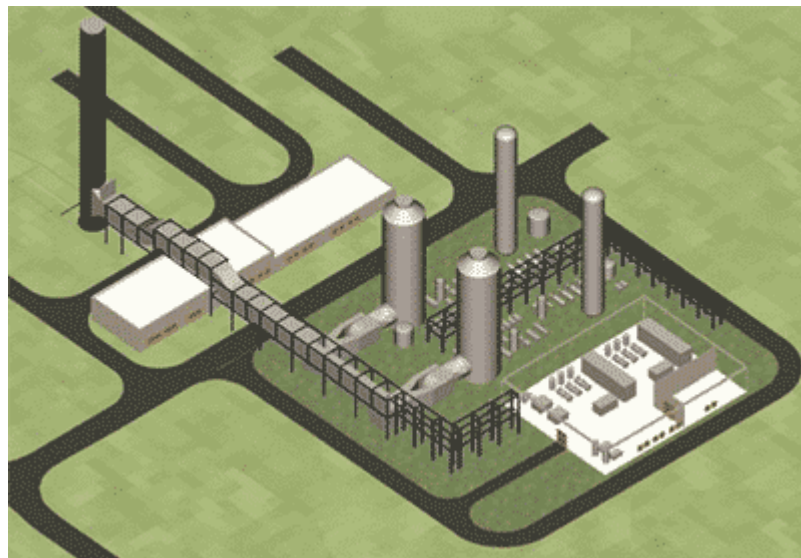


Figure 24: Envisaged pilot plant PCC unit

In Figure 25 an overview is given of the performance of the solvent developed by HTC. The reported results seem to be promising.



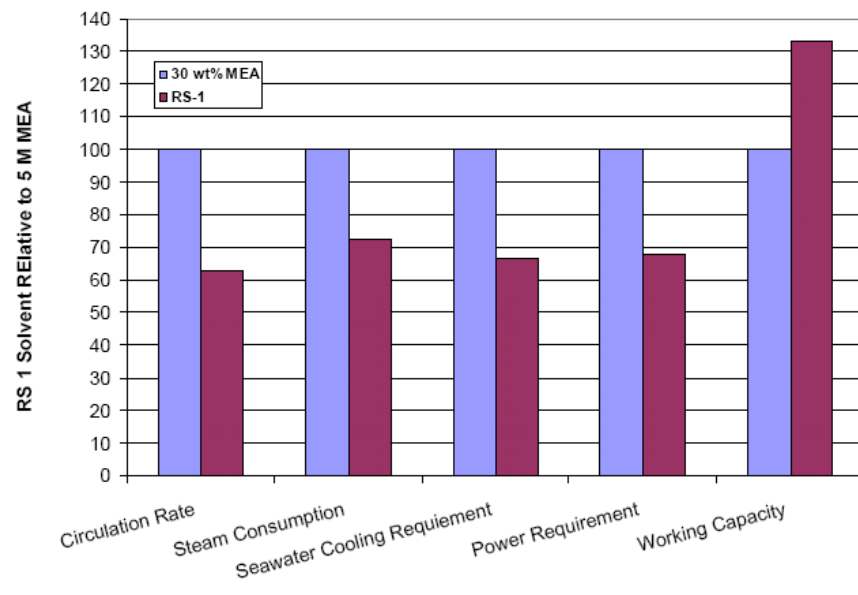


Figure 25: performance of RS-1 compared to MEA

## 8 References

- [1] Intergovernmental Panel on Climate Change (IPCC), 2005. Carbon dioxide capture and storage. Cambridge university press.
- [2] Mauna Loa by Scripps Institute of Oceanography, CDIAC, and NOAA/ESRL at [www.esrl.noaa.gov/gmd/ccgg/trends](http://www.esrl.noaa.gov/gmd/ccgg/trends), updated January 2008.
- [3] Intergovernmental Panel on Climate Change (IPCC), 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.
- [4] European Union, 2007a. In: Press release 2785<sup>th</sup> council meeting environment Brussels.
- [5] European Environmental Agency (EEA) Report, 2008. Greenhouse gas emission trends and projections in Europe, tracking progress towards Kyoto targets. Report number 5/2008.
- [6] International Energy Agency (IEA), 2006. World Energy-Related CO<sub>2</sub> Emissions by Sector in the Reference Scenario," World Energy Outlook 2006, Paris, p. 80.
- [7] Birol, F., Argiri, M., 1999. World energy prospects to 2020. Energy, 24, 905-918.
- [8] International Energy Agency, 2005. World energy outlook 2005. OECD/IEA.
- [9] Kohl, A., Nielsen, R., 1997. Gas purification. 5<sup>th</sup> edition, Gulf publishing company.
- [10] International Energy Agency (IEA) greenhouse gas R&D programme, 2007. Capturing CO<sub>2</sub>. By Christopher Lewis, © Separations research program 2007.
- [11] Rao, A.B., Rubin, E.S., 2002. A technical, economic, and environmental assessment of amine-based CO<sub>2</sub> capture technology for power plant greenhouse gas control. Environ. Sci. Technol. 36, 4467-4475.
- [12] Zanganeh, K., Shafeen, A., 2007. A novel process integration, optimization, and design approach for large-scale implementation of oxy-fired coal power plant with CO<sub>2</sub> capture. J. GHG control, 1, 47-54.
- [13] Varagani, R., Chatel-Pelage, F., Gautier, F., Pranda, P., McDonald, D., Devault, D., Farzan, H., Schoff, R., Ciferno, J., Bose, A., 2006. Oxy-

combustion process for CO<sub>2</sub> capture from coal fired power plants: An overview of techno-economic study and engineering feasibility analysis. Proceedings of Inter. Con. GHG Con. Tech., Trondheim, Norway.

- [14] Wall, T., 2007. Combustion processes for carbon capture. Proceedings of the combustion institute, 31, 31-47.
- [15] International Energy Agency (IEA) greenhouse gas R&D programme, 2004. Impact of Impurities on CO<sub>2</sub> capture, transport and storage, Report No. PH4/32.
- [16] International Energy Agency (IEA) greenhouse gas R&D programme, 2005. Towards zero emission coal-fired power plants. Clean coal centre, report No. CCC/101.
- [17] Stromberg, L., 2005. Technology benchmarking studies in Oxy-fuel Combustion. Presentation to IEA Oxy-Fuel Combustion Research Network, Cottbus, Germany.
- [18] ZEPP
- [19] Feron, P., 2005. Progress in post-combustion CO<sub>2</sub> capture. Presentation for the international symposium, reduction of emissions and geological storage of CO<sub>2</sub>.
- [20] Chapel, D., Ernst, J., Mariz, C., 1999. Recovery of CO<sub>2</sub> from flue gases: commercial trends. Can. Society of Chem. Eng. (Oct 4-6).
- [21] Barchas, R., 1992. The Kerr-McGee/ABB Lummus Crest technology for recovery of CO<sub>2</sub> from stack gases. Energy Convers. Mgm. 33, 333-340.
- [22] Alie, C., Backham, L., Croiset, E., Douglas, P., 2005. Simulation of CO<sub>2</sub> capture using MEA scrubbing: a flow sheet decomposition method. Energy Convers. Mgm. 46, 475-487.
- [23] Singh, D., Croiset, E., Douglas, P., Douglas, M., 2003. Techno-economic study of CO<sub>2</sub> capture from an existing coal-fired power plant: MEA scrubbing vs. O<sub>2</sub>/CO<sub>2</sub> recycle combustion. Energy Convers. Mgm. 44, 3073-3091.
- [24] Sander, M., Mariz, C., 1992. The Fluor Daniel Econamine FG process: past experience and present day focus. Energy Convers. Mgm. 33, 5-8, 341-348.
- [25] Imai, N., 2003. Advanced solvent to capture CO<sub>2</sub> from flue gas. 2<sup>nd</sup> International forum on geological sequestration of CO<sub>2</sub> in deep, unmineable coal seams.
- [26] Mimura, T., Shimojo, S., Suda, T., Iijima, M., Mitsuoka, S., 1995. Research and development on energy saving technology for flue gas

- carbon dioxide recovery and steam system in power plant. *Energy Convers. Mgmt.* 36, 6-9, 397-400.
- [27] Suda, T., Fujii, M., Yoshida, K., Lijima, M., Seto, T., 1992. Mitsuoka S, Development of flue gas carbon dioxide recovery technology. *Energy Convers. Mgm.* 33, 5-8, 317-324.
- [28] Abu-Zahra, M., Schneiders, L., Niederer, J., Feron, P., Versteeg, G., 2007. CO<sub>2</sub> capture from power plants part I: A parametric study of the technical Performance based on Mono-Ethanolamine. *Inter. J. GHG Con.*, 1, 37-46.
- [29] Danckwerts, P., Sharma, M., 1966. The absorption of carbon dioxide into solutions of alkalis and amines (with some notes on hydrogen sulphide and carbonyl sulphide)". *Chem. Eng.*, 10, CE244.
- [30] Danckwerts, P., 1979. The reaction of CO<sub>2</sub> with Ethanolamines. *Chem. Eng. Sci.*, 34, 443-445.
- [31] Versteeg, G., Van Dijk, L., Van Swaij, W., 1996. On the kinetics between CO<sub>2</sub> and Alkanolamines both in aqueous and non-aqueous solutions: An overview. *Chem. Eng. Comm.*, 144, 113-158.
- [32] Blauwhoff, P., Versteeg, G., Van Swaij, W., 1984. A study on the reaction between CO<sub>2</sub> and Alkanolamines in aqueous solutions. *Chem. Eng. Sci.*, 39, 207-225.
- [33] Bosch, H., Versteeg, G., Van Swaij, W., 1989. Gas-liquid mass transfer with parallel reversible reactions-I. Absorption of CO<sub>2</sub> into solutions of sterically hindered amines. *Chem. Eng. Sci.*, 44, 11, 2723-2734.
- [34] Versteeg, G., Van Swaij, W., 1988. On the kinetics between CO<sub>2</sub> and Alkanolamines both in aqueous and non-aqueous solutions-I primary and secondary amines. *Chem. Eng. Sci.*, 43, 3, 573-585.
- [35] Cornelisse, R., Beenackers, A., Van Beckum, F., Van Swaij, W., 1980. Numerical calculations of simultaneous mass transfer of two gases accompanied by complex reversible reactions. *Chem. Eng. Sci.*, 35, 1245-1260.
- [36] Kucka, L., Muller, I., Kenig, E., Gorak, A., 2003. On the modelling and simulation of sour gas absorption by aqueous amine solutions. *Chem. Eng. Sci.*, 58, 3571-3578.
- [37] Austgen, D., Rochelle, G., Peng, X., Chen, C., 1989. Model of vapour-liquid equilibria for aqueous acid gas-alkanolamine systems using the Electrolyte-NRTL equation. *Ind. Eng. Chem. Res.*, 28, 1060-1073.
- [38] Cheng, S., Meisen, A., 1996. Predict amine solution properties accurately. *Hydrocarbon Processing*, Feb. P81-84.

- [39] Chang, H., Shih, C., 2005. Simulation and optimization for power plant flue gas CO<sub>2</sub> absorption-stripping systems. *Sep. Sci. Technol.* 40, 877-909.
- [40] Reddy, S., 2008. Econamine FG plus<sup>SM</sup> technology for post-combustion CO<sub>2</sub> capture. Presentation of the 11<sup>th</sup> meeting of the international post-combustion CO<sub>2</sub> capture network, Vienna, Austria.
- [41] The united state department of energy, 2002. Evaluation of fossil fuel power plants with CO<sub>2</sub> recovery. Contract no. DE-AM26-99FT40465 between NETL and CTC, subcontract no. 990700362 between CTC and Parsons Infrastructure and technology group Inc.
- [42] Steeneveldt, R., Berger, B., Torp, A., 2006. CO<sub>2</sub> capture and storage closing the knowing-doing gap. *Chem. Eng. Res. Design*, 84 (A9), 739-763.
- [43] Damen, K., 2007. Reforming fossil fuel use: The merits, costs and risks of carbon dioxide capture and storage. PhD thesis, Utrecht university, Netherlands.
- [44] Jansen, D., 2007. Overview European CCS activities and R&D work at ECN. CCS workshop RITE, Kyoto, Japan.
- [45] Gale, J., 2007. CCS summer school.
- [46] Eurostat, 2008. European statistics webstie: <http://epp.eurostat.ec.europa.eu>.