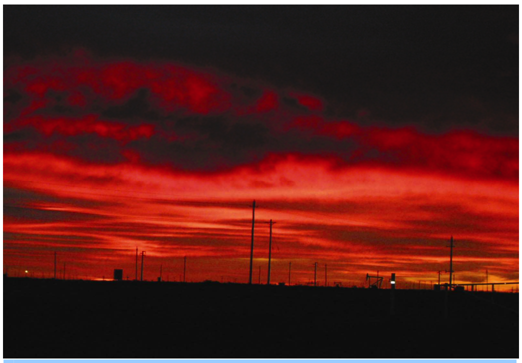

Carbon Capture and Storage in Industrial Applications:

Technology Synthesis Report
Working Paper - November 2010

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Disclaimer

This document represents work in progress and is intended to generate comment and discussion. It is not a fully polished publication. The views expressed herein are those of the authors and do not necessarily reflect the views of the United Nations Industrial Development Organisation and its partners.

Acknowledgments

This carbon capture and storage (CCS) technology synthesis report is the collective effort of a large number of organisations. The Norwegian Ministry of Petroleum and Energy and the Global CCS Institute funded the project, which was coordinated by the United Nations Industrial Development Organisation (UNIDO). The International Energy Agency (IEA) supplied most of the data used in the document. The IEA Greenhouse Gas R&D Programme and MASDAR provided substantial inputs and MASDAR and Shell hosted meetings on the work in Abu Dhabi and Amsterdam, respectively.

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Foreword

Currently direct industrial carbon dioxide (CO_2) emissions account for one third of total global energy use and for 40% of process CO_2 emissions (IEA Energy Technology Perspectives 2010). Industrial energy use and CO_2 emissions are projected to further grow in the coming decades. The processes in industry are diverse, and so are the options to reduce emissions, now and in the future.

In industry, there are two situations in which CCS can be demonstrated and applied early. First, as many industrial CO_2 emissions are inherent to industrial processes, it is technically and economically more difficult to reduce these emissions in industry than in other sectors. In such cases, CCS - as a mitigation option in industry - becomes one of the only options for large scale emissions reductions. Second, some industries vent high-purity CO_2 into the atmosphere. Such'pure'sources of CO_2 are relatively cost-effective to capture and could therefore represent early opportunities for CCS to be demonstrated. For deep emission cuts, CCS is a key emissions abatement option in industry, in addition to energy efficiency measures. However, the vast majority of research and development (R&D) and demonstration funds as well as policy efforts for CCS are aimed at the power sector.

Currently, there are few incentives for CCS from industrial CO_2 sources, even for the low-cost options. In the short term and in some regions, enhanced oil recovery (EOR) can provide a financial incentive to capturing and injecting CO_2, in a project, and therefore act as a"market pull"for developing CO_2 capture technology. Policy for industrial CO_2 reduction in industry is more challenging than in the power sector with its domestic focus, because industry more often operates on a global market, facing global competition. The implementation of CCS-policies in one country may cause companies to relocate their operations to countries without such policies. Thus, the industry sector requires international agreements on policies and measures to prevent such carbon leakage and relocation.

Industrial CO_2 streams are typically smaller than coal power plant CO_2 streams. While the smaller scale may raise the cost per tonne of CO_2 captured, interesting integrated process designs are under development which can lower this cost. Finally, the technologies required in industry are more diverse than in power generation and therefore need a more diverse demonstration programme.

This technical synthesis report captures the main findings drawn from five sectoral assessment reports that were commissioned by expert consultants to the CCS Industrial Sector Roadmap project, namely: high purity CO_2 sources, refineries, cement, iron and steel and biomass based; and from the reports from the workshops undertaken as part of the development of the Roadmap.

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna, 2010

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Summary for policymakers

This Technical synthesis report describes the main technology options available to the industry sectors which have the highest potential for CO_2 mitigation, since they are large emitters and have potential for the application of CCS. It provides summary descriptions, highlights case studies and provides cost estimates for research, demonstration and commercial projects being planned or developed.

The analysis has been undertaken based on the International Energy Agency´s (IEA) projection of the contribution that CCS would need to make out to cost effectively reduce greenhouse gas emissions to half of 2005 levels by 2050. The IEA´s modeling is based on their BLUE Map scenario[1]. This scenario assumes that policies are in place (such as a carbon price) to provide strong incentives for low-carbon technologies, including CCS. It is also assumed that CCS would compete in a global market of mitigation options.

The deployment of CCS in industry has a number of similar challenges as in the power industry. Unproven technology, increased energy use and the cost of innovative technology will hamper many projects. However, the heterogeneity of industrial processes means that certain early opportunities exist, whereby steams of near pure CO_2 could be captured at a relatively low cost compared to the flue gases of other energy and industrial processes. In addition to contribution to CO_2 abatement that investment in such high purity CCS projects could bring about, experience and knowledge of transport and storage of CO_2 can be accumulated, removing barriers for further CCS projects.

Demonstration plants are needed to prove the feasibility of industrial CCS, and to provide clarity concerning the cost of CCS. From a market perspective, CCS would have value by avoiding the payment of a CO_2 tax or having to acquire CO_2 emission credits, or by the sale of unneeded CO_2 credits. But such incentives are still absent or insufficient in most of the world. At present, in most potential applications of CCS in industry, the value proposition is insufficient for a viable CCS business model.

A regulatory or pricing system that creates an incentive for CCS and other mitigation options is required. If a global system is not possible, a policy framework will need to be developed to avoid the possibility of carbon leakage, whereby industrial production moves to regions with no CO_2 emission restrictions. Global sectoral approaches (i.e. policies applied to particular industrial sectors globally) could constitute one way ahead for the short term.

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[1] The IEA BLUE Map scenario is the result of a modeling exercise which identifies the most cost effective portfolio of technologies needed to achieve a reduction in GHG to half that of 2005 levels.

Introduction

Carbon capture and storage (CCS) can play a significant role in mitigating climate change. The technology is currently commonly viewed as having the greatest potential to achieve CO_2 savings from coal-fired power generation. However, much of the most promising short-term potential for CCS and half of the global economic potential by 2050 lies in industrial applications, particularly in the developing world. Industry has fewer alternatives to CCS than the power sector for achieving deep CO_2 emission reductions. This area has so far not been in the focus of discussions and therefore more attention needs to be paid to the application of CCS to industrial CO_2 sources if the full potential of CCS is to be unlocked.

Industrialisation is an essential component of economic development and the improvement of standards of living in developing countries (UN DESA, 2007; UNIDO, 2009). In emerging economies, manufacturing output has been the mainstay of economic growth and poverty alleviation, but it has also resulted in rapidly increasing energy use and environmental impacts (International Energy Agency (IEA), 2010). Industry accounted for almost 40%[2] of all CO_2 emissions in 2007. Two-thirds of these emissions were attributable to industrial activity in the developing world and this share is projected to grow in the future (IEA, 2009a). Globally, the climate change that is expected to result from increasing greenhouse-gas (GHG) emissions is likely negatively to impact on development (IPCC, 2007).

In order to prevent dangerous climate change, the Intergovernmental Panel on Climate Change (IPCC, 2007) estimates that global CO_2 emissions need to decrease by between 50% and 85% of their 2000 levels by 2050. Even if developed countries make very significant reductions in their emissions, developing countries will also have to reduce their absolute level of emissions if this outcome is to be achieved, notwithstanding the expectation that their use of fossil fuels in industry and their consumption of energy to support economic development are expected to increase (IEA, 2010).

In power and industry, with the exception of energy efficiency measures, CO_2 capture and storage is the only technology that allows for the continued use of fossil fuels while significantly reducing carbon emissions. The IEA (2010) projects that achieving a 50% cut in emissions compared to 2005 would require a reduction of 43 gigatonnes (Gt) of CO_2 in 2050. The IEA identifies the most cost effective portfolio of technologies to achieve the required emission reduction. According to this portfolio energy efficiency and the greater use of renewables would be expected to make the largest contributions to such an outcome, however CCS is expected to make a significant contribution of 19% to reduction targets. Of this 19% contribution from CCS, roughly half would be expected to come from each of the power generation and industrial sectors. If CCS is excluded from the mitigation portfolio, the global cost of achieving a 50% reduction in 2050 is also estimated to increase significantly (IEA 2009a).

CCS is a relatively new technology. Despite the fact that all existing operational demonstrations of CCS are in industry (Global CCS Institute, 2010) and that most of the

[2] Including indirect emissions from power generation.

short-term and cost-effective potential for CCS, especially in developing countries, is in respect of industrial sources of CO_2 (Zakkour et al., 2008; Bakker et al., 2009; IEA, 2009b), most studies on the potential application of CCS have focused on the power sector, in particular in relation to coal-fired power generation (IPCC, 2005; IEA, 2009b). The same imbalance in attention is reflected in the makeup of the 80 large-scale CCS demonstration projects that are currently planned or operational (Global CCS Institute, 2010).

If CCS is to make the maximum contribution to overall emission reductions, this imbalance needs to be addressed. The IEA and the Carbon Sequestration Leadership Forum in partnership with the Global CCS Institute (IEA & CSLF, 2010), in their report to the Muskoka 2010 G8 Summit, call for the identification of a larger number of projects in industrial sectors and support for the development of CCS in developing countries. If developing countries are to implement CCS in the short to medium term, specific developing country issues need to be addressed and steps need to be taken to increase awareness of the possibilities for CCS in industrial applications.

2. Objective and approach of this report

The objective of the proposed Global Technology Roadmap for CCS in Industry is to provide relevant information on actions and milestones to government and industry decision-makers, with a focus on developing countries. This report provides the technical, economic and policy background to the Roadmap.

2.1 Background to this report

This report aims to provide a technological, economic and policy underpinning for the development of a Global Technology Roadmap for CCS in Industry (for convenience referred to as "the Roadmap" in this report). The Roadmap will build on the IEA Roadmap on CCS (IEA, 2009b) that has already outlined a set of actions and milestones for CCS in the power sector and for industry as a whole. It will also build on the IEA Global Technology Roadmap for the cement industry (IEA & WBCSD, 2009). The Roadmap will focus on five main industrial sectors: high-purity CO_2 sources, iron and steel, cement, refineries and biofuel production.

The objectives of the Roadmap are:

To provide stakeholders with a vision for the development of the application of CCS in industry up to 2050. The CCS Industrial Sector Roadmap will provide a vision for the short and medium term. It will help pave the way towards the progressive contribution of CCS to low-carbon industrial growth in both industrialised and developing countries.

To strengthen the capacities of various stakeholders with regard to industrial CCS. The Roadmap will provide a common context for CCS experts and CCS stakeholders in developing countries. Strengthened collaboration will particularly benefit developing countries with energy intensive industries. Future climate change mitigation agreements may well depend on developing countries decoupling their GHG emissions growth from their economic growth. It is therefore essential that those countries participate fully in efforts related to the application of low-carbon technologies.

To inform policymakers and investors about the potential of CCS technology. The Roadmap will provide insights that will assist policymakers to evaluate the benefits of CCS technology and better informed decision making. It will also provide investors with an objective assessment of the potential for CCS in industry to help underpin investment decision making.

The development of the Roadmap is led by the United Nations Industrial Development Organisation (UNIDO) in partnership with the Global CCS Institute (funders), the Norwegian Ministry for Petroleum and Energy (funders), the IEA, the IEA Greenhouse Gas R&D programme and the Energy research Centre of the Netherlands (ECN).

As part of the Roadmap process, two workshops were held in 2010. The first workshop, hosted by MASDAR (Abu Dhabi Future Energy Company) in Abu Dhabi, discussed a set of sectoral assessments. The second workshop, hosted by Shell in Amsterdam, reviewed the gaps and barriers to the wider application of CCS in industry and identified potential value chains and specific projects that might be pursued. Summaries of the two workshops are included in Annex I and II of this report.

2.2 Objective of this report

As part of the Roadmap process, in-depth sectoral assessments have been developed for the five sectors that will be covered in the Roadmap, *i.e.* high-purity CO_2 sources, iron and steel, cement, refineries and biofuel production. These sectoral assessments have provided valuable information at a technically detailed level. This report synthesises this information in such a way as to enable and facilitate the subsequent drafting of the Roadmap itself.

2.3 Scope of this report

This report addresses the industrial sectors that are significant emitters of CO_2 and which offer the most promising potential for the early application of CCS, especially in developing countries. It focuses on applications which: offer a prospect of relatively easy capture of large volumes of CO_2; provide good projections for cost-effective deployment in the coming decades; have the potential to make a significant contribution to global emission reductions; and are consistent with long-term sustainable development strategies in developing countries.

2.3.1 Sectors and technologies

The sectors, sources and technologies to be covered by the Report are described in the following table::

Table 2.1 sectors, sources and technologies presented in the report

Sector	Production process	Capture technology
High-purity industrial sources	Natural gas processing (onshore/offshore)	Existing industrial gas separation techniques[3]
	Coal-to-liquids (CtL)	
	Ethylene oxide production	
	Ammonia production	
Iron and steel	Blast furnace (pig iron)	Top gas recycling (TGR) Oxyfuel blast furnace
	Direct reduction of iron (DRI)	Pre combustion (gasification) + PSA[4], VPSA[5] or chemical absorption

[3] There are a number of existing gas separation techniques such as membrane separation, chemical absorption using solvents including amine-based solutions monoethanolamine (MEA), methyldiethanolamine (MDEA) and hot potassium carbonate based processes, physical sorbent based process, pressure swing absorption (PSA) and cryogenic separation process. Selection of the appropriate process is dependent on a number of factors including end use specification, gas inlet pressure, cost, size, weight and maintenance needs (Zakkour & Cook, 2010).

[4] Pressure swing adsorption

[5] Vacuum pressure swing adsorption

Sector	Production process	Capture technology
	FINEX technologies	PSA[6]
	The HIsarna process	PSA or VPSA
Cement	Kiln/calcination	Post combustion technology using chemical solvents, Oxyfuel technology
Refineries	Hydrogen production	Chemical absorption, PSA
	Hydrogen gasification residues	Pre combustion (gasification) + chemical absorption
	Fluidised catalytic cracking	Post combustion using chemical absorption, or oxyfuel technology
	Process heat	Post combustion using chemical absorption, or oxyfuel technology
Biomass conversion	Synthetic natural gas	Pre combustion (gasification) + chemical absorption
	Ethanol production	Dehydration only
	Hydrogen production from biomass	Pre combustion (gasification) + chemical absorption
	Black liquor processing in pulp and paper manufacturing	Pre combustion (gasification) + chemical absorption

2.3.2 Capture technologies

Most applications of CCS in industry – for example for boilers, turbines, iron & steel furnaces and cement kilns - require a capture step to concentrate relatively dilute streams of CO_2 to a level that will enable economic transportation and storage. There are some industry processes that already produce an almost pure CO_2 stream.

Capture technologies fall into three main categories:

- Post combustion capture – where the flue gases exiting a combustion plant are treated using chemical or physical sorbents to selectively remove CO_2 from the gas mixture. The sorbents are then regenerated, using for example steam, to produce a concentrated CO_2 stream from a stripping column.

- Pre-combustion capture – where input fossil fuels or biomass is gasified to a synthetic fuel (synfuel) mixture, which is then subject to water-gas shift reaction and subsequent gas clean up to separate the hydrogen and CO_2 produced. The hydrogen is used as the input fuel to the combustion process. The CO_2 is available in a concentrated form for potential compression, transport and storage.

- Oxyfuel technologies – where the combustion process takes place in a relatively pure oxygen environment, resulting in flue gases with high concentrations of CO_2,

[6] Understood a most suitable capture technology (Posco, 2008).

which after particulate removal and flue gas desulphurization the CO_2 is suitable for transport and storage.

A number of other industrial processes depend on the removal of CO_2 as part of the process itself. In many of these processes, the CO_2 arises from processes other than the combustion of fossil fuels. They result in highly-concentrated CO_2 offgases. These sources of high-purity CO_2 offer potentially significant early opportunities for CCS in their own right and are further explored in section 3.1.

In this analysis, the early opportunities that are presented by the industrial sources of high-purity CO_2 are for this analysis grouped in one sector. The refinery, cement and iron and steel sectors are included because they are currently large emitters of CO_2 and are expected to remain so in the future. The biofuel production sector is included because, with CCS, it has the potential to enable the production of energy with net negative carbon impacts and is projected to be a significant source of carbon emission reductions in the future.

2.3.3 Transport and storage

The application of CCS in industry, as in any other sector, depends on transporting the CO_2 from a source (or sources) to a suitable storage site, and then storing it. An extensive global roadmap on the transport and storage components of the CCS value chain has already been completed by the IEA (2009b). In this report, the combination of high-purity CO_2 sources with revenue-generating storage options such as Enhanced Oil Recovery (EOR) and Enhanced Coal-Bed Methane recovery (ECBM) is taken to offer potentially early options. Particular attention is given to EOR as a relatively mature technology that provides a significant incentive for CO_2 capture and could become relevant to oil-producing developing countries.

In relation to transport, the main implication for industrial CCS is the need to meet required gas specifications. The industrial sources of CO_2 location and the proximity to storage reservoirs may also be a factor. These issues are addressed later in the report, together with a more general brief summary of important transport and storage issues relevant to industry.

2.4 Approach

Information relevant to CCS, such as current emissions, capture techniques, costs, cost reduction prospects and global deployment potentials, is less readily available in respect of the industrial sector than in relation to the power sector. Data are often scattered across the literature, and can be based on different assumptions or reported in slightly different units. For many industrial technologies, no actual CCS installations exist, so technological and economic data are estimates rather than real costs. In addition, much data are not in the public domain given their commercial sensitivity. Furthermore, economic figures in this report depend on the basic assumptions of the calculations, including fossil fuel, electricity and carbon prices which incorporate uncertainties to the estimations.

The sectoral assessments (referenced in section 9.1) provide extensive information on the technology, costs and prospects of the five industrial sectors addressed in this report. Chapter 3 of this report synthesises the information in these sectoral assessments. The technical information and cost data are organised by CO_2 source type or capture technology. Each sector describes several types of CO_2 source and several types of capture technology. For example, the cement sector analysis includes oxyfuel and carbonate looping technologies, and the high-purity source analysis includes natural gas processing installations and coal-to-liquid (CtL) plants. Technology and cost data are based as far as possible on a set of standard variables and parameters. The largest constraint on the consistency of this analysis is the availability and quality of the relevant data.

Chapter 4 reviews the transport and storage considerations relevant to the application of CCS in industry. Chapter 5 addresses the current and projected future CO_2 emissions and the emission reduction potentials of the industrial sectors under review. Current emissions are derived from the sectoral assessments and are based on a range of data sources. Most projections and emission reduction potentials are based on data provided by the IEA in their Energy Technology Perspectives (2010) and Energy Technology Transitions in Industry (2009a) publications.

Chapters 6 and 7 are based on information and insights arising from the Abu Dhabi and Amsterdam workshops and on a study of the relevant literature. Chapter 6 looks at possible policy measures to enable CCS in industrial applications. In chapter 7, specific attention is given to the CCS value chain in industrial applications and the business models and propositions that may facilitate industrial CCS. Chapter 8 concludes the report by identifying a range of gaps in current knowledge that need to be filled and proposing actions that may be taken to accelerate the adoption of CCS in industrial applications.

3. Technology characterization

The heterogeneity of industrial processes poses challenges but also opportunities for CCS development. High purity CO_2 streams can be identified in a number of industrial processes, whereby the CO_2 needs minor treatment prior to compression, transport and storage. Conversely, beyond the burning of fossil fuels for heating purposes, CO_2 plays an integral role in the conventional production processes of cement and iron and steel. In a number of cases, capturing 'process CO_2' will require the reengineering of certain established and reliable production techniques.

3.1 High-purity CO_2 sources

A number of processes in industry and fuel production result in a high purity, high concentration CO_2 off-gas, which can be readily dehydrated, compressed, transported and stored. These processes include natural gas processing, hydrogen production (including for the production of ammonia and ammonia-based fertilisers), synthetic fuel production (*e.g.* CtL, gas-to-liquids (GtL)) and a range of organic chemical production processes (*e.g.* ethylene oxide production). All the industrial process mentioned above produce streams of waste gas with CO_2 concentrations of between 30% to 100% (further detail presented in table 3.1). On a global scale, the CO_2 emissions from these activities are relatively modest when compared to emissions from other activities (Figure 3.1). But these CO_2 streams offer particularly important potential for 'early opportunity' CCS demonstration projects. The processes that offer the best prospects for such projects are discussed in more detail in the following sections.

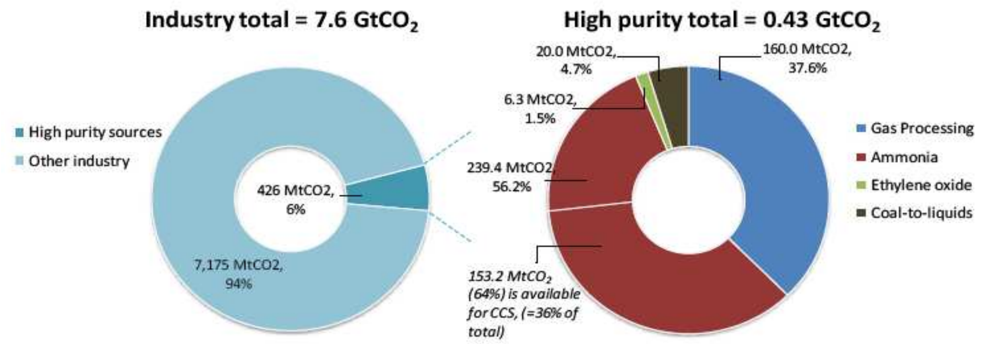

Figure 3.1 Global industrial emissions and high-purity sources[7]

3.1.1 Natural gas processing

Natural gas typically undergoes processing before it is exported to markets. This can involve a range of processes from the simple quick expansion (flashing) of lighter gaseous phases through to more complex treatments including liquefaction and conversion to liquid fuels (GtL). Raw natural gas has a CO_2 content of between 2% and

[7] Industry total excludes emissions from refining.

70% by volume. This needs to be reduced to below 2% for gas distribution grids, and no higher than 0.2% if the gas is to be converted to liquefied natural gas (LNG) or used for GtL production. The basic natural gas processing (NGP) configuration for removing CO_2 from natural gas, termed 'gas sweetening', is shown in Figure 3.2. The process results in an offgas which comprises between 96% and 99% CO_2, which is currently immediately vented.

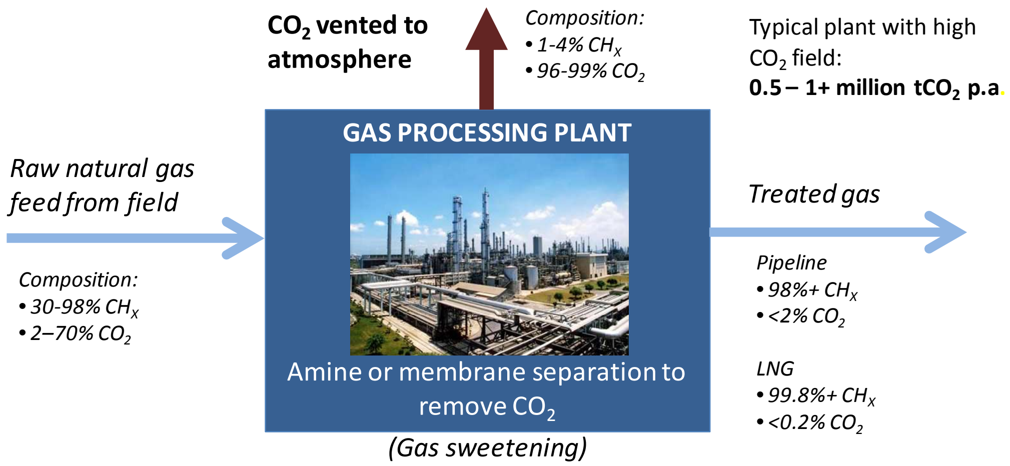

Figure 3.2 Natural gas sweetening configuration

3.1.2 Hydrogen production

Globally, around 45 - 50 million tonnes (Mt) of hydrogen are produced each year, the majority of which is produced using fossil fuel feedstocks (Hydrogen Association; Evers, 2008). Around half is used to produce ammonia and around a quarter is used for hydrocracking in petroleum refining. The balance is used to make methanol and in other industrial applications including CtL production. The processes used to produce hydrogen from fossil fuel or biomass feedstocks include steam reforming, auto-thermal reforming (ATR), partial oxidation (POX), and gasification. The choice of technology in any particular context depends on economics, the need for plant flexibility and the most appropriate feedstock source. A generalised schematic of the industrial hydrogen production process is shown in Figure 3.3.

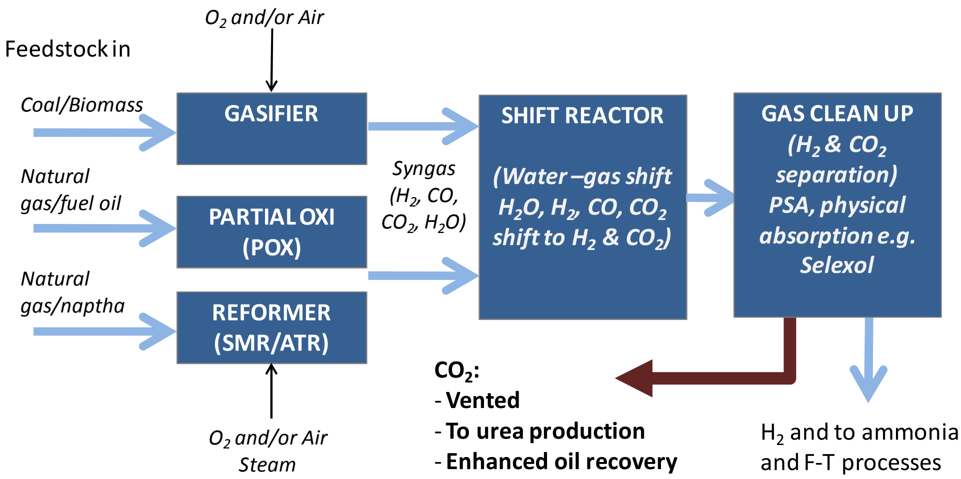

Figure 3.3 Generalised process flow for industrial hydrogen and syngas production

There are number of hydrogen production processes, via gasification, partial oxidation or steam reforming. All routes involve the application of solid fuel gasification or natural gas reforming technologies to produce a syngas which is purified via a gas clean-up step to produce a reformed syngas mix or hydrogen (H_2) for use as feedstock for the production of various final products. The water-gas shift reaction process converts syngas to a mixture of CO_2 and hydrogen in varying amounts. In the case of hydrogen production, the CO_2 must be removed to produce a purified stream, whilst for synthetic fuel production, the water-gas shift conversion and gas clean-up steps are carefully controlled to optimise the H_2/CO ratio. The hydrogen production processes here are also used in ammonia (and fertiliser) production, and for the manufacture of synthetic transport fuel (including coal-to-liquids), DiMethly Ether (DME) and methanol.

3.1.3 Ethylene oxide production

Ethylene oxide is a colourless flammable gas produced by direct oxidation of ethylene in the presence of a silver catalyst. Because of its special molecular structure, ethylene oxide easily participates in the addition reaction, allowing it to easily polymerize into larger compounds. It therefore has a range of uses in the chemical sector. During the absorption stage of the production process (see Figure 4.4), a stream of gas comprising of between 30-100% CO_2 by volume is removed and vented. In addition to water, small quantities of acetaldehyde and traces of formaldehyde are other byproducts of the process, and the presence of these chemicals may affect the selection of the most suitable capture technology.

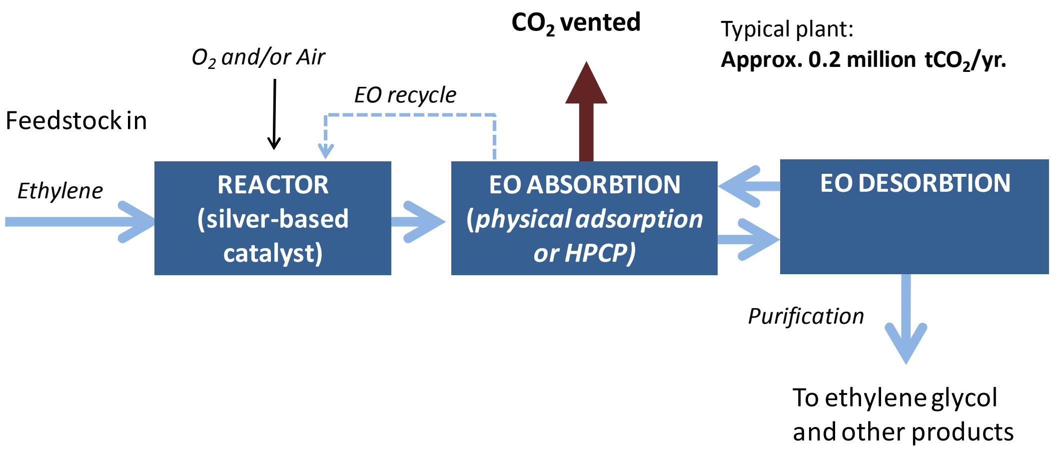

Figure 3.4 Generalised schematic of ethylene oxide (EO) production by direct oxidation

The data on the rates of CO_2 generation in the production of ethylene oxide are extremely limited. The stoichiometry of the process suggests it is produced at a ratio of 6/2 ethylene oxide/CO_2, *i.e.* that it produces about a third as much CO_2 as ethylene oxygen. If so, this would suggest that the process produces globally around 6.2 Mt of high purity CO_2 every year. Other literature suggests that the concentration of CO_2 in the reactor gas is around 8% (IPCC, 2005), which would suggest that the process produces around 1.5 Mt of high purity CO_2 a year.

3.1.4 Ammonia production

Production of hydrogen using processes described in the previous section is the first step in the manufacture of ammonia in the Haber-Bosch process. The Haber-Bosch process involves the synthesis of hydrogen with gaseous nitrogen using an iron or ruthenium enriched catalyst at high temperature and high pressure.

Around 80% of all ammonia manufactured worldwide is used to produce inorganic nitrogen based fertilisers. Other important uses of ammonia include the manufacture of nitric acid, nylon and other polyamides, refrigerants, dyes, explosives and cleaning solutions.

The challenges associated with storing and transporting hydrogen mean that ammonia and fertiliser producers manufacture hydrogen onsite. The International Fertiliser Association (IFA) reports that the predominant source of hydrogen for ammonia production is natural gas, although coal also forms a significant proportion, especially in China. In terms of the preferred hydrogen production method, a variety of different techniques as described in the previous section are used, with no publicly available data on the different types of plants in operation today.

The International Fertiliser Association reports that the industry already utilises around 36% of the CO_2 removed from the syngas in the gas clean-up step (IFA, 2010b). Of this, around 33% is used for the synthesis of ammonia into urea, whilst the remaining 2.2% is sold on to other uses (5.2 $MtCO_2$), such as CO_2 use for enhanced oil recovery (IFA, 2010b; see Figure 13; Section 3.1.2).

3.1.5 Capture technologies for industrial gas separation

The underlying production processes involved in all of the activities described above require the application of a CO_2 removal step to purify intermediate or final products. The removal of CO_2 from these streams is more straightforward than the capture of CO_2 from flue gases because of the smaller volumes, lower temperatures and higher pressures and partial pressure of CO_2 in the gas streams requiring separation (Table 3.1).

Table 3.1 Typical properties of gas streams that are subject to CO_2 separation

Activity	Source stream	CO_2 concentration (%; inlet)	Pressure (MPa[1])	Partial pressure (MPa[1];CO_2)	CO_2 concentration (%; outlet)
Gas processing	Reservoir gas feed	2 - 65	0.9-8	0.05-4.4	95-100
Ammonia	ATR/Steam Methane Reforming/Gasifier	15 - 20	2.8	0.5	30-100
CTL	Gasifier	10 - 15	2.8	0.5	95-100
Ethylene oxide	Reactor	8	2.5	0.2	30-100

Source: based on IPCC, 2005, drawn from Chauval and Lefebre, 1989; Maddox and Morgan, 1998; IEA GHG, 2002
Note 1: Megapascal

The technologies predominantly used to separate CO_2 from gas mixtures include:

- Membrane separation;
- Chemical solvents, including amine-based solutions (*e.g.* monoethanolamine (MEA) and methyldiethanolamine (MDEA) and hot potassium carbonate based processes (*e.g.* the Benfield™ process);
- Physical sorbents (*e.g.* Selexol™, Rectisol);
- Pressure swing adsorption (PSA); and
- Cryogenic separation.

Selection of the appropriate process is dependent on a number of factors including end use specifications, gas inlet pressures, cost, size, weight and maintenance needs of the equipment.

Some of these gas treatment processes create streams that contain a number of trace contaminants such as elemental nitrogen, water, carbon monoxide and/or methanol. These may need to be removed to avoid corrosion during transport and injection.

3.1.6 Costs of CCS deployment in the high-purity sector

Capturing the CO_2 from these high purity sources is relatively low cost, compared to the cost of separating and capturing CO_2 from flue gas streams. Additional costs are likely to be limited to the cost of acquiring and running compressors, dryers, pumps and coolers, and in some cases on-site power generation capacity to meet compressor power requirements. The cost of transporting and storing CO_2 from these sources may also be relatively low, given that candidate plants are typically in the proximity of industrial complexes or coastal locations; some of which will have good access to potential offshore storage sites. Some ammonia and steam methane reforming (SMR) hydrogen production facilities are located close to natural gas feedstock reservoirs and capture from some gas processing facilities may offer the potential for *in situ* CO_2 injection.

Table 3.2 CCS costs from high-purity CO_2 sources

Source	Cost estimate (USD/tCO_2)	Comments	References
LNG plant	9	Retrofit to existing LNG plant; compressed gas injected into a depleted gas field.	IEA GHG (2008a) all capital costs based on 2012 prices and discounted at 12.5% over 21 years; cost of transport and storage assumed to be paid as gate fee by the capture plant operator. This reflects average costs across a range of developing country gas fields and pipeline transport distances including *in situ* injection
Offshore NGP (deep water)	31	Retrofit to existing deep water NGP facility; compressed gas injected into a depleted gas field.	
Offshore NGP (shallow water)	18-21	Range indicates difference in capital cost between retrofit (higher cost) and new-build (lower cost) NG plant; compressed gas injected into a depleted gas field.	
Onshore NGP	16-19	Range indicates difference in capital cost between retrofit (higher cost) and new-build (lower cost) NG plant; compressed gas injected into a depleted gas field.	
Ammonia	4-47	Different figures indicate capture from pure CO_2 stream (lower cost) and flue gas (8% CO_2 content, higher cost); data exclude cost of compression, which would add c. USD 10-15/tCO_2.	Hendriks, C. *et al* (2004) capital costs discounted at 10% over 25 years; EUR/tCO_2 figures converted to USD/tCO_2 on basis of 1 EUR: 1.3 USD
Hydrogen	15	Capture costs only	IPCC, (2005)
Ethylene oxide	-	No known cost studies	-
Coal-to-Liquids	‹ 25	Cost analysis covering liquid-only and poly-generation CtL production using Selexol™ and MEA capture indicates CCS is cost effective with a carbon tax of USD 25/tCO_2 at oil price of USD 100 per barrel (bbl)	Matripraganda. and Rubin (2009)

3.1.6 Current status of CCS in the high-purity sector

The capture and storage of CO_2 from high-CO_2 content natural gas fields presents some of the least cost 'earliest opportunities' for the large-scale deployment of integrated CCS projects in a number of world regions. Gas processing facilities typically have access to *in situ* or nearby storage sites with known geological characteristics. And there is a considerable skills and knowledge base within the oil and gas industry able to undertake large commercial-scale projects. There are currently five fully integrated, commercial-scale CCS projects in operation worldwide, of which four are associated with the separation of CO_2 from natural gas and one is associated with the separation of CO_2 from coal-based synthetic natural gas (SNG) production.

The Sleipner and Snøhvit projects (Norway) and the In Salah (Algeria) project involve the stripping of CO_2 from high-CO_2 content natural gas to achieve sales-grade quality natural gas. The CO_2 is stripped, collected and stored securely in underground geological formations. The Rangely project (United States) uses CO_2 captured from natural gas processing at the ExxonMobil LaBarge gas plant in Wyoming, and uses the CO_2 for EOR and storage at the Rangely field in Colorado.

CO_2 is routinely captured from ammonia plants for use in the production of urea and nitro-phosphates, often within the same integrated plant. Where there is no demand for the CO_2 stream for urea production or from other nearby industrial production activities, the emissions are normally vented to the atmosphere. Exceptionally, the Enid Fertilizer plant in Oklahoma, United States, operated by the Koch Nitrogen Company, has captured over 600000 tCO_2 a year since 2003 for use in EOR. And a CCS project is being proposed at the Coffeyville Resources ammonia and urea ammonium nitrate production facility, based on petroleum coke gasification, in Kansas. The project will capture around 600000 tCO_2 a year for use in domestic EOR and/or for geological storage.

3.2 Cement

Cement production is an energy intensive process, and emits a substantial amount of CO_2. The most energy intensive process in the production of cement is clinker burning. This involves gradually heating calcium carbonate (Ca_2CO_3) with small amounts of additives in a kiln. At approximately 900°C, calcination occurs and CO_2 is released from the calcium carbonate. With additional heating, the process reaches a temperature of around 1450ºC, at which point the calcium oxide reacts and agglomerates with silica, alumina and ferrous oxide to form cement clinker (IEA, 2009a).

3.2.1 Post-combustion CCS technologies

Post-combustion CCS options would not require fundamental changes in the clinker-burning process (Figure 3.5). These could be applied both to new kilns and as retrofits to existing plants. The most promising current technology options involve the chemical absorption of CO_2 from flue gases using amines, ammonia and other chemicals. Chemical absorption with alkanolamines is considered to be a proven technology and has an extensive history in the chemical and gas industries, although at a much smaller scale than would be necessary in the cement industry (IEA, 2009a).

All current pilot and demonstration projects for post-combustion capture both in industry and in the power sector are based on chemical absorption, mainly through the use of amine based systems (ECRA, 2009a). These projects provide the most reliable estimates of the costs and energy requirements of post-combustion capture in the cement industry. These estimates are used in the analysis presented in this report.

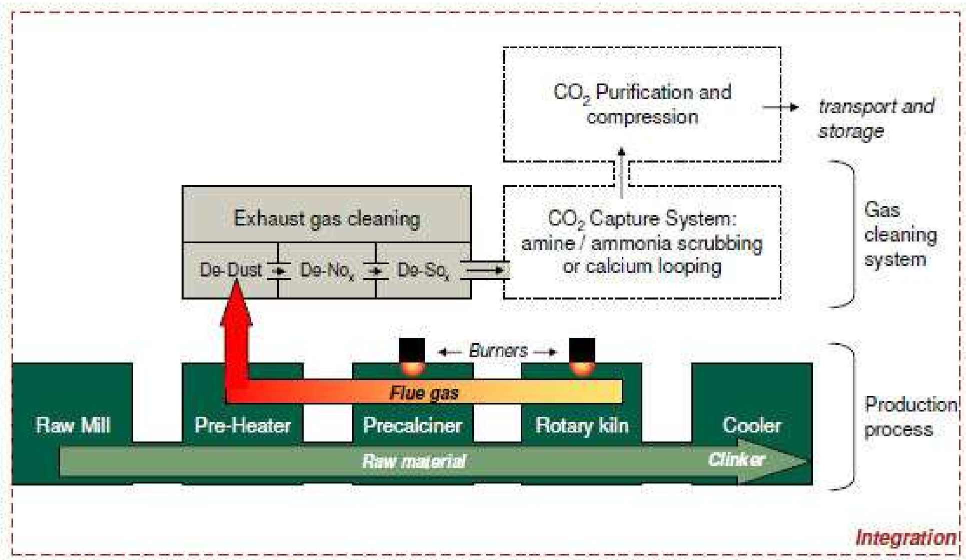

Figure 3.5 Generalised schematic for post-combustion technology applied at a cement plant (LEK, 2009)

3.2.1.1 Cost estimations

The IEA GHG (2008b) undertook a detailed techno-economic evaluation of the deployment on a new-build cement plant in Europe, featuring post-combustion CO_2 absorption using monoethanolamine (MEA). Table 3.3 summarises the key figures. The plant used in the modeling was assumed to be a 5-stage preheater with precalciner dry process cement plant, reflecting the best available technique (BAT) for new build and major upgrades. The results are derived from process modeling using simple performance equations taken from industry data.

Table 3.3 Cost estimations for post-combustion capture at a cement plant (IEA GHG, 2008b)[8]

Parameter	Unit	Without CCS (European scenario)	With post-combustion capture (European scenario)	With post-combustion capture (Asian developing country scenario)
Total investment costs	€M	263	558	647
Net variable operating costs	€M/y	17	31	97
Fixed operating costs	€M/y	19	35	50
Cost tCO_2/avoided	€/t	n/a	107.4	58.8
Costs per tonne product	€/t	65.6	129.4	72.2
Cost tCO_2/captured	€/t	n/a	59.6	Not reported

Assumptions:

Key assumptions	Unit	European Plan	Asia Developing Country Plant
Plant size (cement)	Mt/year (y)	1	3
Emission factor	tCO_2/t cement	0,728	0,728
Plant lifetime	y	25	25
Discount rate	%/annum	10	10
Cost of capital	%/annum	10	10
Load factor	%	90 (60, 1st year)	90 (60, 1st year)
Capture rate	%	85%	85%
CO_2 Compression	bar	110	110
Coal price	€/t	65	65
Pet coke price	€/t	80	80
Power price	€/megawatt hour (MWh)	50	50
CO_2 emissions ext. power	tCO_2/MWh	0.52	0.52

The primary evaluation was based on a 1 Mt/y green-field plant sited in the United Kingdom, adjacent to a limestone quarry. As part of a sensitivity analysis, an Asian developing country scenario based on a 3 Mt/y plant was also developed. The larger plant was considered typical for the Asian cement industry. The Asian developing country scenario results shown in Table 3.3 were based on the following assumptions:

- Equipment costs estimated at 60% of European costs.
- Labour costs estimated at 50% of European costs.
- Administration, rates and insurance costs estimated at 50% of European costs.
- All fuel and raw materials costs, and plant performance, assumed to be the same as in Europe.

[8] The costs include compression, but not transport and storage. The cost/tCO_2 avoided takes into account emissions associated with imported and exported power.

3.1.1.2 Energy requirements

In post-combustion capture, the regeneration of the amines used in the chemical absorption process will result in a substantial increase in specific thermal energy consumption compared to non-CCS cement production. To provide the low-pressure steam needed for amine regeneration and to meet the demand for additional electricity for compressing the captured CO_2 for transport, it is expected that a small combined heat and power (CHP) installation would have to be built close to the cement plant.

ECRA (2009a) provides estimates of the impact of the application of post-combustion CCS technology on energy consumption in a plant producing 2 Mt of cement a year (Figure 3.6). GNR[9] data for the current state-of-the-art cement production technology (dry process with precalcining) indicate that the weighted average for specific thermal energy consumption in 2006 was 3 382 megajoules (MJ) per tonne of clinker and that the global weighted average for specific electrical energy consumption was 111 kWh/t of cement. ECRA (2009a) estimates that these figures would rise by 1000 - 3500 MJ/t clinker and 50-90 kWh/t cement if CO_2 was captured post-combustion.

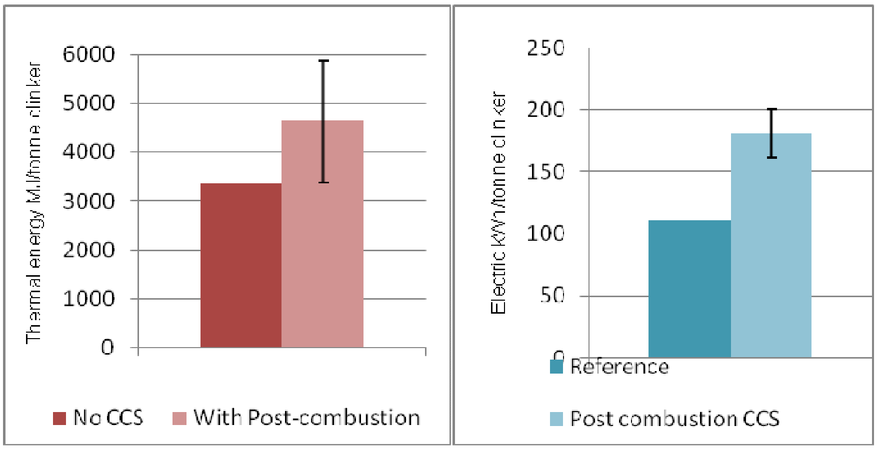

Figure 3.6 Energy consumption for post combustion CCS in the cement sector (data from ECRA, 2009a)[10]

3.2.2 Oxyfuel technologies

Oxyfueling uses oxygen instead of air in the cement production process to generate an almost pure CO_2 stream. Oxyfueling would require substantial alterations to existing cement plants, making it less suitable for retrofitting than post-combustion technologies.

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[9] "Getting the numbers right" (GNR) is a programme by the Cement Sustainability Initiative, and involves the collection of data from over 900 cement plants worldwide.
[10] The bars represent ranges of uncertainty.

Two main CCS options for oxyfueling within the cement industry have been proposed:

- Partial capture – fuel would be burned in an oxygen/CO_2 environment with flue gas recycling in the pre-calciner but not in the rotary kiln. This would enable the recovery of a nearly pure CO_2 stream at the end of one of the dual pre-heaters (Figure 3.7).

- Total capture – fuel would be burned in an oxygen/CO_2 environment with flue gas recycling in both the pre-calciner and the rotary kiln. This would enable the recovery of a nearly pure CO_2 stream from the whole process (Figure 3.8).

IEA & WBSCD (2009) considers that oxyfuel technology could be commercially available by 2025.

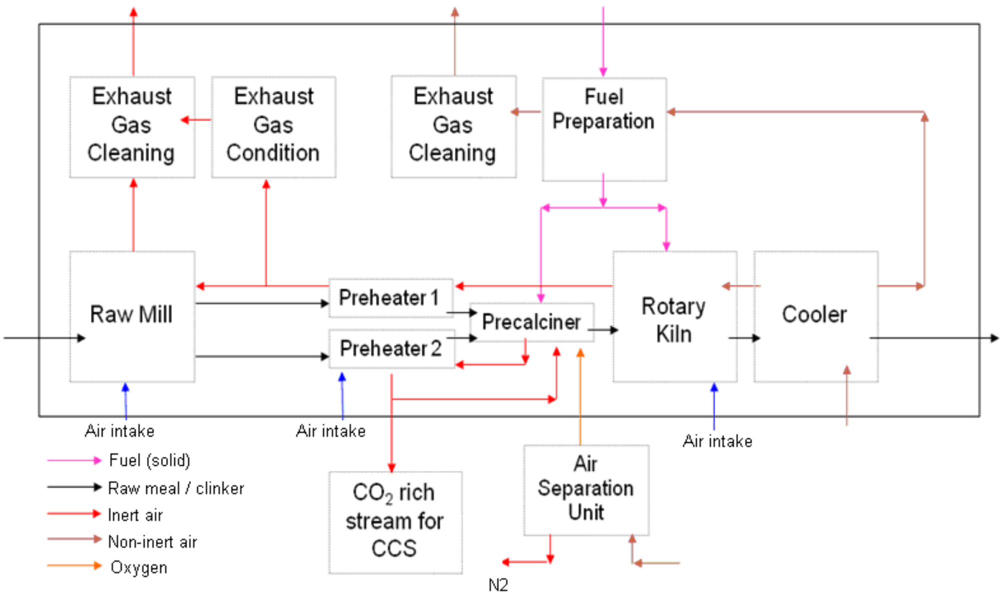

Figure 3.7 Process diagram of a partial capture oxyfuel cement plant design

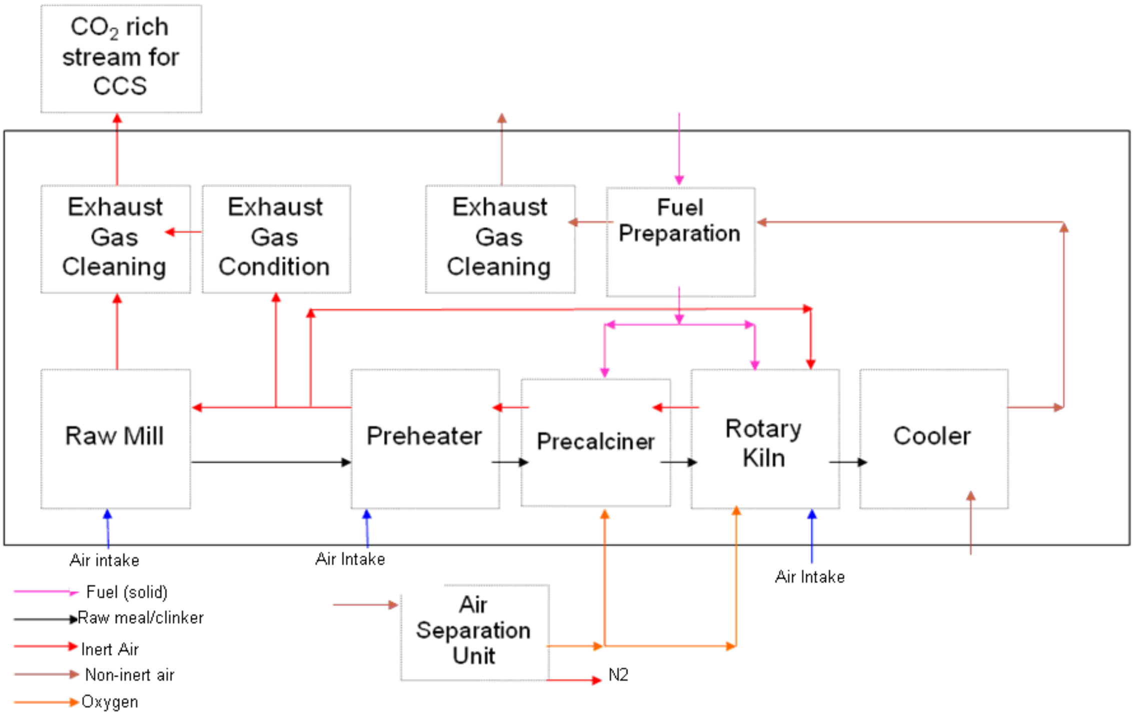

Figure 3.8 Process diagram of a full capture oxyfuel cement plant design

3.2.2.1 Cost estimations

Table 3.4 summarises the figures presented by IEA GHG (2008b) for the costs of a cement plant with partial capture oxyfuel technology capturing 52% of the plant's total emissions. As with the post-combustion study, estimates for both a European and an Asian developing country scenario were produced. With the exception of the capture rate, the oxyfueling model analysis adopted identical assumptions to those used in the post-combustion evaluation shown attached to Table 3.3.

Table 3.4 Cost estimates for cement plant with partial oxyfuel capture (IEA GHG, 2008b)[11]

Parameter	Unit	Without CCS (European scenario)	With oxyfuel capture (European scenario)	With oxyfuel capture (Asian developing country scenario)
Total investment costs	€M	263	327	Not available
Net variable operating costs	€M/y	17	23	Not available
Fixed operating costs	€M/y	19	23	Not available
Cost tCO_2/avoided	€/t	n/a	42.4	22.9
Costs per tonne product	€/t	65.6	82.5	46.4

[11] The costs include compression, but not transport and storage. The cost/tCO_2 avoided takes into account emissions associated with imported and exported power.

Cost tCO_2/captured	€/t	n/a	36.1	Not reported

3.2.2.2 Energy Requirements

Oxyfuel technologies are predicted to consume much less thermal energy than post-combustion capture technologies and therefore to offer the potential to achieve larger CO_2 reductions. But oxyfueling will significantly increase electricity demand, primarily due to the electricity needed to operate the air separation unit which will require approximately 200-240 kWh/tO_2 (IPCC, 2005). ECRA (2009a) estimates that thermal energy use would rise by 90-100 MJ/t clinker and electricity consumption by 110-115 kWh/t clinker in a oxyfueled cement plant.

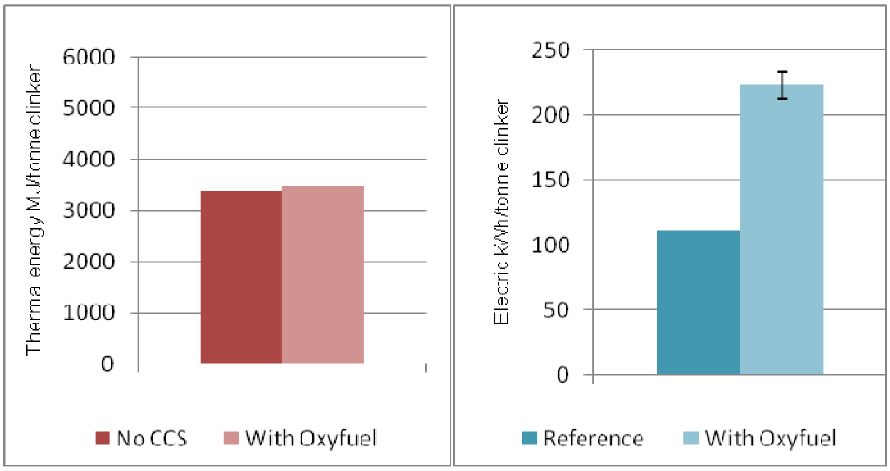

Figure 3.9 Energy consumption for oxyfuel CCS in the cement sector (data from ECRA, 2009a)[12]

3.2.3 Carbonate looping

Carbonate looping is an adsorption process in which calcium oxide is put into contact with the combustion gas containing CO_2 to produce calcium carbonate. This is a technology currently being assessed by the cement industry as a potential retrofit option for existing kilns and in the development of new oxy-firing kilns (IEA & WBSCD, 2009).

Carbonate looping involves two stages: the adsorption of CO_2 with low partial pressure (carbonation); and the regeneration of the sorbent and desorption of CO_2 in a CO_2 enriched atmosphere (calcination) as shown diagrammatically in Figure 3.10. Carbonate looping is understood to be capable of reducing the CO_2 content of the exhaust gases of cement kilns by 80%. Although this technology is at an early stage of development, preliminary investigations have estimated CO_2 avoidance costs at less than USD 30/tCO_2, with minimum process efficiency losses of between 5% and 8% (Epple, 2007).

[12] The bars represent ranges of uncertainty.

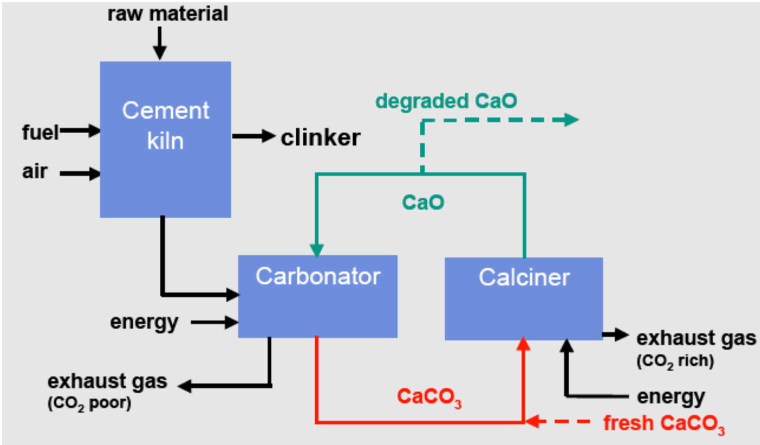

Figure 3.10 Process diagram for a cement plant incorporating carbonate looping (Hoenig, 2007)

3.2.4 Current status of CCS in the cement sector

It is understood that pilot projects are being discussed within the industry but there have been few public announcements. CCS in the cement sector is still in the demonstration phase and is unlikely to be deployed commercially in the short term.

It was reported in March 2010 that Cemex USA had been awarded USD 1.1 million in funding from the US Department of Energy (DOE) to demonstrate a dry sorbent CO_2 capture technology at one of its cement plants in the United States. According to press reports, the plant is expected to store up to 1 Mt of CO_2 a year. Cemex will fund 20% of Phase 1 of the project which will last around 7 months. It is understood that, at the end of this phase, the project will undergo a competitive process to secure additional funding for design, construction and operation.

Skyonic Corporation was awarded a USD 25 million grant from the US DOE in July 2010 to develop a project using its mineralisation technology to capture CO_2 from the flue gases of a cement manufacturing plant run by Capital Aggregates Ltd in San Antonio, Texas. According to a press release issued by Skyonic (2010) the plant is targeted to capture 75 000 t/y of the CO_2 emitted by the cement plant. Construction of the plant is due to commence in the fall of 2010 with the plant being fully operational in the first half of 2012.

A number of providers of post-combustion technology (*e.g.* Cansolv, HTC Pure Energy Canada, Aker Clean Carbon) have mobile test rigs or modular equipments that could in principle be taken to cement plants to test carbon capture processes with the flue gas. ECRA (2009b) estimates that a complete pilot project in the cement industry, excluding any costs for transport and storage, would cost between €6 million and €12 million.

3.3 Iron and steel

Iron is primarily produced in blast furnaces, in which coke, pulverised coal, sinter and bulk ore are heated to approximately 1500ºC. It is technically possible to use CCS technologies to reduce direct emissions from the iron production process, primarily through alterations in blast furnace design, but also through modifications to other steel production routes. The section covers both the potential for CCS application within current iron and steel manufacturing processes, such as the blast furnace and direct reduction of iron (DRI), but also the possibility for the integration of CCS into a new steel production process called HIsarna.

3.3.1 Top Gas Recycling Blast Furnace

Perhaps the most advanced potential CCS technology for the iron and steel sector is the Top Gas Recycling Blast Furnace (TGR-BF) (Figure 3.11). Blast furnace gases are rich in carbon monoxide and CO_2. Reforming this gas[13] can result in CO_2 concentration levels of up to 60% which can then be further concentrated using chemical absorption techniques, transported and stored. For the TGR process to work most efficiently, oxygen is injected into the blast furnace instead of air. This reduces the amount of nitrogen and increases the concentration of CO_2 in the offgas.

In the near term, TGR-BF seems to offer a particularly promising approach to CCS in the sector since existing blast furnaces can be retrofitted with the new technology, thus avoiding the need for investment in a new plant while still achieving significant CO_2 abatement. In addition, the process delivers energy savings as the recycling of the purified gas reduces the coke and coal consumption of the blast furnace. This efficiency increase in part offsets the extra costs involved in capture and storage.

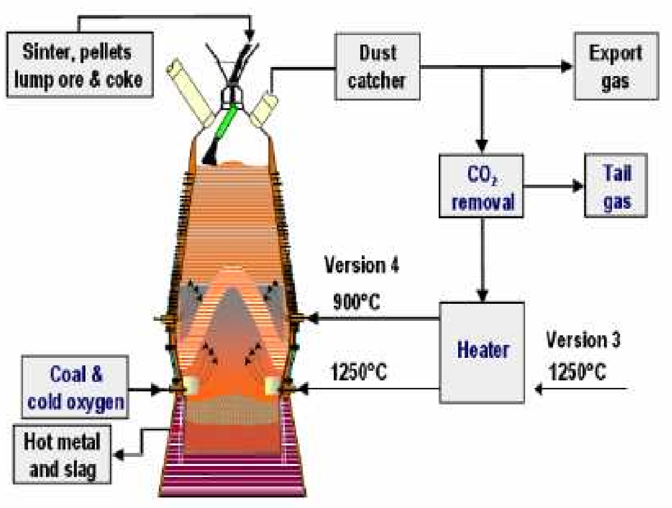

Figure 3.11 Basic diagram of a blast furnace equipped with TGR with capture (Birat, 2010)

[13] Blast furnace gas reforming is understood not to require major changes in the process configuration (IEA 2009a)

3.3.1.1 Energy requirements

A number of approaches to CO_2 capture have the potential to be deployed in iron and steel making, dependent on the production process being used. These include chemical adsorption technologies such as amine scrubbing, physical adsorption technologies such as pressure swing adsorption (PSA) and vacuum pressure swing adsorbtion (VPSA), and cryogenics. Detailed studies, carried out in the context of the European Union's ultra-low carbon CO_2 steelmaking project (ULCOS), have shown that the most effective approach in any circumstance will depend on a number of factors, including in particular the concentration of CO_2 in the stream of gas being treated (Table 3.5).

At the levels of concentration found in TGRs, physical adsorption technologies (PSA and VPSA are likely to be most effective in terms of technical performance and operating and capital costs. However, with reference to Table 3.5, it can be seen that although PSA and VPSA have low energy requirements, they are only able to produce gases with CO_2 concentrations of approximately 80 and 88% respectively. Due to this, additional treatment may be required to remove impurities from the resultant gas stream, which will increase cost and energy usage.

In the iron and steel industry, the energy needed for carbon capture, and the CO_2 reductions that will result, depend heavily on the process involved. Data on the potential to reduce emissions through CO_2 capture in the industry is limited, although indications from research conducted under ULCOS estimates that TGR technologies may cut emissions by approximately 35% compared to a benchmark steel mill. If CO_2 was also captured from an additional stack, for example from a sinter plant, then emission reductions could increase to 75%.

Table 3.5 Performance and energy requirements for a range of capture technologies available for the steel industry[14] (Birat, 2010)

	Unit	Pressure swing adsorption (PSA)	Vacuum pressure swing adsorption (VPSA)	VPSA + compression and cryogenic flash	Amines + compression	PSA + cryogenic distillation + compression
Recycled gas						
CO yield	%	88.0	90.4	97.3	99.9	100
CO	%vol	71.4	68.2	68.9	67.8	69.5
CO_2	%vol	2.7	3.0	3.0	2.9	2.7
N_2	%vol	13.5	15.7	15.6	15.1	15.4
H_2	%vol	12.4	13.0	12.6	12.1	12.4
H_2O	%vol	0	0	0	2.1	0
CO_2 rich-captured gas						
CO	%vol (dry)	12.1	10.7	3.3	0	0
CO_2	%vol (dry)	79.7	87.2	96.3	100	100
N_2	%vol (dry)	5.6	1.6	0.3	0	0

[14] The small table describes the composition of the input gas used for testing

	Unit	Pressure swing adsorption (PSA)	Vacuum pressure swing adsorption (VPSA)	VPSA + compression and cryogenic flash	Amines + compression	PSA + cryogenic distillation + compression
H_2	%vol (dry)	2.5	0.6	0.1	0	0
Suitable for transport and storage		No	No	Yes	Yes	Yes
Energy requirements						
Electricity consumption	kWh/t CO_2	100	105	292	170	310
Capture process	kWh/t CO_2	100	105	160	55	195
Compression for storage	kWh/t CO_2	-	-	132	115	115
LP steam consumption	GJ/t CO_2	0	0	0	3.2	0
Total energy consumption	GJ/t CO_2	0.36	0.38	1.05	3.81	1.12

INPUT GAS	CO	CO_2	N_2	H_2
%vol (dry)	**45**	**37**	**10**	**8**

The relative advantages of individual technologies will vary over time. For example, the amine washing considered in the ULCOS program is based on the present state of the art of this fairly common technology, *i.e.* on the use of commercial MDEA amines that currently require 3.2 GJ/tCO_2 to restore the sorbent. The Japanese COURSE 50 national programme aims to deliver these improvements 10 years from now; where R&D is under way to reduce the energy needed to 1.8 GJ/tCO_2, to work at lower temperatures and to use wasted heat.

3.2.2 CO_2 capture within the Direct Reduced Iron process

The gas-based direct reduced iron (DRI) process is also potentially suited for CCS (IEA 2009a). The DRI process involves the conversion of iron ore to iron through the use of a reduction gas, normally natural gas which is chemically converted to hydrogen, carbon monoxide (CO)and CO_2. CO_2 capture is already widely applied in the DRI process in order to enhance the flue gas quality, although the captured CO_2 is normally vented. Due to the high cost of natural gas, DRI facilities are concentrated in few countries such as the Middle East and Latin America.

Within the last decade, a small number of DRI installations have been combined with coal gasification installations, with the coal-derived syngas used as the reducing gas. This process may be particularly important for countries that have limited gas supplies but large coal reserves, such as India, China, and South Africa. CO_2 from the gasification process can be captured using pre-combustion technologies (Knop et al., 2008). A flow diagram of the ULCORED DRI process using coal-derived syngas and with CO_2 capture is shown in Figure 3.12.

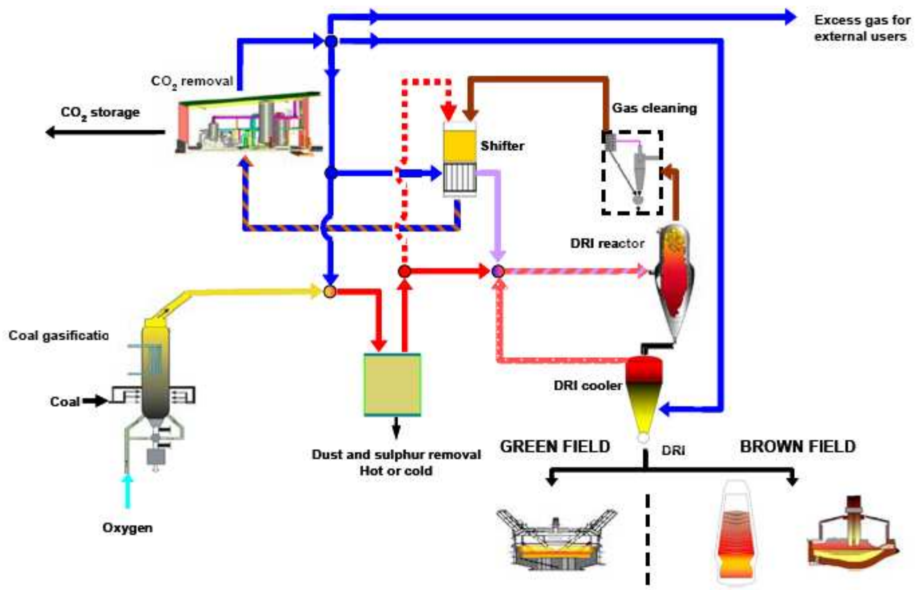

Figure 3.12 DRI process with coal-derived syngas and CO_2 capture (Knop et al., 2008)

3.3.3 The HIsarna process

The HIsarna process offers a longer term strategy for reducing CO_2 from the iron and steel industry. HIsarna is a smelting reduction process which uses pure oxygen and generates an off-gas which is almost ready for storage. It is based on the combination of a hot cyclone developed by Corus, and a bath smelter called HIsarna licensed by Rio Tinto. It incorporates some of the technology of the HIsmelt process.

The HIsarna process removes the need for producing pig iron in a blast furnace prior to the production of steel. As a result, the process is understood to be able to reduce CO_2 emissions from steel production by 20%. If combined with CCS, this reduction could be increased to 80% (Tata Steel, 2010).

An initial pilot plant is currently under construction in the Netherlands. If this plant is successful, commercial deployment is targeted by 2030 (LEK, 2009). There are currently no indications of the cost of applying CCS to a HIsarna plant.

3.3.4 Current status of CCS in the iron and steel sector

The ULCOS is currently the largest initiative to reduce CO_2 emissions from the iron and steel industry, including through the use of CCS. The project is funded roughly equally by the industry partners and the European Union. It is under the ULCOS programme that the first small scale demonstration of a TGR-BF was constructed at LKAB in Sweden in 2007. Japan also has a research programme for CCS in the industry, called the COURSE

50 programme. Despite this evidence of significant interest in CCS in the iron and steel sector, no large scale demonstration plants have yet been developed.

3.4 Refineries

The following section reviews the capture technologies for two significant sources of emission in refineries, which have the high potential for carbon capture, namely the emission from boilers and furnaces used for process and the emission from hydrogen (H_2) production processes, such as steam reforming, emissions from combined heat and power units and from fluidised catalytic crackers (FCC).

In the case of process heating through the use of furnaces and boilers, they account for 30-60% of the emissions (van Straelen et al., 2009). In this section, both post-combustion and oxy-fuel technologies for the abatement of CO_2 in furnaces and boilers are investigated and are covered. For H_2 production it account for 5% and 20% of CO_2 emissions from a refinery, yet it produces concentrated stream of CO_2 often at a high pressure. Thus, it offers a low-cost option for CCS deployment (van Straelen et al., 2009). Finally, CO_2 could also be captured in the combined heat and power (CHP) installations that could replace distributed boilers in some refineries, and also captured from fluidised catalytic cracking units. These capture options are dependent on the configuration of the refinery and reviewed in more detail in the following sub-sections.

3.4.1 CO_2 capture from process heaters

Post-combustion capture and oxyfueling currently offer possibilities for reducing emissions from process heaters in refineries. Technologies that could potentially feature in the future in new build facilities include chemical looping combustion using refinery gas (Morin and Béal, 2005) and pre-combustion capture in the production of hydrogen fuel for use in boilers and heaters (IEA GHG, 2000).

The retrofit of heaters with post-combustion capture technologies is limited due to the wide distribution of heating units within a refinery complex. Hurst and Walker (2005) proposed to resolve this by ducting the gases from dispersed heaters to a central location where CO_2 could be separated and compressed. Straelen et. al. (2010) have questioned the feasibility of such an approach and proposed instead to capture only the CO_2 from the largest on-site stacks.

3.4.2 CO_2 capture from hydrogen production

Between 5% and 20% of refinery CO_2 emissions are linked to the production of hydrogen (H_2). Hydrogen is a by-product of the catalytic reformer and fluid catalytic cracker (FCC) processes but as demand for H_2 has increased with changes in fuel specification (to reduce sulphur content of fuels by hydrodesulphurization), demand now exceeds supply from these processes in most refineries. To meet the increased demand, hydrogen is produced either through the steam methane reforming (SMR) of natural gas or through the gasification of heavy residues and fuel oil. The hydrogen produced in both these processes needs to be separated from other constituents in the flue gases.

Gasification plants for hydrogen manufacture are generally larger than SMR and operate at high pressures of 50-70 bar. These conditions are suitable for the use of physical absorption solvents over chemical absorption solvents because they have higher loadings, require less energy input and produce dry CO_2 under these conditions. With gasification, all the CO_2 emissions associated with conversion end up in the flue gas stream and hence there is a higher rate of capture than SMR.

Traditionally, hydrogen produced in SMR plants was purified using chemical adsorbents such as hot potassium carbonate or amines such as MDEA. In the last thirty years, increasing attention, driven by a market for high purity hydrogen, has been given to separation using pressure swing adsorption (PSA). But PSA results in much lower concentration CO_2 streams which contain 20-30% impurities. The impurities include H_2, CO and methane (CH_4) which make the gas suitable for reuse in fuelling the SMR furnace. This further dilutes the CO_2 in the final flue gas and reduces the feasibility and increases the cost of CO_2 capture (Simbeck, 2005).

3.4.3 CO_2 capture from utilities

In a refinery, processes use steam and/or electricity. The cogeneration of power and heat for steam generation is a well established energy efficiency and carbon abatement measure in refineries. There is a much greater demand for steam than there is for electricity for all refinery configurations. In the near to mid-term, post-combustion technologies are most likely to be deployed for utilities, where they can be retrofitted. Longer term, other technologies such as poly-generation and oxyfueling may offer more potential for new builds.

3.4.4 CO_2 capture from fluidised catalytic cracking

In those refineries that operate fluidised catalytic cracking (FCC) units, such units can account for as much as 50% of refinery CO_2 emissions (Kuuskraa, 2009). Unlike most of the other emissions from a refinery, the emissions from FCCs are process related rather than combustion related. During processing, carbon is deposited on the surface of the catalyst powder. The catalyst is regenerated by oxidising the coke with air.

Depending on the process, the concentration of CO_2 in the flue gas typically ranges from 10% to 20% (de Mello et al.2008). Two technology options exist for the capture of CO_2 from the FCC, one is the more mature, post-combustion capture, and the other, still in development, is oxy-firing of the regeneration process. De Mello et al. compared the potential for both regeneration processes and their relative merits and reported that despite the relatively high capital cost of oxy-firing, the potential of lower operating costs make it attractive proposition in a carbon constrained world.

3.4.5 Costs of CCS deployment in the refining sector

A number of studies have provided initial insights into the cost of CCS deployment in the refining industry. These are summarised in Table 3.6.

Table 3.6 Capture costs for various process units, not including transport and storage.

Process captured	Capture type	Retrofit or new build	Cost of CO_2 avoided [€/t]
Utilities, combined cycle gas turbine	Post-combustion	New	28-75
	Pre-combustion	New	27-76
The Heaters and boilers	Post-combustion	Retrofit	77
	Pre-combustion	Retrofit	49
	Oxy-combustion	Retrofit	44
	Post-combustion	New	96
	Oxy-combustion	New	50
	Chemical looping combustion	New	33-42
Fluid Catalytic Cracker	Post combustion	New	85
	Oxy-combustion	Retrofit	55
Hydrogen production	SMR Post-combustion	New	19-53

Note: data based on Melien and Brown-Roijen (2009), and Lindsay et. al. (2009)

3.4.6 Current status of CCS in the refining sector

At present there is only small-scale testing of CCS in the refinery industry. It is possible to transport and store the CO_2 from hydrogen production units at low cost, and the technologies are available to achieve this. Applying CCS in other areas of existing refineries may be constrained by space limitations and by the need for additional infrastructure for gasification or steam production. For new build refineries, there is currently no established method to incorporate CCS.

A CCS field demonstration on a Petrobras 60 bbl/day FCC in Brazil is currently underway (Kuuskraa, 2009). Small-scale testing shows that it is technically feasible to maintain stable operation of an FCC in oxy-firing mode (de Mello et al., 2008). The figures in Table 3.6 for post-combustion CO_2 capture from an FCC are based on a 10 000 m³/day residual FCC, using the Kerr-McGee CO_2 recovery system with an MEA solvent for post-combustion capture and a scrubber to reduce the concentration of sulphur oxides (SO_x) to 7 parts per million (ppm). The oxy-firing figures are based on using an air separation unit to produce either 99.9% or 95% by volume oxygen. SO_x in the hot flue gases are removed with a SO_x scrubber prior to dehydration and compression.

The Norwegian Mongstad refinery CHP project is one of the first gas-based power plants which could be fitted with CCS. An investment decisions is expected in 2014, however the plans consists of a 280 MW_{el} natural gas-fired CHP power plant that is capable of producing up to 350 MW_{th} of steam. In parallel to the CHP plant, a test facility is could be built in which two different post-combustion capture technologies, *i.e.* Aker Clean Carbon's amine based process and Alstom's chilled ammonia process, will be tested side by side (Statoil, 2010). CO_2 from two slip streams of the natural gas fired CHP plant and a slip stream from the adjacent Mongstad refinery FCC process emissions will be used. The carbon capture pilots will begin operation in 2011, capturing 100 000 tCO_2/y between them (TCM DA, 2009).

3.5 Biofuel production

Fossil fuel conversion with CCS typically mitigates 80 to 90% of CO_2 emissions. The application of CCS to biomass conversion processes has the potential to achieve a net removal of CO_2 from the atmosphere since the carbon trapped temporarily by the biomass as it grows is placed in permanent storage (IPCC, 2005).

There are two main routes for CO_2 capture from biomass conversion processes (Figure 3.13). Biological processing, for example fermentation, uses living micro-organisms to breakdown the feedstock and produce liquid and gaseous fuels, in the process producing a relatively pure stream of CO_2. No special equipment is required to capture this CO_2 apart from compressors to prepare it for transport and storage. Biomass may also be processed thermo-chemically, enabling pre-combustion CO_2 capture.

3.5.1 Biochemical biomass conversion with CCS

A common 1st generation process to produce bioethanol involves the fermentation of sugar cane, sugar beet or corn starch. A relatively pure stream of CO_2 is produced as a by-product of the process, almost equal on a mass basis to the liquid ethanol produced. The separation of the CO_2 is straightforward since the compounds are present in different phases. Thus, no additional separation equipment is required. The CO_2-rich off-gases from the fermentation tanks are dried and compressed to facilitate transport and storage. On a bio-ethanol plant with a net output of 235 million litres a year, the addition of compression equipment leads to only a 0.9% increase in capital costs (Rhodes and Keith, 2003).

3.5.2 Thermo-chemical biomass conversion with CCS

Thermo-chemical biomass conversion, or gasification, is a thermal treatment that results in the production of gaseous products and a small amount of char and/or ash (Demirbas, 2002). The biomass is gasified by pyrolysis at temperatures of 875° - 1275°K. To reach these temperatures, an oxidising agent is needed. This can be air or oxygen (Gao et al., 2008). For the production of liquid or gaseous fuels it is essential that only a minimum amount of nitrogen is present during the synthesis. This reduces equipment sizes and costs, and increases the partial pressures of the reactants thereby typically improving the product yield.

Depending on a number of variables such as the feedstock characteristics, the temperature and the gasifying agent, product gases comprise CO, CO_2, H_2, methane and nitrogen, as well as the non-gaseous by-products of char and tars. This gas is known as producer gas. At gasification temperatures above 1275°K, the resulting gas stream consists primarily of hydrogen and carbon monoxide, called synthesis gas or syngas.

3.5.3 CCS in pulp and paper plants

Off-gases of the pulp and paper industry contain 13-14% CO_2. Most CO_2 originates from the combustion of biomass. This CO_2 is usually not counted in emissions statistics. However, it can in principle be captured and stored. The following table provides average CO_2 emission for different type of pulp and paper mills.

Table3.7 average CO_2 emissions for different type of pulp and paper mills (Jönssonn and Berntsson, 2010)

Type of plant	Emissions (tCO_2 /t pulp)	Emissions (tCO_2 /t paper)
Kraft* Market pulp mills	2.6	---
Kraft* Integrated pulp & paper mills	2.8	2.2
Mechanical** pulp & paper mills	0.9	0.47
Stand alone paper mills	---	0.42

*Kraft refers to mills that have the kraft process;
** Mechanical refers to mills that have some mechanical pulping process

For Kraft over 90% of the CO_2 is of biogenic origin, for mechanical around half and for paper mills less than 20%. The average Kraft integrated pulp and paper mill emitted 1.2 Mt of CO_2, the average paper mill 0.17 Mt CO_2 per year.

Based on these numbers, total global CO_2 emissions in the pulp and paper industry are estimated to amount to 540 Mt per year. 66% of these originate from Kraft pulp mills. So over half of total pulp and paper CO_2 emissions are estimated to be of biogenic origin, and the potential for CO_2 capture is around 350 Mt today. In recent years global Kraft pulp production has been stable or growing at a slow rate.

For Kraft mills retrofit of CO_2 capture is an option, using chemical absorption. A combination of process integration and chemical absorption can reduce energy needs substantially. For mechanical pulp and stand-alone paper plants CCS seems less feasible, due to the high cost of capturing small volumes of CO_2.

For Greenfield Kraft pulp/paper plant, black liquor gasification and re-designed lime kilns would offer interesting CO_2 capture opportunities. This has not been assessed in more detail. The optimal solution for retrofit of CCS looks slightly different for stand-alone Kraft pulp mills and integrated pulp and paper mills due to a positive energy balance.

3.5.3 Costs of CCS deployment in the biomass sector

Cost data for biomass-to-biofuel conversion processes are scarce, and even more so for conversion processes combined with CCS, a relatively new field in research and development. Plants for the production of second generation biofuels are mostly at best in the commercial demonstration phase and so are still relatively small. The costs of such plants may not be directly representative of the costs likely to be incurred in larger, commercial plants.

Typically, biomass conversion plants require higher levels of capital investment than fossil fuel conversion plants. This is mainly attributable to the nature of biomass: its energy density is usually lower than that of fossil fuels, its moisture content is higher, and its composition is less homogenous and often more fibrous. It therefore requires more pre-treatment. The need to import biomass on a large scale is also expected to result in higher feedstock prices on an energy basis, contributing to higher prices for biofuels.

The incremental cost of CO_2 capture from biomass conversion processes is generally low, since a high-purity CO_2 stream is readily available for capture. The incremental capture costs are therefore limited to CO_2 dehydration and compression, and typically only amount USD 6 - USD 12/t CO_2 (Hektor and Berntsson, 2009), mainly depending on the pressure needed for CO_2 transportation.

During the calculation of the total CO_2 avoidance cost, the price difference between a biofuel and its fossil fuel substitute is also taken into account. The IEA Blue Map scenario projects a gradual reduction in the commodity price of fossil fuels in the long-term as a result of reduced demand, as a significant part of the demand becomes met by biofuels (IEA, 2010). The effective price of fossil fuels will be much higher, assuming a CO_2 price of USD 175/t CO_2 in 2050.

In the case of the pulp and paper sector, estimates for the cost of retrofitting of stand-alone Kraft pulp mills is between 30 to 35 Euros per tonne of CO_2 abated including storage and transportation costs (Joenson and Algehed, in press). The additional energy use would be in the order of 1.45 GJ primary energy (bark) per tonne of CO_2 captured, provided that there is use for the excess heat. The other half of energy needs would be covered through improved process integration, resulting in a lower capital costs than the retrofit.

For integrated Kraft pulp and paper mills less residual heat is available, therefore the additional energy needs for CO_2 capture will be higher. Avoidance costs for the optimal configuration (heat pump for upgrading low temperature excess heat) range from EUR 35 to 40/t CO_2. This includes pressurization (80 bar), transport and storage (around EUR 7/t CO_2 for the latter two items). This would be a plant with 1 Mt/yr capture and storage (Hektor and Berntsson, 2009).

3.5.4 Current status of CCS in biomass sector

One of the first commercially operated bioethanol plants integrated with CCS, the Arkalon bioethanol plant in Kansas, US, started operation during the third quarter of 2009 (BIC Magazine, 2010). At present, approximately 60% (170 - 180 kt/yr) of the CO_2 produced by the plant is captured and transported to an oil field near Booker, Texas for EOR.

Another pilot project in the United States is managed by the Midwest Geological Survey Consortium. This started operation early in 2010 (MGSC, 2010). This project foresees the injection of 1.0 Mt of CO_2 over three years, obtained from the Archer Daniels Midland Company (ADM) bioethanol plant in Decatur, Illinois, in the Mount Simon Sandstone saline formation.

Although a number of biomass gasifiers have recently entered the market, there are at present no CCS demonstration projects involving the gasification of biomass.

4. Issues related to transport and storage[15]

Issues relating to the transport and storage components of CCS are discussed in the IEA Global Technology Roadmap on CCS (IEA, 2009b). Industrial CCS raises few specific issues in relation to transport and storage, other than those which arise more generally in relation to CCS. Transporting facilities and storage reservoirs are indifferent to the sources of the CO_2 they handle, subject to quality standards being met.

This section discusses the two specific areas in which industrial CCS may raise transport and storage issues, i.e. CO_2 stream quality and the geographical matching of sources and sinks.

4.1 Impurities in the CO_2 stream

The need to reduce impurities in the CO_2 stream depends on the application of the CO_2 and on the method, organisation and distance of the CO_2 transport.

If the CO_2 is to be used for EOR, it must contain only very low oxygen levels. This might be an issue if the CO_2 originates from an oxy-fired cement kiln. If the transport is long-distance or in a network with a range of sources, dehydration is important to prevent corrosion and leakage. But if the CO_2 is intended for EOR and the source is close by, it might be more cost-effective to build a short stainless steel pipeline and to leave the water in the CO_2, as water does no pose a problem for re-injection with CO_2 for EOR.

More reserach needs to be done to identify the specific issues related to gas impurities in transport and storage, and to inform the planning of potential industrial CCS applications about these.

4.2 Geological storage capacity and industrial sources

For the biomass, cement and iron and steel sectors, decisions on the location of the potential CO_2 sources are made independently of considerations of the location of likely geological storage reservoirs. Cement plants, for example, are generally built near limestone reservoirs. But there is no geological relationship between limestone reservoirs and underground sedimentary basins, so it is a matter of chance whether cement plants are located reasonably near to potential storage sites or not.

For gas processing plants, there is a higher likelihood that sources and reservoirs are close together, as the plants tend to be sited near to the sedimentary basins from which the gas is sourced, which also may prove good sites for CO_2 storage. This factor underpins the Sleipner and In Salah projects.

Refineries have no operational or economic need to be sited near oil or gas fields or to other sedimentary basins. But they are often built near the coast to allow for the marine transport of oil, and some may therefore be sited relatively close to prospective storage sites.

[15] This Chapter is based on the conclusions of the Abu Dhabi meeting.

5. Industrial CO_2 sources: emissions, projections and CCS

Industry[16] produces nearly 40% of global energy-related CO_2 emissions. In 2007, estimated direct emissions from industrial production amounted to 7.6 $GtCO_2$, with an additional 3.9 $GtCO_2$ from the power generation sector attributable to electricity use in industry. Data on current industry emissions are often of low quality and incomplete. Projections of business-as-usual CO_2 emissions are even more uncertain and may be based on different methods and assumptions. But the CO_2 emissions of most sectors discussed in this report are projected to grow by of the order of 15% to 40% between 2007 and 2050. CO_2 emissions from industrial sources can be reduced through energy efficiency improvements, fuel substitution and energy recovery. But substantial deployment of CCS in industry will be necessary if the sector is to make its due contribution to the reaching of emission reduction targets consistent with halving CO_2 emissions in 2050 compare to 2005 level. These reductions are needed to limit the atmospheric CO_2 concentration to 450 parts per million.

5.1 Current and business-as-usual projected emissions

Industry emits CO_2 both directly and indirectly. The indirect emissions include emissions associated with the generation of the electricity consumed in industrial processes. These emissions are not discussed in this report as they fall to be addressed by the application of CCS in the electricity sector, rather than in the industry sector. The data in this report therefore only include the direct industrial emissions of CO_2. All the numbers reported here are subject to significant uncertainties, and the absence of standardized emissions monitoring methodologies, boundary setting and measurement techniques in certain industries lead to significant variations in the figures reported.

Within industry, 30% of direct CO_2 emissions are attributed to the production of iron and steel, 26% to cement production and 17% to the production of chemicals (IEA, 2010). The analysis in IEA (2010) however does not separate out some of the sectors in this report, such as the sources of CO_2 in the high-purity category and in oil refineries. The reported emissions of each industry are also frequently disputed, given non-consistent data collection methodologies and a lack of data collection capacity in some countries.

The reported emissions from the iron and steel sector highlight the considerable uncertainty inherent in currently available data. The IEA data report emissions of 2.3 $GtCO_2$ in 2007. A report from the Energy Policy and Economics group (LEP-CNRS) at the University of Grenoble, France, reports significantly lower emissions from the sector at around 1.6 $GtCO_2$ a year in 2005 (Birat, 2010). Available data on direct emissions from the cement sector are more consistent at around 2.0 $GtCO_2$ in 2007.

McKinsey (2008) estimates emissions from the oil refining sector at approximately 1.1 $GtCO_2$ in 2008. The IEA GHG (2008a) estimates emissions at 0.713 $GtCO_2$ based on data from 2007, using data in its CO_2 sources database.

[16] Data based on IEA analysis (IEA, 2010); *i.e.* including the industrial sources of iron and steel, cement, pulp and paper, chemicals, aluminium and other industry, excluding emissions from refineries.

High-purity sources are currently estimated to produce 0.43 $GtCO_2$ a year (Zakkour & Cook, 2010). This includes emissions from gas processing (160 $MtCO_2$), ammonia production (236 $MtCO_2$), ethylene oxide production (6.3 $MtCO_2$) and CtL production (27.6 $MtCO_2$).

Current emissions from biofuel production are relatively low compared to those from the other sectors as the level of biofuel production is still relatively modest. Data on emissions from bioethanol production, which represents by far the bulk of current biofuel production, vary greatly. IEA Bioenergy (2008) estimates 2007 emissions at 32 $MtCO_2$ based on the production of 42 billion litres of bioethanol in Brazil and the United States. The IEA GHG (2008), however, estimates emissions at roughly 69 $MtCO_2$ from 190 sources, mainly in Brazil. Most of the IEA GHG data originate from 2003, so this number is likely to be an underestimate of current production.

In terms of projections for industry emissions, the IEA (2010; 2009a) gives an internally consistent projection for business-as-usual emissions to 2050 (Figure 5.1). This shows the projected emissions in a baseline scenario and in a mitigation scenario for different industrial sectors and different (low/high) growth scenarios developed by the IEA. The refinery sector and most high-purity sources are not included in these data.

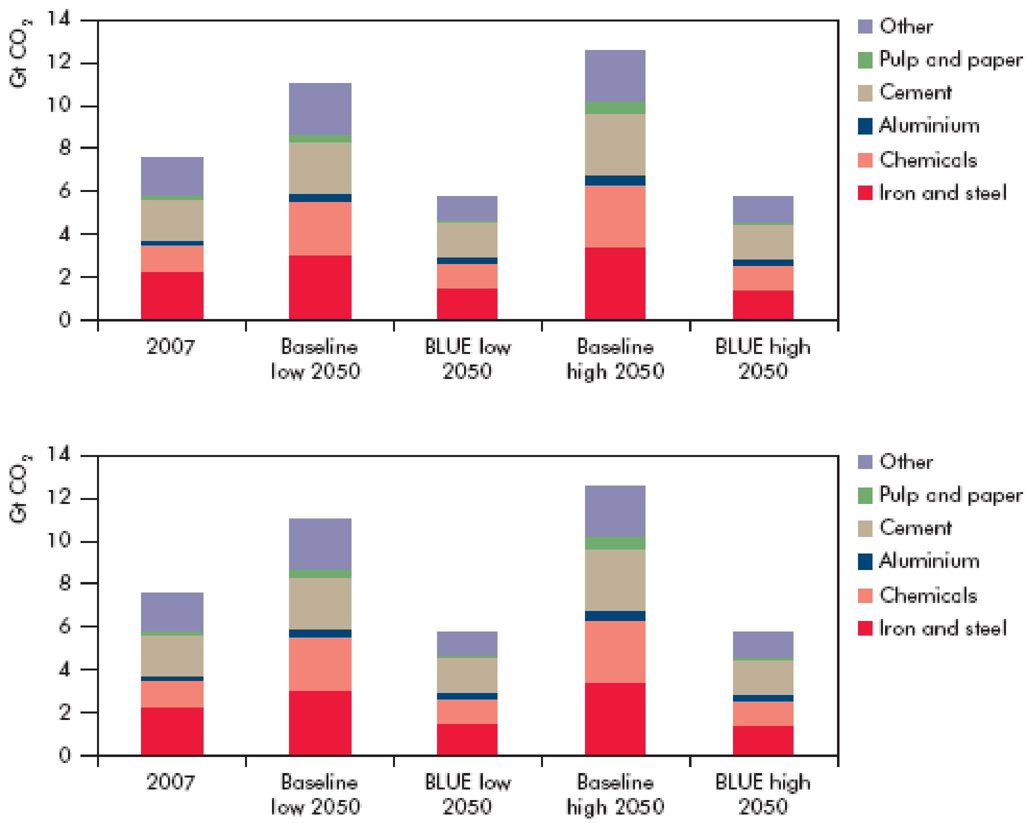

Figure 5.1 Industrial CO2 emission projections (IEA, 2010)

Zakkour & Cook (2010) project an increase in emissions from the production of natural gas, hydrogen, ethylene oxide and synthetic fuels increasing from 537 $MtCO_2$ in 2020 to 1.113 $GtCO_2$ in 2050 in a business-as-usual scenario (Figure 5.2).

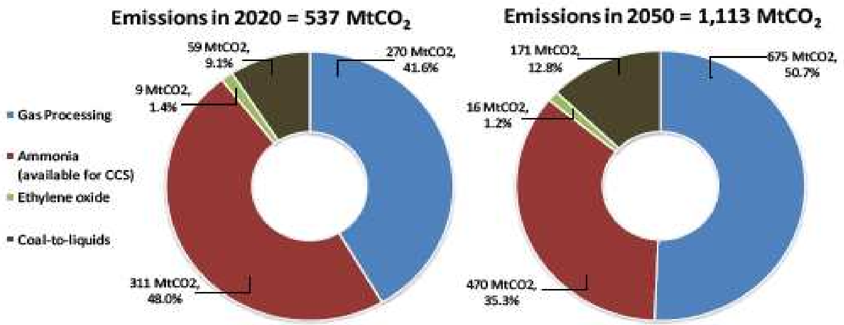

Figure 5.2 Emissions from high-purity sources in 2020 and 2050 in a business-as-usual scenario (Zakkour & Cook, 2010)

For biofuel production, the situation is complex as the outcome of the projection depends strongly on the assumptions in the model. The IEA (2010) foresees a major role for biodiesel, resulting in a complete absence of other biofuels. However, in reality, different biofuels are likely to co-exist. Official and internally consistent projections do not exist for CO_2-capture-amenable biofuel sources. The numbers in the graph are an interpolation of scaled IEA data (see Carbo, 2010 for more information).

Figure 5.3 provides a summary of such data as are available for current (2005 - 2007) emissions and projected emissions in 2050 for the five sectors in this report.

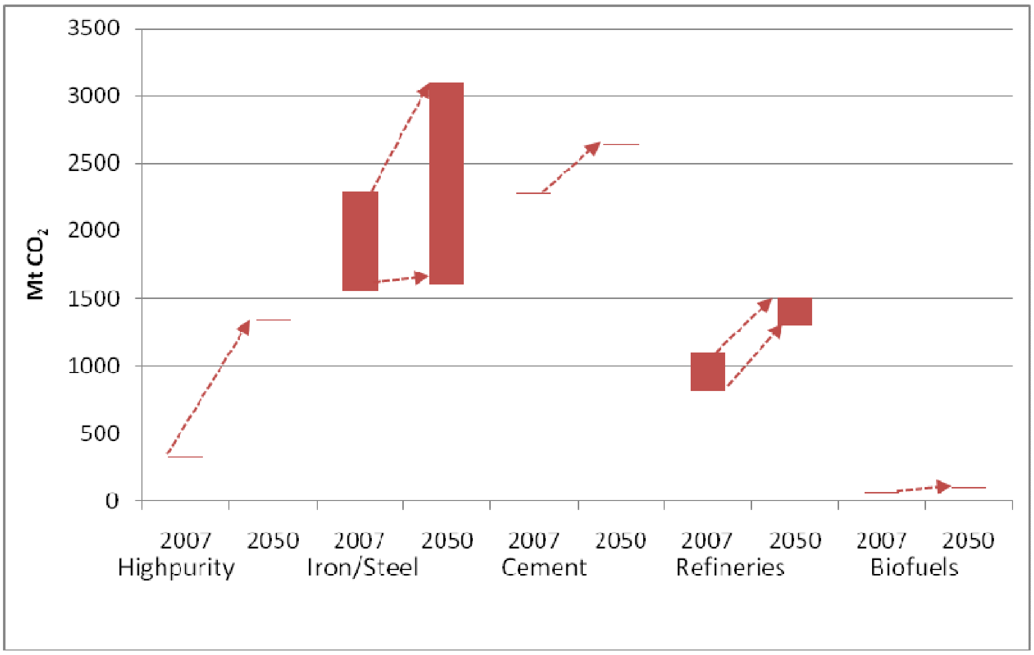

Figure 5.3 Ranges for current and 2050 business as usual CO_2 emissions from industrial sectors covered.

5.2 Projected potential for the use of CCS in industrial applications

Based on projections of emissions to 2050, the IEA CCS roadmap estimates the amount of CO_2 that could be captured and stored over time and the distribution of CCS implementation between different regions (IEA, 2009b). The data are analysed by reference to the power, industry and upstream sectors.

The IEA BLUE Map scenario used to project the potential role of CCS by 2050 in a very carbon constrained global economy, assumes that policies are in place to provide strong incentives for low-carbon technologies, including CCS. CCS is assumed to compete in a global market of mitigation options. The implementation such policies is projected to have a range of impacts on the likely application of CCS to industrial sources.

As shown in Figure 5.4, in the cement sector, almost 500 $MtCO_2$ a year is projected to be captured and stored in the IEA BLUE "low" scenario (Barker, 2010; IEA, 20010). In high-purity sector, almost all of the ethylene oxide production CO_2 emissions, and more than half of the CtL, natural gas processing and ammonia emissions are expected to be available for storage (see figure 5.5). On this basis, more than 700 $MtCO_2$ would be captured and stored from this sector.

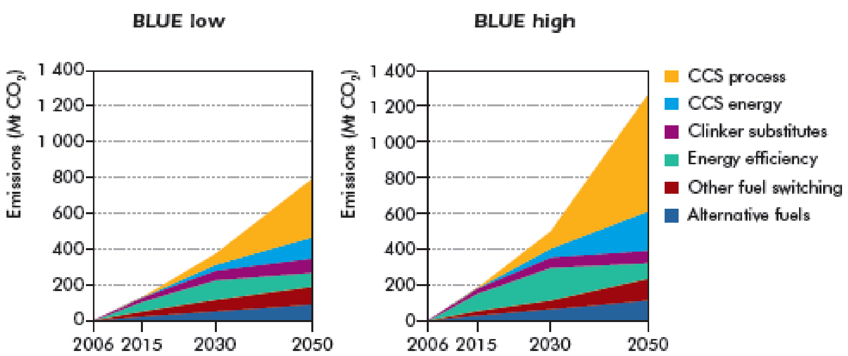

Figure 5.4 CO2 emissions reductions within the cement industry (IEA, 2009a)

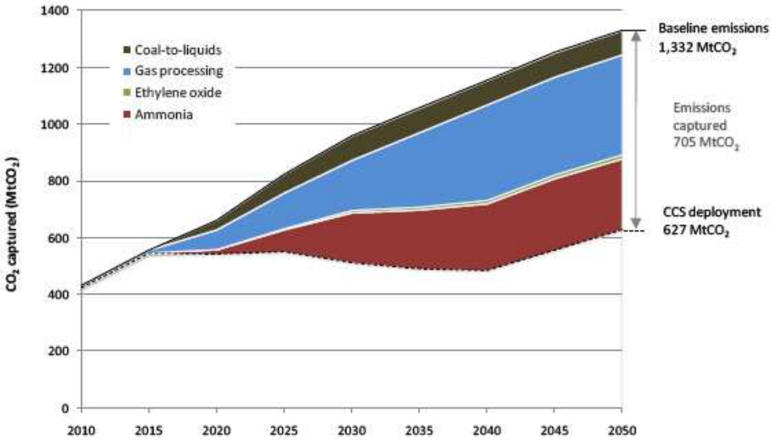

Figure 5.5 Global deployment of CCS from high purity CO_2 sources 2010-2050 (Zakkour & Cook, 2010)

In the iron and steel sector, the IEA projects a significant role for CCS with around 822 $MtCO_2$ stored annually by 2050 (IEA, 2009b).

For biofuels, the IEA projections foresee a large role for biomass synfuels and hydrogen, leading to almost half of the industry and upstream capture taking place in that sector, in the process reducing emissions by more than 2 $GtCO_2$ in 2050 (IEA, 2009b). Of this, 0.6 $GtCO_2$ savings are projected to come from hydrogen production and 1.5 $GtCO_2$ savings from biodiesel production. CCS from bioethanol and biogas production have not been considered.

No projections for the role of CCS in the refining sector are available. The most viable CO_2 source in a refinery is in relation to hydrogen production, but the size and CCS potential of such sources vary from refinery to refinery. It is therefore difficult to make sectoral projections. However, it is clear that some short-term and relatively low-cost potential exists.

6. Enabling policies for CCS in industrial sectors

Industrial CCS has a large potential (IEA, 2010). It can be technologically mature in most sectors in the next ten years (see the sectoral assessments referenced in Chapter 9). But it is currently a reality in only a limited number of cases (Global CCS Institute, 2010).

Many barriers to industrial CCS, such as those related to legal frameworks and public perception, are similar to the barriers faced by CCS in general. These are discussed in the IEA Global Technology Roadmap on CCS (2009b). There are some areas, however, in which the wider deployment of CCS in industry requires specific enabling actions. The most urgent issue is how to provide an incentive for the implementation of CCS in industry, as currently costs exceed benefits in the vast majority of potential projects. But costs are not the only barrier to be overcome. This section also reviews a number of other potential policy measures to address a range of economic, knowledge and awareness barriers to CCS in industry.

6.1 Incentives for CCS in industry

6.1.1 Carbon prices or taxes

The most commonly considered policy incentive for CCS is the creation of a sufficiently high, long-term and stable price on carbon emissions. Carbon prices can be induced through emissions trading schemes, which involve setting a cap on CO_2 emissions, or through the imposition of carbon taxes.

If emission trading schemes are to signal carbon prices that are strong and stable enough to incentivise industrial CCS, tight caps need to be set, and good information about emission reduction volumes and costs in the market needs to be available to market participants. The EU Emissions Trading Scheme (ETS) is the most mature of the operational CO_2 markets, and these conditions have not been met. Carbon prices have varied considerably over recent years and are currently at an insufficient level to incentivise CCS. CCS is currently excluded from the Kyoto Protocol's Clean Development Mechanism (CDM) (see section 6.3).

There are few examples of strong economy-wide carbon taxes other than in Norway. Several of Norway's gas fields contain significant amounts of CO_2 that has traditionally been separated and vented into the atmosphere when the gas was recovered. In the 1990s, Norway decided to tax CO_2 emissions from its offshore industry (mostly oil and gas production) at a rate of around USD 35/tCO_2 emitted. As a result of the tax, Statoil decided in its North Sea Sleipner project to inject the separated CO_2 into a saline formation around 800 m below the sea floor, but above the gas field. Sleipner started in 1996 and was the first CCS project globally. The reported cost of applying CCS in the Sleipner project is around USD 17/tCO_2, which made the project worthwhile for Statoil. In 2008, Statoil implemented another CCS gas processing project, Snøhvit, in the Barents Sea.

In the EU, the ETS-driven price incentive of EUR 11 - EUR15/tCO_2 has not yet led to any CCS projects as the price is too low to outbalance the costs and high technology risks implicit in such projects, and is highly variable. No other countries have structural carbon price incentives.

6.1.2 Subsidies and tax credits

Several countries have announced non-market and non-taxation instruments to enable CCS. These include subsidies to cover additional upfront investment costs, tax credits, CO_2 price guarantees (where an ETS is in place but providing an insufficient incentive for CCS) and governmental loan guarantees for CCS investments. These instruments all weigh on government budgets.

Subsidies for CCS are implemented more commonly than carbon prices or taxes. According to the IEA & CSLF (2010), between USD 26 and USD 36 billion has been committed by developed countries to subsidise CCS projects (Table 6.1). Most of this demonstration funding is intended for CCS in power generation, but in Australia, Canada and Europe, industrial CCS projects have also been eligible for funding.

Table 6.1 Funding committed to CCS demonstration in the form of subsidies (IEA & CSLF, 2010).

Country	Funding committed to date (billion USD)
Australia	2 to 6
Canada	3.5
European Commission[a]	4 to 6
Japan	0.1
Norway	1
Korea, Republic of	1
United Kingdom[b]	11 to 14.5
United States	4
TOTAL	**26.6 to 36.1**

[a] The number for the European Commission includes the EUR 300 million allowances from the ETS New Entrants Reserve that have been reserved for innovative low-carbon technologies.
[b] UK funding includes operational support for 10 to 15 years of CCS operations. Note that UK funds may be used in conjunction with EC funds.

6.1.3 Mandates and standards

Regulatory instruments such as technology mandates and standards could also be used to incentivise CCS in industrial applications. Governments might, for example, mandate an obligation to implement CCS on certain installations or in certain industries, such as on new CtL plants as a condition of their obtaining a license to operate. Governments could also consider prohibiting CO_2 venting from natural gas processing plants or from all large, pure point sources of CO_2.

In regulating standards, governments might subject industries to a GHG emission standard per unit of product. For example, a standard in the steel industry could take the form of a maximum allowable tonnage of CO_2 emissions per tonne of steel produced. Such standards could be set at such a level that they enabled CCS.

Currently, there are no known examples of mandates or standards relevant to CCS.

6.2 International collaboration

International collaboration can play an important role in developing the implementation of new technologies, for example by allowing the sharing of learning, by improving the evidence base on which decisions are taken, and by raising levels of understanding among key stakeholders.

A number of initiatives already exist to foster international collaboration on CCS in industry. The IEA GHG R&D Programme, an IEA Implementing Agreement, has been enabling knowledge exchange on CCS in industry since 1991. The Global CCS Institute aims to facilitate demonstration of CCS, including in industry, and facilitates capacity building and knowledge sharing.

6.2.1 Sectoral agreements

Sectoral agreements can provide a good basis for effective international collaboration. Sectoral agreements can take many forms and can have different participants. They may be based on multilateral agreements between governments to reduce GHG emissions in a given sector (Bodansky, 2007) or they may be based on international or domestic agreements between industry actors within a sector to implement certain practices that reduce energy use and GHG emissions.

Stronger variants could potentially involve the setting of CO_2 emission standards for the production of goods such as cement or steel, or prohibiting CO_2 venting from the gas industry. It is likely that the enforcing power of states would be required to underpin such agreements. At a less constraining level, structural agreements might include arrangements for knowledge exchange, common R&D programmes and the development of best practices in specific sectors. Such agreements can be implemented voluntarily through international industrial associations or public-private partnerships.

CCS is currently the subject of no formal sectoral agreements, although the IEA Global Technology Roadmap on cement highlights a sectoral approach on emission reduction in the cement industry that also involves CCS (IEA & WBCSD, 2009). The IEA Roadmap on CCS recommends the creation of new CCS collaborative efforts for the most important industrial sectors by 2012 (IEA, 2009b).

6.2.2 Copenhagen Accord instruments

In the 2009 Copenhagen Accord, several new international instruments have been agreed, although not officially accepted by the United Nations Framework Convention on Climate Change (UNFCCC). It is likely that many of these instruments will be included in any UNFCCC agreement on a post-2012 climate regime. Discussions for such an agreement are currently under way in the Ad hoc Working Group of the UNFCCC on Long-term Collaborative Action.

Several of the potential post-Copenhagen instruments may have significance for CCS (Hagemann et al., 2010). These include:

- Nationally Appropriate Mitigation Actions (NAMAs), which are actions undertaken by developing countries or emerging economies that contribute to GHG mitigation. Variants include unilateral NAMAs, undertaken by the developing country, supported NAMAs, undertaken in a developing country but with support from a donor country, and credited NAMAs, in which a developing country receives funding resembling a carbon credit for its NAMA.
- The Technology Mechanism, which would include actions for collaborative research, development and demonstration (RD&D), as well as enabling a climate technology centre and network of regional centres or hubs. Both the RD&D and the technology centre and network could be relevant to CCS.
- Other provisions for measurable, reportable and verifiable actions and efforts. As CCS, both in industry and elsewhere, has challenges in terms of the monitoring of emission reductions, discussions on measurability, reporting and verification may have impacts for CCS in all sectors. Steps need to be taken to ensure that CCS-related issues are specifically and sufficiently considered in this context.

6.2.3 Overcoming knowledge and awareness barriers

Considering its potential, industrial CCS has so far not received the attention it requires. Overcoming the lack of knowledge and awareness of industrial CCS among the stakeholders who may eventually need to be engaged with it is a long-term process. It requires familiarising regulators with the issues, educating students and engineers, and gaining experience in practice.

A number of measures can be taken to speed up the process:

- Best practices: the development and dissemination of best practices for CO_2 capture in industry would enable faster learning on the application of the relevant technologies in practice. Industry participation in these best practices is essential. The role of governments should be to enable their development in demonstration programmes and to support their dissemination.
- Capacity building: education programmes need to be developed at universities and technical schools, particularly in developing countries and in the economies in transition.
- Regional networks: knowledge circles need to be developed in countries and regions which involve all the relevant stakeholders. In developing countries, multilateral banks and donors should also be involved. Regional networks can also facilitate regulatory learning between governmental actors.

If the potential of CCS in industrial applications is to be fully realised, governments and industry decision-makers in developed and developing countries alike need rapidly to start forming regional networks, to start ensuring the inclusion of CCS in curricula for universities and technical schools, and to consider the scope for undertaking or funding capacity development activities around CCS.

6.3 Specific policies and activities in developing countries

For developing countries, the CDM offers currently the only incentive to reduce CO_2 emissions. Discussions on CCS in the CDM, however, have proven controversial (Coninck, 2008). They have been going on since 2005 and have stalled on matters related to questions of liability, potential seepage and environmental impacts (UNFCCC, 2009). Currently, it seems unlikely that CCS projects will be allowed under the CDM even after the Kyoto Protocol's first commitment period.

Sectoral approaches could be particularly relevant to developing countries. The involvement of developing countries in such sectoral approaches would help support the making of provisions for technology transfer and facilitate international collaboration on RD&D between industry and research organisations, including those in developing countries, where the capacity needs are greatest.

The new post-Copenhagen instruments are still under discussion. A few developing countries have included CCS in their submissions on NAMAs to the UNFCCC. Developing countries with significant oil and gas industries and large current or future industrial CO_2 emissions could consider CCS as part of their industrial development strategy, and could include this in their potential low-emission development strategy documents.

The UNFCCC also aims to advance technologies though collaborative R&D and technology transfer. These ambitions are likely to be elaborated in the proposed Technology Mechanism. The inclusion of CCS in these activities could open possibilities for developing countries to develop capacity on CCS through, for example, twinning arrangements with developed country institutions and cooperative technology R&D programmes. Such approaches will only succeed if sufficient financial resources underpin the Technology Mechanism.

Many of these activities can also be undertaken outside the Copenhagen Accord or the official climate negotiations. Regional networks could serve to exchange knowledge and experience, for instance within regions with many similar high-purity CO_2 sources or significant potential for EOR. Bilateral sources of finance could be available.

7. Industry value and business models for industrial CCS

A business model defines how a business seeks to create and deliver value. A business model requires a value proposition. CCS or CCS technology development can create value for an organisation in a number of ways, but it is primarily by meeting requirements to reduce greenhouse gas emissions. Similarly, it allows a business to remain viable by continuing to use fossil fuels in carbon-constrained environment. This value is directly realized by an organization by avoiding the payment of a CO_2 tax, avoiding having to acquire CO_2 emission credits, or by the sale of unneeded CO_2 credits. CCS can also create value when the injection and permanent storage of CO_2 is done in conjunction with using to CO_2 to enhance the recovery of hydrocarbons, such as enhanced oil recovery (EOR, see below). CCS technologies can also create value by creating opportunities to market and sell new technologies or expertise that has been developed. But such incentives are still absent or insufficient in most of the world. At present, in most potential applications of CCS in industry, the value proposition is insufficient for a viable CCS business model.

Organisations in some industries may obtain other benefits from reusing the CO_2 as a commercial product in itself, besides as an input for EOR. These additional CO_2 re-use opportunities include: fertiliser – urea manufacturing; other oil and gas industry applications (some of which have been referred to in this report); applications in the food and beverage industry; pharmaceutical processes; water treatment; electronics; and refigerant gas. There are also a number of potential or emerging CO_2 uses around mineralisation and liquid fuels.

However, in terms of CO_2 reuse, EOR is currently the most viable reuse option. Plus, unlike the other reuse opportunities mentioned above, EOR or other types enhanced hydrocarbon recovery opportunities can be done in conjunction with permanent geological storage, and thus qualify as CCS. This is particularly viable where high-purity exhaust gases are produced at a site in close proximity to an onshore oil field suitable for EOR, where the value of the additional oil extracted may be able more than to offset the additional CCS costs. These costs, however, also include requirements to properly evaluate the site and undertake monitoring and verification to ensure that the CO_2 will be permanently stored. EOR operations that traditionally are unconcerned with permanent storage have not had to meet such requirements.

In addition to any early opportunities that may materialise in the short term, in the longer term other business models may emerge as governments commit to mitigate emissions and as the costs of emitting CO_2 rise. Some businesses have started to identify innovative business strategies for CCS that align with their long-term strategic objectives. This section reviews some of these business models for CCS in industry.

7.1 Industrial CCS projects with Enhanced Oil Recovery

The use of CO_2 from high purity industrial sources for EOR could be economically attractive. EOR is applied on a large scale in North America, albeit in connection with CCS only in five onshore locations (the Weyburn project in Canada, and the Rangely, Sharon Ridge, Enid Fertilizer and Slat Creek projects in the USA). The price paid for the

CO_2 used to enhance the oil recovery is in the range of USD 15-30/tCO_2. This price could support early capture opportunities. EOR has also been tested in developing countries, in projects such as the Buracica project in Brazil, which has reinjected CO_2 in the period 1991-2009, and the Jilin Oilfield in China in 2000-2003. While the storage potential for EOR in the long term is uncertain, it can help to get early demonstration projects off the ground.

EOR projects using CO_2 need to meet a number of technological requirements. Traditionally, EOR is done on oil fields in decline, and after water flooding and gas injection is applied. In some regions, natural gas is more readily available than CO_2. In these regions, natural gas will tend to be the agent of choice for EOR, resulting in a lost opportunity to reduce CO_2 emissions. This is in part because of a lack of effective coordination between the industries producing the CO_2 and the industries in need of it. Exceptionally, MASDAR in the United Arab Emirates is actively searching for effective source/sink combinations to use CO_2 for EOR and then permanent storage.

Three other aspects which are of importance when considering the challenges in matching sources and sinks:

- the demand for CO_2 by a particular project for EOR is not constant: the injection profile requires much more CO_2 to be used initially than in the later stages of recovery as the reservoir is saturated and the CO_2 produced with the oil is recycled back into the reservoir;
- the timing of the availability of the CO_2 is crucial. Once an oil field has been abandoned, it is not economical to reopen it for EOR; and
- EOR activities can be optimised for CO_2 injection, or for oil recovery, but not for both. Currently, they are generally optimised for oil recovery. This could be changed to maximise the volume of CO_2 stored, but more experience is needed to determine how this would work in practice.

In 2002, IEA GHG published a study which matched revenue-generating enhanced hydrocarbon recovery based sinks and high-purity sources of CO_2 within a 50 km distance from each other in order to identify potential early applications of CCS (IEA GHG, 2002b). The study showed that the projects that might be expected to go ahead even with low or no incentives could potentially sequester a total of 360 MtCO_2 a year. This figure will have changed in recent years as the total volume of available high-purity CO_2 is likely to have increased in size. Other important factors that have changed significantly since 2002 are the expected costs of undertaking CO_2 capture, transportation, and monitoring, and the price of oil. Both sets of factors will impact the economics of EOR by itself driving CCS. Furthemore, the large potential for ECBM recovery envisaged in the 2002 study is now probably much smaller.

7.2 Industrial agglomerations

While the business case for a single project may be limited, applying CCS to a cluster of CO_2 and other GHG sources may improve economies of scale, and have advantages in terms of planning requirements, public acceptance and transport infrastructure (McKinsey & Company 2008). The concentration of low-carbon industries within a region could also create industrial hubs of CCS expertise. There have been a number of propositions for industrial collaborations on CCS within Europe and Australia which seek to exploit these opportunities.

The proposed CCS cluster in the Port of Rotterdam in the Netherlands is probably the most advanced of these. The port and the surrounding area is highly industrialised, with a large number of refineries and petrochemical companies. In 2007, as part of the Rotterdam Climate Initiative, a roadmap was devised to deploy a number of CCS demonstration installations in the region before 2025, in both the power and industry sectors, capable of annually capturing 20Mt/y at full deployment (DCMR, 2009). The development of the CCS cluster has been assisted through engagement and dialogue with companies such as Shell, E.ON, Essent, Air Products, Gaz de France, TAGA and Wintershall. All the companies are involved operating either production facilities in the port area or oil and gas extraction platforms off the coast of the Netherlands in the North Sea.

There are separate proposals for a CCS cluster in the Teesside region in the North-East of the United Kingdom. The proposed CCS installations include a new 800 MW integrated gasification combined power plant planned by Centrica plc, and the retrofit of CCS to the 420 MW Lynemouth coal-fired power station owned by Rio Tinto Alcan. The implementation of these initial projects is expected to capture 7.5 Mt CO_2 a year, with the possibility of including other industries in the cluster to double this to 15 MtCO_2 a year. In addition to reducing CO_2 emissions, the regional development agency views the development of the cluster as an opportunity to safeguard current jobs and to stimulate further employment in the area. The implementation of the proposed CCS installations is dependent on government funding.

In Sweden, research is being undertaken to study a cluster of CCS opportuntities in the Skagerrak region. The aim of this project is to link identified suitable sinks to CO_2 sources above 0.5 M tonne/year in the region which include: three power plants, three refineries, two cement plants, one petrochemical plant, one paper & pulp mill, one ammonia and one ethylene plant. The total emissions from these plants are about 12 M tonne/year. The potential sinks identified in the region including onshore and offshore aquifers as well as oil and gas fields in the North Sea.

7.3 One-company value chains: BP's Decarbonised Fuel projects

One of the barriers to the implementation of CCS is the diversity of industries involved. This ranges from risk-seeking oil and gas companies with high profit margins, to risk-averse power companies, to industries that compete in global markets with very tight margins.

BP has been exploring the possibility of creating value from CCS through its vertical operations by establishing a model which would enable the delivery of decarbonised fuel (DF) to customers. In the Peterhead (or DF-1) project in the United Kingdom, BP aimed to extract oil, to gasify it to produce CO_2 and hydrogen, to separate the CO_2 to use for EOR, and to supply the hydrogen to a power plant. The viability of the project was dependent on a subsidy from the government which did not in the event materialise.

Two other DF-projects, the Carson project in the United States involving pet coke and the Kwinana project in Australia, were abandoned for a range of other reasons.

A further DF project (DF-4) may now potentially to go ahead. Hydrogen Power Abu Dhabi (HPAD) was launched in 2007 as a joint venture between BP Alternative Energy and MASDAR (the Abu Dhabi Future Energy Company). The joint venture plans to produce hydrogen from natural gas and then to use the hydrogen to operate a 400 MW power plant. This will constitute 5% of Abu Dhabi's power capacity. 90% of the CO_2 resulting from the hydrogen production process will be captured and transported by pipeline to be used for EOR in the area, ultimately being stored. The project, expected to be operating commercially by 2012, will store 1.7 Mt of CO_2 a year.

7.4 Synergies between industrial production and power generation

Opportunities also exist to collocate a number of industrial plants, or a number of industrial and power plants, to maximise the opportunities for sharing equipment, or one plant utilising the waste process from another, and thereby reduce the costs of carbon capture. For instance, industrial plants which need large volumes of oxygen for oxyfuel processes could be sited near, and share the output from, a single air separation plant.

Within individual industries, a number of synergistic opportunities also offer themselves. Two specific such opportunities are outlined below.

7.4.1 Polygeneration opportunities in steel production

Liu et al. (2010) highlights a number of breakthrough concepts which may have a significant impact on enabling the application of CCS to reduce CO_2 emissions from China's steel production and power generation industries.

One of the concepts is the possibility of combining a new form of blast furnace with a combined cycle power generation unit. The blast furnace would be fuelled by the injection of super-enriched air with a higher than normal oxygen content. The top gas produced within the blast furnace would be recovered and used for power generation.

In this concept, the increased oxygen level would enhance the ability of the coal feed to act as an iron reductant, and allow it to be gasified within the blast furnace to produce a top gas with improved fuel properties (Lanyi et al. 2010). The blast furnace top gas would be primarily made up of CO and H_2. In order to increase the concentration of H_2 (the fuel content) in the gas before it was fed into the turbine of the power plant, CO would need to be removed. This could be achieved using a shift reactor which converted the CO into CO_2, which could then be efficiently removed using conventional CO_2 removal techniques. The process is outlined in figure 7.1.

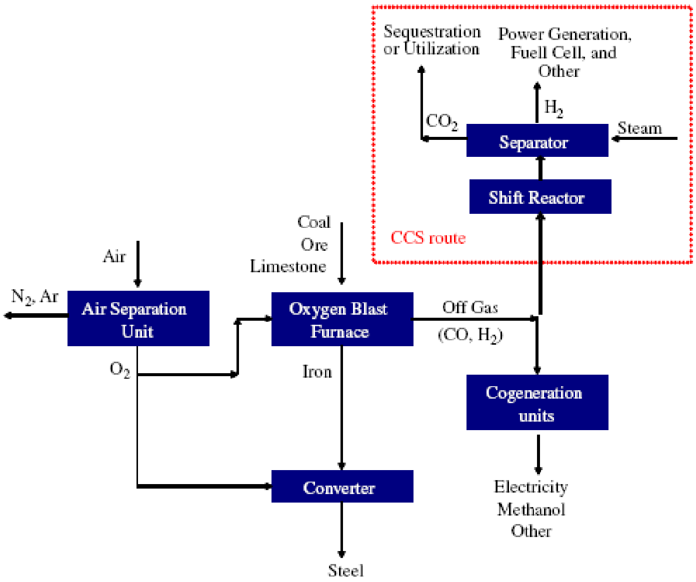

Fig. 14. Schematic view of P-OBF.

Figure 7.1 Oxygen blast furnace with combined cycle power plant (Liu et al. 2010)

As discussed in section 3.3.2 above, a small number of direct reduced iron (DRI) installations have been combined with coal gasification installations and configured to use the coal-derived syngas as the reducing gas for iron production. CO_2 from the gasification process could be captured using pre-combustion technologies (Knop et al., 2008). It would also be possible also to use H_2 from the gasifier to run a combined cycle power plant.

DRI based on synfuel has significant potential for application in developing countries with limited access to natural gas but an abundance of coal. The DRI syngas combination is already in successful operation in China. It seems likely to grow as an approach, given China's accelerating investment in gasification technology (Liu et al., 2008).

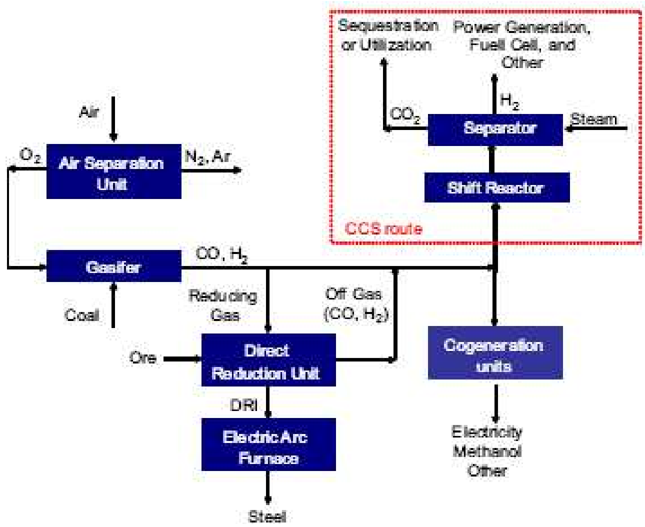

Figure 7.2 DRI process with a combined cycle power plant (Liu et al. 2010)

7.4.2 Carbonate looping and CO_2 capture from power plants

In carbonate looping, calcium oxide is put into contact with the combustion gas containing CO_2 to produce calcium carbonate. The calcium oxide is regenerated by calcination, giving a CO_2 offgas. The carbonation and calcination loop can be used to capture the CO_2 from the flue gases of combustion chambers, such the boilers of power plants. In some circumstances, it may theoretically be possible to combine a power plant and a cement plant, with the clinker burning process utilising the degraded CaO from the looping process (see Figure 7.3).

Carbonation technology is not yet sufficiently developed to enable CO_2 capture, and the potential synergy between power and cement plants has yet to be tested (ECRA, 2009b).

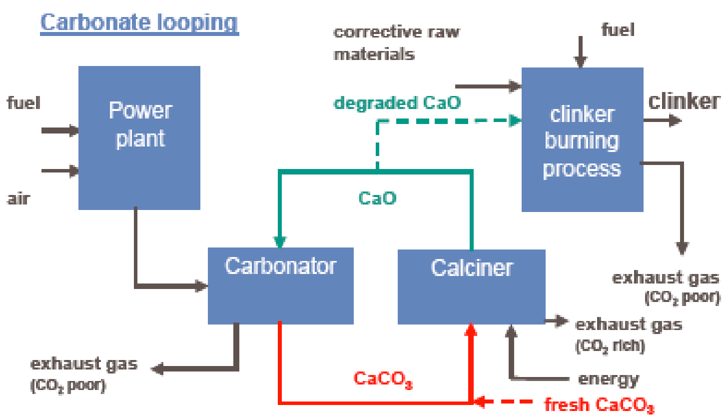

Figure 7.3 Combination of power plant and cement plant with carbonate looping (ECRA, 2009b)

8. Main gaps for CCS in industrial CO_2 sources

Although a good deal of information is available on the technology, economics and policies relevant to industrial CCS, many gaps and challenges in knowledge and action remain. The most important ones include:

- Lack of emission and emission projection data;
- Lack of real data on engineering costs;
- Inconsistencies in reporting on estimated cost data;
- The confidentiality of industrial data;
- Lack of awareness and political will to deliver industrial CCS;
- Low awareness and limited relevant human capacity in developing countries; and
- Lack of progress on developing policies for CCS in a global framework.

What needs to be done?

Industrial CCS cost could be reduced through transportation and storage infrastructure. Spatial planning aiming for industrial hubs can facilitate CCS.

Risks must be reduced. Demonstration plants are needed to prove the feasibility of industrial CCS, ascertain smooth operation and create more clarity concerning CCS cost. A regulatory or pricing system that creates an incentive for CCS and other mitigation options is required. If a global system is not possible, a policy framework must correct for trade-distorting effects. Global sectoral approaches could constitute one way ahead for the short term.

Industrial CCS should be supplemented by a long-term strategy to wean industry off carbon containing energy carriers. Electricity and hydrogen from zero-carbon sources and development of new materials and services with low energy intensity need to be pursued further.

Demonstration projects

It is recommended to build demonstration plants in developed and developing countries. Involvement of China will be critical as the country accounts for half of global primary steel, cement and clinker production. In addition, China's industry is largely coal-based. The Middle East could play a critical role in the demonstration phase because of interesting CO_2-EOR opportunities.

In order to scale-up the technology, the IEA has proposed that 100 additional commercial scale demonstration projects will be needed by 2020, in a number of countries and settings (*IEA Technology Roadmap Carbon capture and storage, 2009*). Data on project demonstration real cost needs to be made available.

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Annex I : Abridged meeting report Abu Dhabi – full report available from UNIDO

The Global Technology Roadmap on CCS in Industry

In February 2010, a project was launched to develop a global technology roadmap on carbon capture and storage applications in industry. CCS is generally associated with applications in the power sector, however there are potential opportunities to deploy the same basic fundamental technologies in many of the world's largest industrial sectors. Critically, there still remain significant knowledge gaps in moving towards commercial implementation of carbon capture and storage, especially in industry. The roadmap will explore the technical details, deployment potential and specific policy and regulatory aspects of CCS deployment in industry, while simultaneously raising the awareness of the subject.

Initiated by the United Nations Industrial Development Organization (UNIDO), the EUR 500,000 project is supported by the Norwegian Ministry of Petroleum and Energy and the Global Carbon Capture and Storage (CCS) Institute. The project will draw from the methodologies and experience of the partners in technology foresight and road-mapping, and provide relevant stakeholders with a vision of industrial carbon capture and storage up to 2050. It will have a focus on developing countries with energy intensive industries, and aim to inform policymakers and investors about the potential of such technologies. The roadmap is due for completion by the end of 2010.

As part of the project, two workshops will be organized. This document serves as the report of the first workshop in Abu Dhabi, which congregated an international group of industry representatives and experts.

Objective of the meeting

The workshop has served several purposes. First, it was intended to provide the Global Technology Roadmap on CCS in Industry with information about the sectors by bringing together experts and discussing the work done so far. Second, it was intended as an opportunity for stakeholders from a wide range of countries, including developing countries, to gain insights on potential opportunities for CCS.

The workshop was structured in a plenary session setting the scene, and four parallel breakout sessions with a sectoral focus. In addition, there were crosscutting issues in which representatives of the different sectoral workshops could discuss alignment, similarities, differences and overlap on four different topics: long-term vision, data and projections; costs and financing, incentives and regulation, and technical issues for transport and storage. The crosscutting groups report back into the sectoral workshops, and the sectoral workshops presented the outcomes in the plenary.

1. Introductory sessions

1.1. Opening

During the opening session, the speakers highlighted the importance of advancing CCS in industry. A presentation was given on behalf of one of the sponsors of the Roadmap, the Global Carbon Capture and Storage Institute (Global CCS Institute). The objective of the Global CCS Institute is to bring together the public and private sectors to build and share the know-how and expertise necessary to ensure that carbon capture and storage (CCS) can make a significant impact on reducing the world's greenhouse gas emissions. The Institute facilitates the deployment of CCS projects by sharing knowledge; fact-based advocacy and assisting projects. The Global CCS Institute aims to encourage CCS demonstration projects, of which a 'balanced portfolio' of CCS demonstrations between developing and developed countries, and between the power sector and industry are needed.

MASDAR, a partner in the Roadmap and host of the meeting, also provided an opening speech. It was highlighted that although the Emirate of Abu Dhabi is a fossil-fuel dependent economy, the governing bodies are aware that such resources are finite, and that it is important to look into renewable sources of energy, and to explore CCS in attempts to mitigate climate change.

1.2. Scene Setting

During the scene setting part of the meeting, presentations were given by UNIDO, the IEA and the Energy research Centre of the Netherlands (ECN). Brief summaries of each are shown in respective order below.

Industry accounts for approximately 40% of total energy-related CO_2 emissions. The majority of industrial energy use takes place in developing countries, and the involvement of such countries in technological development is important. In certain industrial sectors, such as the cement sector, CCS is the only way to significantly reduce CO_2 emissions. So far, the majority of attention has been given to CCS deployment within the power sector.

According to the IEA, not considering CCS as a mitigation option will increase the costs of achieving a 50% reduction on 1990 CO_2 levels by 2050, by approximately 70%. Within the IEA Technology Roadmap for Carbon Capture and Storage (2009), almost half of the emission reduction potential using CCS needs to occur in industry, if this target will be reached at the lowest possible cost.

A roadmap is actionable, and should provide an agenda to act for government, industry and the financial sector. The progress through a roadmap can be measured by defining milestones to be reach, for example, a certain number of CCS demonstrations in industry by a specific point in time. This Roadmap starts with an assessment of the current situation, and then uses data, methods and assumptions to derive a vision of the future.

Actions and milestones, gaps and barriers and relevant actors and stakeholders will then be identified.

2. Sectoral workshops

The sectoral workshops had three sessions: one scene-setting session on the background, data and broad characteristics of the sector; the second session on the gaps and barriers to a future, low-carbon vision for the sector, and the third on potential actions and milestones to be included in the roadmap. The sectors discussed were:

1) High-purity CO_2 sources
2) Cement
3) Iron and steel
4) Refineries
5) Biomass-based sources

2.1. High-purity CO_2 sources

The UNIDO CCS Roadmap for industry - high purity sector workshop - brought together a range of expertise from the natural gas production industry (e.g. OMV, BP, PTTEP), equipment and service providers (e.g. Schlumberger, Linde) and secondary manufacturers (e.g. the Indian Fertiliser Association), as well as respected academics in the field of carbon capture and storage (CCS).

The sectors to be included in the high-purity section are gas processing/refining; hydrogen production/ammonia production (and fertiliser production from NH3); synthetic fuel production (synthetic gas production/coal-to-liquids/gas-to-liquids); and ethylene oxide production. The unifying feature between the sectors is the production of high CO_2 concentration process offgas streams, which are readily available for CCS without the need to "capture" CO_2 (i.e. without the need to concentrate a dilute stream of CO_2 to make it economically viable to transport and store).

Most current CCS demonstration projects are taking place in the high purity sector (e.g. Sleipner, In Salah), and the skills and technologies have for CCS have been used in this sector for many years (e.g. gasification technology). The fertiliser industry is also capturing CO_2 from flue gas to provide additional CO_2 for urea production. High purity sources offer the lowest capture costs – as little as \$8/tCO_2 – compared to the "typical" costs cited for CCS deployment (e.g. in the range \$50-\$100/tCO_2 for the power sector).

Enhanced oil recovery using CO_2 should also act as a major pull factor to potentially develop early opportunity CCS projects using CO_2 from high purity sources. The evidence that this can be achieved is demonstrated through the network of CO_2 infrastructure in the United States. Here low cost and mined CO_2 is supplied at a price of c. \$35/tCO_2 at the wellhead to oil field operators for tertiary oil recovery in mature fields; the economic benefits are clear as 1tCO_2 can deliver 2-3 incremental barrels of oil (this adds around \$11-17 to the marginal production cost per barrel in these regions, which is still economically attractive). This discussion set the tone for many subsequent sessions of the workshop, where a focus was maintained on the role of CO_2-EOR in pulling in high-purity CO_2 sources as a form of early demonstration for CCS technology (in the absence of CO_2 price incentives).

The second session focused on gaps and barriers to CCS deployment. Gaps were highlighted in a range of areas including the lack of CO_2 transportation networks in which to place high purity CO_2 (to deliver it to oilfields); the need for better source-sink matching to understand potential; improved understanding of offshore EOR potential (and challenges); a lack of data on future emissions from natural gas production; clearer understanding of future fertilizer production pathways; and understanding of possible perverse outcomes through incentivising CCS for process offgas streams. Indentified barriers to deployment included: the lack of a CO_2 price incentive; oilfield economics (for EOR); whether high purity sources are sufficient for EOR; and operator perception of CO_2 injection into oilfields.

The third session focused on actions and milestones for CCS deployment in the sector. Near-term actions were highlighted as: identification of candidate regions with early CCS opportunities linked to high purity CO_2, raising of awareness amongst policy makers and other stakeholders of the role of early opportunities linked to high purity CO_2, cooperation and sharing of data; and the development of coherent policies and industrial strategies for CCS demonstration and deployment. A range of milestones were highlighted including the need to recognise CCS as a mitigation activity under UN mechanisms; recognition of CO_2-EOR as a mitigation activity; the establishment of standardised monitoring, reporting and verification requirements for CCS; and better information sharing through development such as a CO_2 storage map for key regions such as the Middle East.

2.2. Cement

During the cement sectoral session, the attendees agreed that deep reductions in CO_2 emissions within the cement sector would only be possible with CCS. Also from the discussion it was noted that of the gaps and barriers were shared with other sectors. A financing mechanism, the typical location of cement plants to limestone quarries rather than CO_2 sinks, the reliance of the industry on technology providers to undertake the necessary R&D and the reluctance of cement producers to undertake non-core business operations (such as CO_2 capture, transport and storage) were some of key barriers identified by the group.

Although within the group it was generally felt the projections by the IEA regarding uptake of CCS were optimistic the importance and need for engagement with India and China was identified. Regulatory clarity and funding of demonstration projects (particularly oxyfuel cement plants) also emerged as key actions.

2.3. Iron and steel

The iron and steel sector is rather proactive in terms of CO_2-lean steelmaking, with programs aimed at developing breakthrough technologies that have been launched across the world for almost 10 years. The most comprehensive and ambitious program in the sector is the EU ULCOS program, which has presently reached the point where a demonstrator of one of its 4 flagship projects is proceeding towards a full CCS implementation on a blast furnace in France (ULCOS-BF), with storage in a deep saline aquifer. Other programs are active and exchange news on their progress in a Forum of Worldsteel, the sectoral business association, called "CO_2 Breakthrough Program Committee". The project of MASDAR and Emirates Steel to capture and use the CO_2 for EOR is also quite exemplary. Both the ULCOS-BF and the UAE projects should go on stream around 2015.

CCS has a large role to play in the steel sector, because carbon is used in the sector as a metallurgical reducing agent, not as a fuel for combustion. This, however, raises issues as technologies tailored for the sector have to be developed. Favored are so-called "in-process" capture, which does not match any of the categories familiar in the case of combustion, which offer the promise of reducing energy needs and increasing productivity in parallel to their effect on GHG mitigation. There are however, longer term options, also under development in ULCOS, which are post-carbon society solutions, based on the use of electricity, hydrogen and biomass and thus different from CCS.

Currently, there are many hurdles to overcome until this vision is turned into practical, commercial implementation, with hoards of risks. None of the steel CCS solutions are no-regret as they imply extra OPEX and CAPEX, the financing of which remains very uncertain today - which is not helpful in a business context. To ensure that the new technologies are actually developed calls for large subsidies from governments and regional organizations to let the process gear up to speed; some more political solutions will be needed to ensure deployment of the technology, foremost of which is a world level playing field to avoid carbon leakage to carbon-haven countries. A worst case scenario, where all the risks would materialize, would mean that the implementation of CCS might not take place at all, beyond an initial demonstration stage. The issue of the social acceptance of CCS was also discussed, with the uncertainties that it carries.

It was also pointed out that the temporalities for developing new technologies and deploying them is not in line with the target of, for example, 100 CCS plants by 2020, posted in the IEA Blue Map. The process will be much slower at the beginning than expected by international organizations, because time needed to practically move forward has been underestimated by them. The point of developing very many demonstrators, like what is preferred in the coal-based electricity sector, does not apply in the steel sector, at least in the short term (until 2020, when technologies like HIsarna or ULCORED will become ripe). A single demonstrator or very few of them seems to be sufficient.

The barriers to CCS deployment in the sector were also discussed. The issue of the quality of the data on present emissions and energy consumptions was also debated, with a strong focus on their uncertainties and fuzziness. There is a lack of knowledge regarding the geology of the underground, worldwide, especially regarding the deep saline aquifer geological layers of interest. This data gathering is needed and it is probably the responsibility of the states to take care of it. There is also a lack of experience, competence and knowledge on CCS in the iron and steel sector. Efforts in capacity building will be needed. A strong communication program, oriented towards a general public, is also important.

The concept of "CCS ready" can make sense in the steel sector, for the ULCOS-BF, for example, where it would mean operating the furnace with pure oxygen and recycling the top gas after de-carbonizing it. This is a major technology shift, with does not simply mean that provisions have been made for later storage, like what is often meant in the power sector. The concept may be a bit fuzzy and needs clarification.

2.4. Refineries

Participants who took part in this sector workshop agreed that the technical challenge with refineries is the complexity and the variation in the unit operations at each facility and hence the vastly different emissions sources at each. Because of this a simplification is considered the best approach and the methodology used was acceptable, but when defining capture options it is important to make distinction between Greenfield and Brownfield installations. A point may be to investigate the proportion of IOCs, NOCs, and JVs in the refining industry and the relative willingness of each category to undertake CCS. There is also a need to comment on the impact non-conventional fuels are likely to have on the refining industry, eg. NGLs, GTLs, CTLs & bio-fuels. The participants could not offer any recommendations of data sources for emissions projections or for the role of CCS in the refining sector, but did offer some good technical references.

The second session focused on the gaps and barriers, associated with deploying CCS in the refining sector. For this section gaps and barriers were categorised as specific to the sector or applicable to all CCS deployment. Issues specific to refining industry are: low refining margins, lack of real estate to retrofit CCS technology, multiple relatively small sources of different CO_2 specifications. Issues which are more broadly related to all sectors are: finance, storage, water and electricity supplies, CO_2 specification, and legislation. A weakness for this discussion was the technical background of the participants, which lead to a focus on issues at a more detailed level than policy.

The third and final session attempted to specify some sector specific actions and milestones to roll out CCS. The conversation concentrated on lack of actual data and experience with CCS. It was felt in order to put any sort of legislation in place there was a need to introduce standard methodologies for emissions measurement and develop a comprehensive emissions inventory. There is also a need to increase awareness of CCS in the refining industry, particularly amongst the engineers and professionals, both through course and design guidelines/standards. Outside of Europe and North America, CCS is a relatively unknown technology. Knowledge transfer and sharing with developing nations is considered very important to the quick deployment of CCS. Under all scenarios, there is a need to demonstrate CCS technology and the high purity CO_2 sources in the refining industry offer the opportunity for low cost demonstration, to prove to the developing regions that technology is viable. Local “champions” for CCS technology will increase the opportunities to demonstrate and disseminate the technology.

2.5. Biomass-based sources

Biomass-based industrial CO_2 sources form an indispensable solution in pursuit of low GHG concentration stabilization levels in the atmosphere. A wide array of biomass-based industrial CO_2 sources are expected to be available in both short- and long-term future, and as a result the CO_2 capture costs for biomass-based CO_2 sources will probably vary significantly. CO_2 capture during ethanol production offers a large-scale near-term opportunity at relatively low CO_2 capture costs. CO_2 capture during production of synfuels and H2 from biomass is projected to capture 2.1 Gt CO_2 by 2050, according to the BLUE map high scenario presented in the IEA technology roadmap for CCS (2009). However, less than a handful of pilot and demonstration plants are planned or under construction to date.

Bio Energy with Carbon Capture and Storage (BECCS) is a forgotten technology at present; it is overlooked by both biomass and CCS communities. The technology lacks industrial champions to pursue broad implementation, while there is a lack of awareness amongst policy makers. Consequently, BECCS is excluded from any incentive or demonstration programme that is currently in place.

One of the first actions to be undertaken is the formation of a BECCS stakeholder network. This requires mobilization of all relevant communities: policy makers, NGO's, scientific community and industry champions. The involvement of bodies such as the IEA, UNIDO and the Global CCS Institute is considered to be essential in the formation of such a network. Other early movers are nations that could have a short-term interest in application, being Brazil, Sweden, the USA and Indonesia. The UNFCCC could play key role in recognizing negative emission accounting for BECCS. More detailed scientific studies are needed on costs, long-term contribution on GHG reduction and early opportunities. Dedicated BECCS pilot and demonstration projects should be facilitated.

3. Crosscutting issues

In addition to the specific sectoral sessions, the participants were also invited to take part in one of the cross-cutting sessions, 5 of which ran in parallel on the second day of the workshop. The topics covered in these cross-cutting sessions (see 5.1 – 5.5) were considered important for all industrial sectors.

3.1. Long-term vision, data and uncertainties

This session commenced with a discussion of the new data which would be released by the IEA within the Energy Technology Perspectives (ETP) 2010 report on the 1st July 2010. Insights were provided into how the data and information in the new report may have altered since the previous Energy Technology Perspectives 2008 report. A key difference is the use of the updated World Energy Outlook 2009 emission baseline data, which accounts for the global economic crisis in 2008, It was highlighted that the due to the economic crisis, the baseline scenario for CO_2 emissions up until 2050 has been reduced by approximately 5 Gt. The projections for CCS deployment were also understood to have decreased, although no exact figure could be presented.

The projections for CCS deployment in industry presented in the IEA Technology Roadmap Carbon Capture and Storage (2009) were reviewed. The representatives of the sectors were asked to give their expert opinion on the plausibility of the data presented in the document, specifically in terms of the levels of emissions that were projected to be abated in each sector by 2020. Within the session, experts in the field of biomass, steel and cement production were present. There was a general consensus that the level of CCS deployment by 2020 presented in the IEA roadmap was unattainable given the current status of the technology, this was particularly so for the biomass sector due to the relative immaturity and low scale of biomass-to-liquid (BTL) and hydrogen production (via biomass).

The model used by the IEA to generate such projections identifies the lowest cost combination of technologies to achieve a 50% reduction in CO_2 emissions from 1990 levels, by 2050 (The IEA Blue MAP scenario). The model is intrinsically optimistic, which explains the high projections of CCS deployment in industry. Nevertheless, it was challenged that producing a roadmap with potentially unrealistic deployment potentials may not be well received by industry stakeholders, and thus the value of the roadmap could be significantly reduced. The use of alternative scenarios for the roadmap were discussed, however no conclusion was reached.

3.2. Costs, financing and business models

It is generally accepted that taxation and emissions trading schemes are going to adversely affect industry, unless a truly global deal is found. Until there are better incentives and prices on carbon then it is unlikely that CCS will be widely deployed commercially. Until such a time there are still niche markets for financing some projects through sale of carbon credits to either high priced carbon countries such as Norway and Sweden or by the Chicago carbon exchange, through EOR and also biomass CCS. Carbon credit mechanisms are limited in size, given the Chicago exchange only deals in about 10 Mt of credits per year. Biomass has the potential to get double credit for CO_2 sequestered and EOR because of the oil value.

It is felt that the public sector will probably have to make some of the initial investments to demonstrate technology and to build infrastructure. Private-public partnerships are seen as one method for governments to raise capital. Parallels were drawn with the initial deployment of natural gas and electricity infrastructure and the large public investments that were made in the initial deployments of these technologies. One of the big fears with adding CCS, is increasing the price to consumers and hence inducing fuel and energy poverty on them.

In terms of funding technology, US$40 billion has been pledged by nations at the Copenhagen Summit and UK, US and Australia all have funds for developing CCS in China. In order to reduce the risk to investors to raise finance, fundamental issues such as the security of utilities, carbon accounting mechanisms all need to be agreed at the highest levels. In summary until a global deal is agreed, there is limited financial opportunity available for a few small projects, enough to prove the technology, but not enough to deploy it as widely as required to meet international targets.

3.3. Incentives, policy and regulation

One of the key issues during this workshop was the general lack of sufficient financial incentives to deploy CCS. There are incentives to reduce CO_2 emissions within the

European Union through the Emission Trading Scheme (ETS), and Norway has introduced a carbon tax, however the prices are currently too low to stimulate investment in CCS. In developing countries, there are no incentives to deploy CCS, as emission reductions through CCS will not be assigned emission reduction credits under the UNFCCC Clean Development Mechanism (CDM). One of the complexities of a global price on carbon, is how you distribute the burden of cost across various economies in different stages of development across the globe.

It was recognized that in the EU, CCS demonstrations are also encouraged through direct government support, however these have tended to focus on the power sector. There is also no regulatory framework that exists that could incentive negative CO_2 emissions through the combination of CCS and biomass, and there is little funding or attention for such technologies.

The use of CO_2 collected from high-purity CO_2 sources and used for enhanced oil recovery (EOR) could lead to very low abatement costs, however EOR maybe more attractive and realistic in some regions than others. The lack of clear policy and regulatory guidelines linking EOR with a global climate framework is certainly a barrier to further deployment.

A main talking point in the session concerned 'carbon leakage'. Carbon leakage can occur when businesses shift production from nations with stringent regulatory regimes including high emission taxes or permit schemes, to nations with little or no regulatory enforcement in order to avoid losing profits. This could mean that instead of an overall reduction in carbon emissions, merely the distribution of emissions would be shifted across the globe. Due to issues such as proximity to markets, the mobility of industries and corporate strategy, it is unknown how serious the problem of carbon leakage may be, however it is a potential problem which may have to be addressed through policy.

A regulatory framework to cover issues such as public awareness and environmental impact statements were called for, and it was stated that policy and regulatory development must receive the same attention of technology development. In certain countries, existing legislation may block the deployment of CCS, for example in South Africa, anybody wanting to store CO_2 geologically would need to pay for a mineral right, in France a demonstration plant took 4 years to obtain an environmental permit, and in Indonesia it was thought that the current legislative framework could not 'handle' CCS.

The requirement for monitoring, measurement and verification (MMV) of CCS projects. A globally unified approach to MMV of CCS projects was called for, and it was agreed that capacity building is required to be able to ensure that MMV is completed correctly. MMV is particularly important under the scenario that geologically stored CO_2 would receive credits under the CDM, and the liability issues of CO_2 leakage over longer timeframes was also discussed.

3.4. Technical issues for CO_2 compression, transport and storage

The crosscutting group on technical issues related to transport and storage of CO_2 from industrial sources discussed two broad issues: 1) likelihood that industrial sources are close to storage reservoirs; 2) impurities requirements for transport and storage. The group had one representative from each sectoral workshop, and two from the refineries group.

With regard to the first issue, for biomass, cement and iron/steel there does not seem to be a relation between CO_2 source locations and geological storage reservoirs. Cement plants are generally built near limestone reservoirs, but there is no relationship between limestone and underground sedimentary basins. For gas processing plants, there is a relatively high likelihood that sources and reservoirs are close together, as the gas is recovered from a sedimentary basin. This explains the short transport distances in the Sleipner and In Salah projects. For refineries, there is not necessarily a proximity to oil or gas fields or to other sedimentary basins, but refineries are often built near the coast to allow for marine transport of oil, where prospective storage is also regularly located. This suggests a weak bias towards proximity of refineries to storage reservoirs.

Requirements for impurities in the CO_2 stream depend on the application of the CO_2 and on the mode, organization and distance of the CO_2 transport. If the CO_2 is used for EOR, its requirements for low oxygen levels are very strict. This might be an issue if the CO_2 originates from an oxy-fired cement kiln. If the transport is long-distance or in a network with various sources, dehydration is important to prevent leaking of pipelines, but if the CO_2 is intended for EOR and the source is close by, it might be more cost-effective to build a short stainless steel pipeline, and leave the water in the CO_2, as it is no problem to inject water with CO_2 for EOR. There may also be a requirement to have phase purity to ease compression. In general, however, if a transport network is designed in which a variety of industrial and electricity sources of CO_2 feed the CO_2, and various storage applications. What was also flagged was a lack of awareness with the CO_2-emitting industries about underground storage issues, such as impurities.

It is recommended that guidelines and standards for impurities are drafted with ranges in mind. Guidelines should recommend to start basing impurity requirements with requirements for storage or EOR and work via the transport phase to what the source of CO_2 should do to meet the requirements. This could be done in a flow diagram or a table.

4. Early opportunities in the Middle East

Most countries in the Middle East can be characterized as energy-intensive economies because of a large oil and gas industry and associated industrial activities. It is projected that demand for electricity and gas will increase rapidly in the region. Another characteristic, relevant to CCS that is inherent in the region is the opportunity to implement CO_2-EOR. Contrary to other places in the world, EOR can be seen as a main driver for CCS – it can provide the demand pull factor for separation and use of CO_2, instead of its emission to the atmosphere.

The crosscutting group resulted in a distribution of Middle Eastern countries over three main categories:

1) Countries in which CCS (with EOR) will take 10 to 15 years to materialize. The oil and gas demand is there and EOR opportunities are there. Knowledge build-up is taking

place and there are some government activities, but it will not be until 2020 or after that CCS is a broad possibility. Examples could be Saudi Arabia and Kuwait.

2) Countries that are a step further: There is political will to act on climate change, there are sources of CO_2, but the possibilities for EOR are limited in the short term. With an incentive and more capacity development, these countries could start relatively soon with implementation, possibly within 10 years. Examples could be Qatar and Oman.
3) Countries for which all ingredients are in place: EOR capacity, sources of CO_2, political will, human capacity and companies to implement (such as Masdar). These countries lack the level of organization and the interaction between sources and reservoirs of CO_2. Examples: UAE and Iran (although the technological availability in Iran is an issue)

The different categories of countries would require different action plans. In some countries, international organizations could play a role to see whether political will can be built. On the other hand, however, the limitations will need to be understood; in particular the lack of a global climate change agreement with clear incentives for emission reductions, which means that an EOR demand pull is essential for short-term rollout of CCS.

5. Next steps

The next steps towards the preparation of the Global Technology Roadmap on CCS in Industry are:

- Finalization of the sectoral assessments based on the sectoral workshop inputs and further information. Circulation for review by July 28.
- Drafting of the Roadmap. Circulation for review among stakeholders on August 15.
- Organization of a second meeting for review of the Roadmap around GHGT10 in Amsterdam.
- Finalization of the full roadmap, publication of sectoral assessment and launch.

Annex II Meeting report Amsterdam

1. The Global Technology Roadmap on CCS in Industry

This document serves as the report of the second workshop in Amsterdam, which congregated an international group of industry representatives and experts.

2. Objective of the meeting

The goal of the meeting was to gather further input for improving and advancing the roadmap. Prior to the meeting, five sectoral assessments and a zero-order draft roadmap was distributed to the selected participants. The participants included a mix of representatives from industry, governmental and non-governmental organizations, from both developed and developing countries. Specifically, the workshop had been arranged to:

- Highlight issues such as data availability and data variables experienced by the roadmap authors, and collect input on possible ways forward
- Discuss a number of selected topics that are to be covered extensively in the final roadmap document, such as business models for CCS in industry, source/sink matching and the identification of concrete early opportunities for CCS in developing countries
- Gather feedback on the draft roadmap document

The opening session presentations were given by representatives of the project implementing agency (UNIDO), the meeting hosts (Shell), the project sponsors (the Global CCS Institute and the Norwegian Ministry of Petroleum and Energy) and the lead consultants (ECN) (section 3). The remainder of the meeting was organised into two sets of three parallel breakout sessions, covering six selected topics of discussion (section 4) and a feedback session (section 5). Section 6 of this report discussed the next steps.

3. Opening session

After the opening of the meeting by Dolf Gielen (Chief - Industrial Energy Efficiency at UNIDO), Wilfried Maas (Shell Amsterdam) welcomed the participants on behalf of the Shell Research and Technology Centre in Amsterdam. Mr. Maas explained the activities taking place on the Shell premises, the features of the new building and the urban development taking place around the premises.

Tim Bertels, Shell's CCS Projects Portfolio Manager, presented Shell's extensive CCS activities and experiences. To continue meeting the world's growing energy demand, while reducing greenhouse gas (GHG) emissions, several pathways must be pursued. CCS is one of the key pathways that Shell is progressing along with energy efficiency, low CO_2 fuel options, and advocating more effective CO_2 regulations to reduce global GHGs. Shell's CCS project portfolio includes industrial scale projects in development, including involvement in the Mongstad refinery project planned for 2014 in Norway, the

Quest Athabasca oil sands project in Canada planned for 2015, and the Gorgon Liquefied Natural Gas Project planned for 2014 in Australia.

Bob Pegler, Senior Vice President of the Global CCS Institute, briefly reinstated that the objectives of the Global CCS Institute. The objective of the Global CCS Institute is to bring together the public and private sectors to build and share the know-how and expertise necessary to ensure that carbon capture and storage (CCS) can make a significant impact on reducing the world's greenhouse gas emissions. The Institute facilitates the deployment of CCS projects by sharing knowledge; fact-based advocacy and assisting projects. The Global CCS Institute aims to encourage CCS demonstration projects. A 'balanced portfolio' is needed of CCS demonstrations in developing and developed countries, and in the power sector and industry.

Kristoffer Stabrun of the Climate, Industry and Technology Department of the Norwegian Ministry of Petroleum and Energy reiterated the need for increased attention for CCS demonstrations in industry, and highlighted that CO_2 has been injected in the Sleipner and Snøhvit fields in Norway successfully for a number of years, to a large degree thanks to a tax on CO_2 emissions. The Norwegian government is committed to developing CCS on a large scale, and the total public spending on CCS in 2009-2010 combined was approximately US$800 million.

Dolf Gielen then introduced the Global Technology Roadmap on CCS from industrial CO_2 sources project and the main objectives of the roadmap. Industry accounts for approximately 40% of total energy-related CO_2 emissions. The majority of industrial energy use takes place in developing countries, and the involvement of such countries in technological development is important. In certain industrial sectors, such as the cement sector, CCS is the only way to significantly reduce CO_2 emissions. However so far, the majority of attention has been devoted to CCS deployment within the power sector.

Since the beginning of the roadmap project in February 2010, assessments of the potential for CCS in the cement, iron and steel, refinery, biomass-based and high-purity (including natural gas, hydrogen production and coal-to-liquids) industrial sectors have been commissioned and completed. An initial two day workshop has taken place in Abu Dhabi on June 30th to August 1st, hosted by MASDAR, involving a technology scoping exercise for the industrial sectors covered. The information provided in the sector assessments have been incorporated in a draft roadmap that has recently be released. Furthermore, it has been deemed necessary to commission two further studies to support the roadmap, providing greater detail on source-sink matching and the possibilities for CO_2 enhanced oil recovery in developing countries. Although it is not expected that the final roadmap will be available in time for the 16th Conference of the Parties (COP) to the United Nations Framework on Climate Change Conference (UNFCCC) in Cancún, Mexico starting at the end of November 2010, a technical synthesis report and a short policy document summarizing the key roadmap messages is likely to be released for COP16.

The final presentation of the opening session was made by the principal consultant of the roadmap, Heleen de Coninck (Energy research Centre of the Netherlands). A roadmap is actionable, and should provide an agenda to act for government, industry and the financial sector. The progress through a roadmap can be measured by defining milestones to be reached, for example, a certain number of CCS demonstrations in industry by a specific point in time. De Coninck explained that it turned out more difficult than expected to distil consistent, comparable data from the different sectors covered in the roadmap, including projections to 2050, and recent emissions data for certain sectors. In addition, for some sectors, cost data are commercially sensitive and hard to get by. This is one of the reasons why more time is allocated for making a technological synthesis report. The data did not allow for the immediate translation of the sectoral assessments to a full and actionable roadmap. However, the Roadmap process has already raised the interest of industry and government for CCS in industrial sources, and has already led to higher awareness in developing countries.

4. Breakout groups

During the meeting, two rounds of three parallel breakout sessions took place, lasting roughly 1.5 hours each. Each breakout sessions was appointed a moderator (in brackets):

1a) Technology characterization (Chaired by Dolf Gielen)
b) Business models for CCS in industry, including EOR (Chaired by Wilfried Maas)
c) Bringing industrial CCS higher on the global agenda, and engaging developing countries and economies in transition (Chaired by Bob Pegler)

2a) Actions and milestones (Chaired by Kristoffer Stabrun and Bob Pegler)
b) Matching sources and sinks (Chaired by Mohammad Abuzahra, IEAGHG)
c) Identification of early opportunity projects (Chaired by Nathalie Trudeau, IEA)

The participants were asked to choose which session reflected the interests and expertise. Minutes of each breakout session can be found below.

4.1. Technology characterization

This session focused on the technology and data scope of the sectoral assessments, the technology synthesis report, and eventually the roadmap. The discussion focused on two key questions: what are the essential technologies to be included under the sectors, and what key variables affect CCS cost numbers?

The rationale for this session was that the data on the various sectors, for current emissions, projections and/or costs, were found to be highly variable and sometimes inconsistent. It was the aim of this particular breakout session to agree a list of technologies and identify the references for these technologies.

Data variables

Utilizing a set of common metrics for the CCS cost data for each of the individual industrial sectors was considered the best approach. Issues exist in choosing the most suitable reference to compare a industrial installation with CCS. For example, in the iron and steel industry, if you move from a blast furnace to a DRI process with capture, is the reference case a blast furnace without CCS or a DRI installation without capture? Further complications were also highlighted including the differences in global energy prices, average plant sizes and a suitable discount rate to use in economic assessments. Setting a consistent discount rate, or use of a typical commercial rate for a number of regions was recommended by participants. A sensitivity analysis could be conducted using different discount rates, however this was considered impractical given the amount of data and time restrictions.

It was discussed that by presenting both annualized costs, and upfront investment cost for CCS, the roadmap would be useful for both industry and policy makers. It was also recommended that the costs for CCS could be presented as a cost of an industrial product, cement for example, produced in a plant with and without capture. However, it was agreed that industry may not be so forthcoming with basic manufacturing costs.

Technology selection
It was raised by members of the cement industry that carbonate looping is a potential abatement option for the industry, and should receive attention in the roadmap.

For refineries, CO_2 capture from onsite hydrogen production plants would be the lowest-cost option to deploy CCS in the refining sector. The next-lowest cost was likely to be a fluid catalytic cracker (FCC) combined with oxyfuel technology. In addition, post or pre-combustion CCS could be applied to refinery plant utilities. Pre-combustion at utilities could unlock the potential for polygeneration, and the use of biomass.

Finally it was stressed that contrary to common assumptions, modern hydrogen manufacture does not typically result in high-purity CO_2 off-gases. However, the concentrations would be higher than those of CO_2 in coal or gas combustion exhausts.

4.2. Business models for CCS in industry, including EOR

The draft roadmap/technology synthesis report currently mentions four potential business models through which CCS from industrial CO_2 sources could become viable: industrial CCS projects with CO_2-EOR, certain industrial agglomerations, BP's Decarbonised Fuel projects, and oxyfuel in cement and steel. The discussion in the breakout group focussed primarily at possibilities for enhanced oil recovery, as being the low-hanging fruit in combination with industrial sources, and further on how storage providers and CO_2-emitting industries collaborate, how financing and investments can be enticed towards CCS, on sharing infrastructures, and on for which industries CCS is a cost only.

The group discussed EOR issues at length, and briefly also other revenue-generating options: Enhanced Coal Bed Methane and Enhanced Gas Recovery. CO_2-EOR can be a " leading-in" technology, as there is not enough potential to store all needed CO_2 emissions in EOR operations or even depleted oil fields (without EOR). The economic viability of CO_2-EOR depends on many factors: the reservoir specifics, the capture cost of CO_2 are both very important. In Indonesia, there are examples where cost recovery is not sufficient. In addition, CO_2-EOR has a distinct time window in the reservoir lifetime. All current CO_2-EOR activities are onshore, experience needs to be gained offshore, R&D

needs to take place to evaluate potential environmental impacts Regulation might need to be developed. It was also suggested that abandonment of oil recovery operations might have to be delayed in order to allow for CO_2 storage.

The need to help storage providers with a commercial model for CCS was emphasised. One of the potential models that was mentioned was that of CO_2 becoming an in-demand commodity to store, by providing a subsidy on storing CO_2. Storage providers, potentially oil and gas companies who already have much underground capabilities, will then source suppliers of affordable CO_2. Also, regulation on post-liability transfer and help with overcoming demonstration barriers is needed.

Policy to incentivise CCS needs to be in line with what investors and finance providers want to see to make CCS projects “bankable”. For this, the CCS community could learn from the renewable energy sector, as another sector with high upfront investment costs. A price on CO_2 or equivalent policy is a first condition as CCS, in by far most cases, is not economically viable.

A potential business case for CCS in industrial sources might be by sharing infrastructures and making use of industrial agglomerations. The Rotterdam Climate Initiative in the Rotterdam Harbour is a potential example of that. In certain specific areas, sharing infrastructure for transport and storage can make the business case for CCS more viable. It was recommended that the Roadmap looks for those areas and should attempt to make companies in such agglomerations aware of CCS.

4.3. Bringing industrial CCS higher on the global agenda, and engaging developing countries and economies in transition

The session reviewed the general understanding of the role of CCS in the global agenda and the motivation and actions needed to engage developing countries and economies in transition.

While identifying the reasons why most attention to CCS goes to capture from the power sector, as shown at the GHGT10 conference during which only one session was dedicated to CCS applications in industry, the following reasons were identified:

- a lack of climate commitments or concern for domestic mitigation actions prevents developing countries from considering certain technologies
- the fact that the current terminology/ language used for CCS promotion is structured by the power sector. The challenge for developing countries is that power generation is a domestic based sector, so it cannot attain the direct benefit from being carbon neutral in countries in which no mitigation target or regulations are in place. Moreover, most developing countries do not consider CCS as a competitor mitigation measure for renewable energy sources for CO_2 mitigation.
- Discussion in developing countries are of an academic or technical nature and have yet to mature into considering CCS as a business proposition.

The direct actions identified in order to raise the profile of CCS in industry higher on the scientific, industry and policy agenda are not easy to achieve and mainly depend on political decisions at country level. However, the following measures were discussed as actions that may trigger the interest of policymakers and decision makers:

- Involving global actors in the promotion of CCS for industry such as multilateral banks and international companies which may disseminate their knowledge and experience in countries in which national stakeholders are unaware or not engaged in the progress of CCS. For example, some Multilateral Development Banks, such as the World Bank and Asian Development Banks have raised awareness of CCS when requiring that new power generation units must capture ready in order to be financed.
- Identifying sources for funding for early stage development (R&D), and also promote capacity building in institutions which may become instrumental for development of CCS as a business such as financial institutions providing finance.

The main action to be taken to seize the attention of countries to CCS is raising the discussion level, by promoting a policy path which involves first defining Climate Change policies at national level tailored to the capabilities and needs, followed by identifying the need for domestic mitigation actions and finally by promoting technical measures amongst which CCS should be included.

With regards to the international community engaging developing countries and economies in transition, it was suggested that advocacy should be done for CCS as a single technology rather than differentiating industrial and power generation applications. More coordination amongst existing CCS initiatives should be achieved to prevent overwhelming developing country governments, a phenomenon defined as "CCS fatigue".

Finally, when defining which countries should be addressed first it was recognised that CCs priorities should consider the following criteria:

- ✓ Time and impact – where take up may occur faster
- ✓ Regions where there is interest and CCS will be part of the mix
- ✓ Countries which could serve as role models for regions

4.4. Actions and milestones

The sectoral assessments as well as the draft roadmap/technology synthesis report and the Abu Dhabi meeting report talk about gaps and barriers to CCS in industry, and identify a number of actions and milestones. Some of those actions and milestones were reviewed in this session. It was suggested to focus in particular on policy actions and milestones, as at the moment, the lack of a policy framework seems to be the area where most barriers arise. The participants identified governments as main actorsto undertake policy action, but as Copenhagen has delivered little concrete outcomes, the general opinion among the participants was not optimistic. It seemed there was little appetite for industry leadership, although the meeting did acknowledge that in the absence of a strong global framework, this might be necessary to keep CCS moving.

A long list of policy actions was discussed, including specific ones aimed at the early opportunities for CCS, such as a “zero-venting” policy for CO_2 from natural gas operations and specific stimulation of using CO_2 EOR possibilities for storage. The World Bank and other multilateral banks should start incorporating CCS in their portfolios, and should pay attention to CCS-readiness. Although a global roadmap on CCS in industrial sectors was seen as a good step, regional or technology-specific roadmaps are needed as a next step. Multilateral funding, possibly through the Copenhagen Accord mechanisms or multilateral banks, were considered to play a role in constructing those roadmaps – and following up in real projects.

For CCS in industrial sectors specifically, it was suggested that an official statement (e.g. by the G20) would help bringing it higher on the agenda. This could release much-needed funding for demonstrations.

4.5. Matching sources and sinks

The spatial distribution of current sources of CO_2 in industry is relatively well-known. The storage potential is surrounded with more uncertainty. The future developments of CO_2 sources in industry is also highly uncertain, despite the fact that the general perception is that matching is driven by storage rather than sources.

There is need define the capacity and type of reservoirs available as sinks and that this activity should be done as early as possible in the development of a CCC project. Participants form the oil and gas sectors stated that even in depleted oil field it takes need 5 to 8 years for testing / risk analysis before injecting. Participants proposed to prioritise opportunities for early stage development even with limited data available.

When considering the technical aspects, participants recognised the need for defining guidelines for the technical considerations of sinks, including their suitability, eligibility and testing required for validation. Matching of sources and sinks must be done considering three dimensions: general capacity of sink over its lifetime, annual volume that the sink may uptake and time match of source and sink. Minimum guidelines were also recommended for specification of gas to be injected, mainly its composition, such as oxygen levels, sour gas and water content. Finally, in term of CO_2 transport, participants were confident that there is sufficient knowledge on the technology and its costs.

Regarding policy issues, global regulations need to be considered, in particular cross-border issues. From example, concerns were raised regarding the London protocol amendment allowing CO_2 transport, that has not yet entered into force (only Norway has ratified). At the same time, participants indicated that CO_2 has been shipped for 30 years .

Participants raised public perception as a key issue since the public is largely unaware of CCS, especially in developing countries. They suggested that the roadmap could serve as a tool for communicating, and proposed that communication strategy should be defined. Such a strategy should explicitly consider local culture.

4.6. Identification of early opportunity projects

This is the most practical session, focused or real industry possibilities. The aim is to identify some 50 “lighthouse” of projects in developing countries, that are as economically and environmentally attractive as possible, and that could be funded – by business, national governments or international funding mechanisms. The idea is to get as far as possible with concrete project ideas in developing countries that can serve as a to-do list in the eventual roadmap.

The session began by discussing whether a criteria was necessary for selecting developing countries where early opportunities exist. It was agreed to use a definition of early opportunities as defined by the IPCC “as projects that [are likely to] “involve CO_2 captured from a high-purity, low-cost source, the transport of CO_2 over distances of less than 50 km, coupled with CO_2 storage in a value-added application such as EOR.”

Beyond the purely technical aspects of CCS, for example the availability of highly-concentrated CO_2 streams with close proximity to suitable storage sites, a number of additional points of consideration were raised. The willingness of a developing country to engage in CCS, the existence of policies relating to CCS, and the relevant capacity in both regulation and engineering were highlighted as important criteria. The selection of the country requires diligence, given the political sensitivities of CO_2 mitigation activities in developing countries. Ideally, the project would be located where it would reduce the most CO_2 emissions, however this may not be possible given the constraints and considerations listed above. It was raised that the selection of a CCS project site would preferably be made in an area with further CCS potential, anticipating that knowledge and capacity would be developed through an initial venture, although this was not considered essential given the uncertainty of funding or incentives for additional projects.

Specifically, a number of potentially suitable locations for CCS projects in developing countries were mentioned. Namely:

- The Recôncavo basin, Brazil. Petrobras have been injecting CO_2 for the purposes of EOR into a number of oil fields in this basin for 24 years. At present the EOR activities are relatively small scale at approximately 120 tonnes CO_2 per day, collected from an ammonia plant and an ethylene oxide production facility. Petrobras are also investigating CO_2 storage potential in a saline acquifer, which could be as high as 4000 tonnes per day. There are ideas to collect CO_2 from planned installations in the area, such as a gasification plant which could provide up to 1.3 $MtCO_2$/yr for EOR and geological storage. However, the project is restricted due to difficulty in attaining capital.
- Daqing and Jilin oilfields and saline aquifers of the Songliao basin, China. Originally investigated under the ‘Near Zero Emission Coal Project’, a joint project between the EU and China. This project has been in operation since 2006, but could be scaled up.
- Other less concrete opportunities exist in areas where enhanced oil recovery already takes place, however CO_2 could replace other injection gases such as

nitrogen (Cantarell oil field, Mexico) and natural gas (many parts of the Persian Gulf).

Iran is a developing country with an interest in CCS. An extensive inventory of CO_2 sources was available within the country, and that the identification of high-purity CO_2 sources for example from natural gas processing would be possible. In the Southern region of Iran, examples were provided of natural gas processing installations that emit approximately 1Mt of high-purity (>96%) CO_2 per year. In addition, the country has significant engineering expertise. However the deployment of CCS in Iran faces challenges such as a lack of capacity for extensive geological monitoring, and difficulties in acquiring compressors due to international sanctions against the country.

A brief discussion regarding the access to international funding mechanisms, such as the Global Environment Facility (GEF), and upon what conditions funding would be granted for a CCS demonstration project.

5. Synthesis session

The synthesis session was intended to disseminate the key points of each of the breakout sessions to all the participants, and to discuss the outcomes. A rapporteur from each of the breakout sessions held a short presentation. A number of questions were raised during the final presentations, which prompted discussion on possible policy approaches for CCS in the industrial sectors.

Leading in the discussions was the notion that with the weak signal from the Copenhagen Accord for emission reductions, CCS, including in industrial sectors, is unlikely to benefit from a global policy framework. Although in several developed countries, incentives are in place for CCS, most of these are for CCS in the power sector, and economic incentives for even low-cost CCS in developing countries is fully absent.

In trade-sensitive sectors, such as the iron and steel industry and refineries, carbon leakage is an important consideration. Alternative regulation for such sectors could be based on the carbon intensity of industrial products. It was suggested that this carbon intensity could be used as a basis for border-tax adjustments or sectoral agreements in which standards or best available technology could be enforced.

6. Next steps

For the roadmap project, the likely next steps are:

- Finalising the sectoral assessments where still needed (October 2010)
- Conducting two more studies: on Enhanced Oil Recovery and on matching sources and sinks (November 2010)
- Constructing a technology synthesis report from the sectoral assessment and complementary data (November 2010)
- Based on the technology synthesis report, write a four-page policy summary, to be finalized (and perhaps presented) at COP16 (December 2010)

- Use the dynamic around the Roadmap to process to identify potential projects and specifically engage relevant governments, companies and financers for such projects to realize those possibilities (continuous).
- Another meeting to discuss the roadmap document (tentatively scheduled for February 2011)
- Publication of the Global Technology Roadmap on CCS in industrial sources (Spring 2011)