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Global Technology Roadmap for CCS in Industry

Background Paper prepared for the Sectoral Workshops

30 June – 1 July 2010
Abu Dhabi, United Arab Emirates

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

BACKGROUND PAPER

Global Technology Roadmap for CCS in Industry

prepared by **Heleen de Coninck** and **Tom Mikunda**
Energy research Centre of the Netherlands (ECN)

for the Sectoral Workshops

30 June – 1 July 2010
Abu Dhabi, United Arab Emirates

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The Global Carbon Capture and Storage Institute is a bold new initiative aimed at accelerating the worldwide commercial deployment of at-scale CCS.

The principal responsibility of the Ministry of Petroleum and Energy is to achieve a coordinated and integrated energy policy for Norway. The Ministry is responsible for CCS matters.

Partners:

The IEA is an intergovernmental organization which acts as energy policy advisor to 28 member countries in their effort to ensure reliable, affordable and clean energy for their citizens.

The IEA GHG is an international collaborative research programme focusing its efforts on studying technologies to reduce greenhouse gas emissions.

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
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1. Introduction

1.1 Rationale

Industrialisation is one of several route to economic development and improved standards of living in developing countries (UN DESA, 2007). Scarcely any countries have developed without industrializing, with industrial output and gross domestic product exhibiting a strong correlation (UNIDO, 2009). The last 30 years has witnessed the emergence of rapidly developing economies, particularly in East Asia, where manufacturing output has been the mainstay for rapid economic growth and substantial poverty alleviation. In the same period, industrial output in the developed world has declined, with levels of income maintained by the expansion of the service sector, and a large percentage of the manufactured goods consumed imported from emerging developing countries. A 'historic absolute shift' of industry to the developing part of the world seems to be well under way (UNIDO, 2009).

Although industrialisation is a fundamental contributor to development, it has negative consequences for climate change. Industrial output[1], regardless of geographical location, accounts for almost 40% of global CO_2 emissions. In 2007, direct emissions from industrial production amounted to 7.6 $GtCO_2$, with an additional 3.9 $GtCO_2$ from the power generation sector due to electricity use in industry. Within industry, iron and steel manufacturing contributes the largest proportion (30%) of CO_2 emissions, followed by cement (26%) and chemical production (17%) (IEA, 2009a). CO_2 emissions from the oil refining industry are estimated at approximately 0.8 Gt in 2002 (IPCC, 2005). China currently dominates the global production of ammonia, cement, iron and steel and methanol. An IEA scenario analysis expects China's production capacity to peak by 2030, however production in India, Africa and the Middle-East, and other developing Asian countries will continue to grow until 2050 (IEA, 2009a). In light of this, it is understood that developing and deploying greenhouse gas abatement technology in OECD countries alone will not deliver the necessary reductions to combat climate change.

Over the last decade, a number of reports have highlighted carbon dioxide capture and storage (CCS) as a technology with the potential to make deep emissions reductions (IEA, 2004; IPCC, 2005). The IEA (2008b) has calculated that an exclusion of CCS from the global mitigation portfolio will increase the cost of achieving emission reductions by 70%. Applications of CCS in the power sector, in particular coal-fired power plants, have been the target of the vast majority of research and development funding and policy initiatives aimed towards demonstrating and commercializing the technology. An emphasis on CCS in the power sector is understandable, as fossil fuel-fired power stations provide the base-load electricity for many of the world's largest economies, with global energy-related CO_2 emissions reaching 11.9 Gt in 2007, and the combustion of coal attributing approximately 66% (IEA, 2009b). Nevertheless, there are number of reasons why a detailed look at CCS in industry is important.

First, industry is a major contributor to global CO_2 emissions. According to the IEA Energy Technology Perspectives Baseline scenario[2], by 2050, industry is expected to

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[1] Including CO&BF, but excluding oil refining

[2] This baseline scenario is consistent with the IEA World Energy Outlook 2007 Reference scenario up until 2030, and then has been extended to 2050 used the IEA Energy Technology Perspectives model analysis.

generate 11.2 Gt of direct CO_2 emissions (IEA, 2008b). Also, in regions of the globe that place monetary incentives to reduce CO_2 from all large point stationary sources either at present or in the future, the industrial sector should have access to the most cost-effective applications of CCS. Furthermore, within the various sectors of industry, a wide diversity of manufacturing processes exist, all with specific requirements in terms of the types of compatible capture equipment. The heterogeneity of industrial processes may pose challenges but also opportunities for CCS development. In addition, contrary to power production, not all industries have the immediate option to achieve deep emission reductions in another way. This is particularly true for key commodities such as steel and cement (IEA, 2008a). Finally, the IEA Blue Map Scenario, which explores the energy implications of a reduction in CO_2 emissions to 50% of 2005 levels by 2050, concludes that CCS can contribute to 19% to CO_2 emissions reductions, of which almost half of which would take place in industry and fuel transformation sectors (see Figure 1).

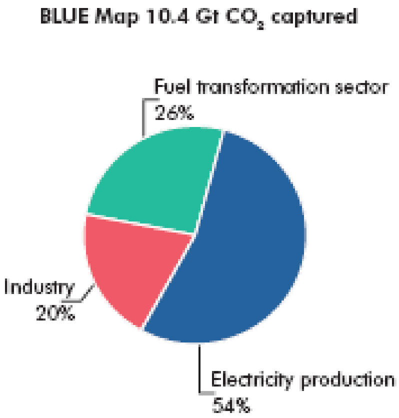

Figure 1:Use of CO_2 capture and storage in the BLUE Map scenario (IEA, 2008b)

Most current applications of CCS are in industry. The natural-gas processing industry has used monoethanolamine (MEA) solvents for 60 years to reduce the CO_2 content of field gas for quality purposes (Anderson and Newell 2003). After capture, it is common practice to simply vent the CO_2, however existing CCS demonstration plants, Sleipner and Snøhvit in Norway and In Salah in Algeria, both inject CO_2 captured from such sources. Natural-gas processing thus falls into a category of CO_2 sources often referred to 'near-term' or 'early' opportunities for CCS. Other industrial practices that are associated with 'near-term' opportunities include ammonia, hydrogen and synthetic fuel production (G8-IEA-CSLF, 2007).

In some cases, near-term opportunities are also defined by the proximity of a suitable storage site, or when the costs of CCS are offset by revenue from enhanced hydrocarbon recovery. The most mature option for this is Enhanced Oil Recovery (EOR), but also Enhanced Coal Bed Methane recovery (ECBM) might be an option. For example, the IEA GHG (2002) concluded that 500Mt of annual CO_2 reductions could be realized through early opportunities, where CO_2 is transported less that 100km to be used for enhanced oil recovery.

In the context of enabling CCS in general, industrial applications can provide valuable experience with regards to capture techniques, transport infrastructure, suitability of storage sites and the behaviour of stored CO_2. The acquired knowledge can then be transferred to larger-scale and more complex CCS deployment in both industry and power generation (IEA, 2009c). In that sense, the application of CCS in industry can serve as a catalyst for broader deployment of CCS.

1.2 Objective and approach of the roadmap

A roadmap provides a structural planning to address obstacles to a certain goal. The goal which the current roadmap works towards is commercial and widespread deployment of CCS in various industry sectors. An important assumption in the study is that this deployment is necessary and desirable from the perspective of cost-effective emission reductions and low-carbon industrial development.

The specific objective of the CCS industrial sector roadmap (hereafter called "the roadmap"), is to provide relevant information on actions and milestones to government and industry decision-makers, that can facilitate the deployment of CCS in industry. This roadmap aims to build on the IEA Roadmap on CCS (2009c) that has already outlined actions and milestones for CCS in the power sector, and for industry as a whole. With the exception of capture technologies for the cement industry, briefly covered in a technological roadmap for the cement industry (IEA, 2009d), much scope remains to outline specific actions and milestones for CCS in a number of individual industry sectors. Without this effort, some of the technically less challenging potential for CCS in industry may be overlooked. Particularly in developing countries, a low awareness of possibilities and required actions and milestones to achieve CCS can be observed, while much of the early potential might be in the developing world. This CCS industry roadmap might therefore be most useful for such countries.

Within the roadmap, specific actions and milestones for five industrial sectors and categories of CO_2 sources will be outlined. The five sectors include high-purity CO_2 sources, the cement, iron and steel, and refinery sectors, and biomass-based non-power sources of CO_2. The combination with storage sites is only addressed in an "early options" framing of combining high-purity CO_2 sources with EOR and ECBM. Transport of CO_2 and other storage options are not discussed in this roadmap.

The roadmap begins by discussing the current and future projected situation for industry in general, and the role of CCS in the larger mitigation portfolio. The sectoral assessments go into the specifics of different sectors and discuss their energy use, emission sources, business model and mitigation options including CO_2 capture possibilities, and, from those characteristics, what gaps and barriers inhibit the use of CCS. From these gaps and barriers, possible actions and milestones are outlined for different actors and stakeholders.

1.3 Objective of this background paper and outline

This background paper serves the following purposes:

- Provide a first draft of the introductory sections of the roadmap
- Give a first discussion and demarcation of the sectors addressed in the roadmap, and frame the analysis
- Indicate what aspects of the sectors are to be discussed in the sectoral assessments. In this way, the background paper can provide a reference for the sectoral consultants
- Give a bibliography of literature and data sources related to CCS in industry.

Section 2 of this background paper discusses in general terms the context, current situation and projections for greenhouse gas emissions in industry, and the role CCS could play to address them. In Section 3, the sectors are discussed in more specific terms.

Section 4 gives an annotated outline of the sectoral assessments, and Section 5 a list of references used in this paper, and likely to be used in the roadmap.

2. Current and future projected situation

At present, industry produces nearly 40% of global energy-related CO_2 emissions. Within industry, 30% of the CO_2 emissions are attributed to the production of iron and steel, followed by cement (26%) and chemical manufacture (17%) (IEA, 2009a). Energy efficiency efforts in industry has led to reduced energy use and lower emissions, however such savings are outweighed by increased global production (IEA, 2009a). China, India and other Asian countries have undergone massive industrial expansion since 1990, and these regions are responsible for more than 80% of the global increase in industrial production over the last 20 years. In 2007, non-OECD countries accounted for 67% of the direct CO_2 emissions, with China's industrial output responsible for almost half of these emissions (IEA, 2009e and IEA, 2009f).

In industry in general, there are a number of approaches to improve energy efficiency and reduce emissions, and in many cases the technologies needed are already available. The IEA (2009a) estimates that if the Best Available Technologies (BAT) were applied throughout all industrial sectors globally, this would lead to a total abatement of 1.3 $GtCO_2$, approximately 12% of total industry emissions, equating to 4% of global emissions (IEA, 2009a). The Energy Technology Perspectives (ETP) BLUE scenario produced by the International Energy Agency (IEA), assesses strategies to reduce total global CO_2 emissions by 50% by 2050. Achieving this global reduction will require industry to reduce its direct emissions in 2050 by 21% compared to 2005 levels. Figure 2 below depicts the most cost-effective combination of technologies to achieve a reduction from a baseline estimation of 11.2 to 5.7 $GtCO_2$ by 2050[3].

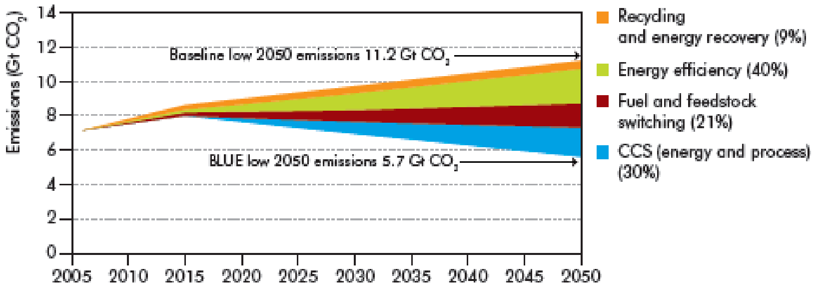

Figure 2: Technologies for reducing direct CO_2 emissions from industry (IEA 2009a)

Energy efficiency improvements account for the largest percentage of direct CO_2 reductions from industry. Technological apparatus common to many industrial processes such as motors, fan systems, steam systems and process heating can be upgraded to improve overall efficiency in conjunction with system optimization. Combined heat and power (CHP) systems have been implemented by industry in certain global regions, however the potential for CHP remains considerable. Fuel and feedstock switching, for example the combustion of biomass instead of fossil fuels, is also expected to contribute to industrial CO_2 emission reductions. According to the IEA (2009c), CCS can be

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[3] This background document is based on IEA scenario analysis reported in Energy Technology Transitions for Industry (IEA 2009a) and Energy Technology Perspecitves 2008 (IEA 2008). An update of the scenario results will be published in Energy Technology Perspecitves 2010 which will be released in July 2010.

regarded as the most important new technology option for reducing direct emissions in industry and upstream processes[4], with the potential to mitigate 1.7 $GtCO_2$ and 2.9 $GtCO_2$ respectively by 2050.

The IEA has recently developed a technological roadmap for CCS, both for the power sector and industry (IEA, 2009c). The roadmap shaped by the IEA addresses, on a cost-efficiency basis, deployment of CCS for industry as a whole. The roadmap adopts a positive approach towards the progression of CCS in industry, estimating that the technology will annually abate 4.6 $GtCO_2$ from industry and upstream industrial processes by 2050. The particular scenario chosen as the basis for the roadmap, is the ETP BLUE 'Map' scenario (IEA, 2008b). This particular scenario requires that major reductions in global emissions be achieved by technologies that are currently not available, or are in early forms of development. These technologies include biofuels and the use of hydrogen fuel cell vehicles. As illustrated by Figure 3, under the BLUE Map scenario, due to a reduction in the use of conventional fuels in the transport sector, a new industrial sector is established for the production of biofuels and hydrogen. This is where CCS is most prominently applied.

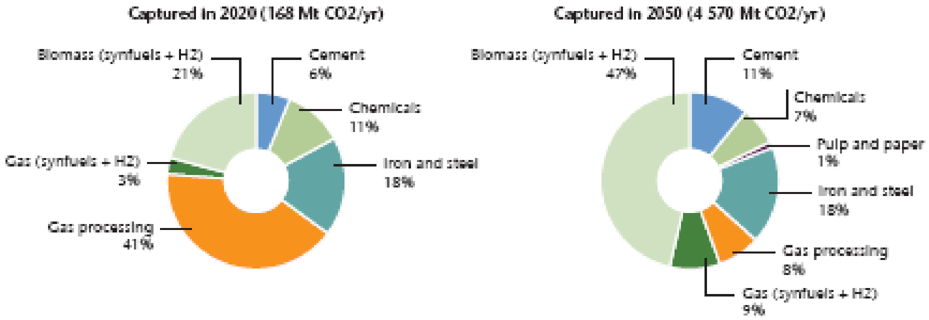

Figure 3: Deployment of CCS in industry in 2020 and 2050 (IEA 2009b)

By 2050, the scenario assumes that CCS technology will be installed on 1730 projects. Based on the marginal abatement costs in figure 4, the additional costs of fitting capture equipment to all of these projects is calculated as USD 691 billion. Including the cost of transport and storage of the capture CO_2, the additional cost for CCS deployment in industry is USD 3370 billion (IEA, 2009b).

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[4] Upstream processes include gas processing and the fuel transformation sector.

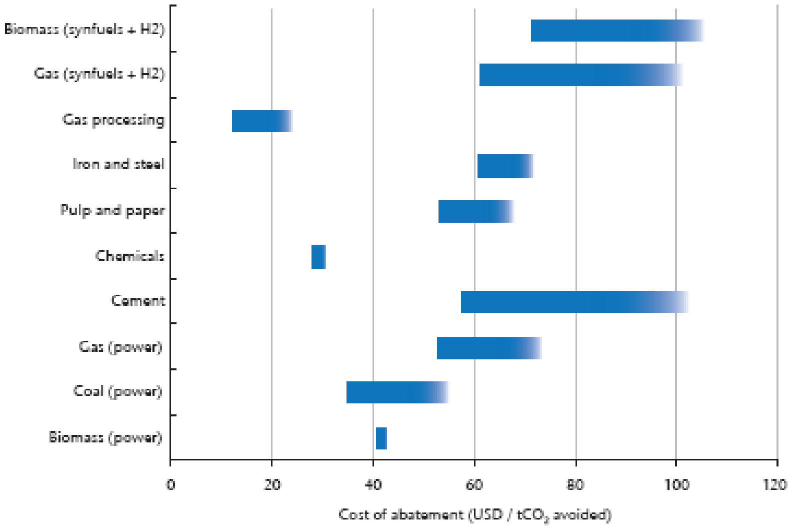

Figure 4: Ranges of CO_2 abatement costs used in the IEA CCS Roadmap (USD/tCO_2 avoided) (IEA 2009b)

3. Description of the sectors

This roadmap aims to address industrial sectors that are both relevant emitters over the next decades and representing potential early applications of CCS. The refinery, cement and iron and steel sectors are currently large emitters of CO_2 and are expected to remain so in the future. The early opportunities that are represented by high-purity sources of CO_2 are grouped in one sector. Last, the biomass conversion sector is both an essential sector as it has the potential to produce energy with negative emissions in the future, and is projected to be a large sector.

3.1 High-purity CO_2 sources

Several processes in industry and fuel production result in a (near)-pure CO_2 stream. As there is no need for the energy-intensive step of CO_2 separation, these provide lower cost options for CCS, sometimes called ‘early opportunities’. The most prominent industrial sources and processes with CO_2 streams that can be readily transported and stored include natural gas processing, coal-to-liquids, hydrogen production in refineries, ammonia and ethanol production.

- Natural gas processing: Natural gas reservoirs, in addition to natural gas, often contain a mixture of acid gas: H_2S and CO_2. As these gases are corrosive, they should be removed until the content is reduced to below 2% by volume for transportation, in order to comply with pipeline specifications (IPCC, 2005). The separated CO_2 can be compressed, transported and stored, as is done in most of the current large scale CCS projects. The CO_2 concentration in natural gas fields varies greatly across the globe with many fields as low as 2% to over 70% in the Natuna field in Indonesia. For developing countries, the potential for CO2 capture is estimated to be over 200 $MtCO_2$/yr for existing and new fields, mainly from South-East Asia, Middle East (Bakker et al., 2010). Costs for CCS (so including transport and storage) are estimated to be in the range of 10 - 30 USD/tCO_2 avoided, depending on whether the field is new or existing, on or off-shore and the proximity of storage site (IEA, 2009c; Zakkour et al., 2008). Three of the four current full-scale CCS projects are associated with natural gas processing plants: the Sleipner (Norway) project (injecting approximately 1 $MtCO_2$/yr since 1996), the In Salah (Algeria) project (about 1 $MtCO_2$/yr since 2004) and the Snøhvit (Norway) project (0.7 $MtCO_2$/yr since 2008).

- Coal-to-liquids: Coal-to-liquids (CTL) produces liquid fuel from coal, which can be used to replace oil-based fuels. In the most commonly used CTL technology, coal is first gasified to produce synthesis gas which, in turn, is catalytically treated in a Fischer-Tropsch (FT) process to produce different liquid fuels like gasoline and diesel. Coal gasification produces a highly concentrated CO_2 stream and FT catalysts require a synthesis gas which is essentially free of CO_2 (Vallentin and Fischendick, 2009). If operated without CCS, CTL results in significantly higher GHG emissions compared to oil-based fuels. As of 2009, 31 CTL plants have been announced globally, 23 of which in China and the US (Vallentin and Fischendick, 2009). In South Africa, the petrochemical group Sasol currently operates a large CTL plant at Secunda, which uses coal and gas to produce a range of petrochemical products, including the bulk of the country's diesel fuel. CTL technologies are particularly attractive to developing countries with large coal supplies, such as India and China.

- Hydrogen from refineries: Globally there are over 600 refineries, which emit close to 1 $GtCO_2$/yr, or 4% of global energy-related emissions. About 5-20% of the CO_2 is emitted as a near-pure stream from a gasifier during the production of hydrogen, which is subsequently used in various processes (Straelen et al., 2009). In the Netherlands, the Pernis refinery uses the CO_2 in summer to fertilise greenhouses. There are plans to store the remainder of the CO_2 in a nearby gas field.

- Ammonia production: Ammonia is one of the most-used inorganic chemicals in the world, mostly for production of fertilizer. The steam-reforming process using natural gas as feedstock is the most common production route. Depending on the design of the process, ammonia production can result in a near-pure stream of CO_2, about half of which is used for production of urea (fertilizer). IEA (2008a) estimates a 180 $MtCO_2$/yr potential for CCS from existing ammonia production facilities. About half of these are in developing countries, and all new plants are expected to be built in these countries as well.

- Bioethanol Production: Biological processing, for example fermentation, uses living micro-organisms to breakdown the feedstock and produce liquid and gaseous fuels. A by-product of this reaction is an almost pure stream of CO_2. To abate this CO_2, no capture equipment is required. On a bio-ethanol plant with a net output of 235 million litres/yr, the addition of compression equipment leads to a 0.9% increase in capital costs (Rhodes and Keith 2003).

Without an incentive on reducing CO_2 emissions, even relatively attractive capture options from high-purity CO_2 sources are not economically feasible. Therefore, the combination of such sources with revenue-generating CO_2 storage options is often mentioned (IEA GHG, 2002).

EOR is a mature technology. It is applied on a 40 $MtCO_2$-scale annually in particularly the United States (IPCC, 2005), mostly for the sole purpose of enhancing oil production. Most of the CO_2 used for EOR originates from naturally occurring CO_2 reservoirs and not from anthropogenic sources. Therefore, current EOR operations do not generally lead to reduction of greenhouse gas emissions. There are two projects that do use anthropogenic CO_2: the Weyburn project in Canada and the Rangely project in the United States (IEA, 2009b). The global potential for EOR is not specifically known and is usually expressed in additionally recovered barrels of oil, not in CO_2 stored. The relation between the two is not easily established. However, some studies suggest the global storage potential could be 500 $MtCO_2$/yr (Bergen et al., 2004; IEA, 2008). Enhanced Coal Bed Methane recovery (ECBM) is a much less mature technology, and although coal beds are widespread, the suitability depends strongly on the coal rank, depth and a number of other factors (IEA, 2008a). In theory and according to modelling, Enhanced Gas Recovery with CO_2 could also be done, but no current projects have demonstrated this successfully (Oldenburg and Benson, 2002).

3.2 Cement

Cement is an essential component of concrete, a material that is used to build a multitude of buildings and structures. In line with economic growth, global cement production has risen from 594 Mt in 1970, to nearly 2.8 billion tonnes in 2007 (USGS). The majority of this growth has occurred in developing countries, with China producing 49% of the global cement production in 2007, followed by India (6%) (USGS). In a recent technological roadmap for the cement industry, scenario studies estimated that by 2050, production could increase to 4.4 billion tonnes (IEA & WBCSD 2009). At present, the cement industry contributes approximately 5% of global CO_2 emissions. There is evidence of reduced carbon intensity on global cement manufacturing process, with global cement production increasing by 54% between 2000 and 2006 (USGS 2008), however absolute CO_2 emissions increased by an estimated 42%, reaching 1.88 Gt in 2006 (IEA 2009e). The thermal fuel CO_2 intensity from major producers can be seen in figure 4.

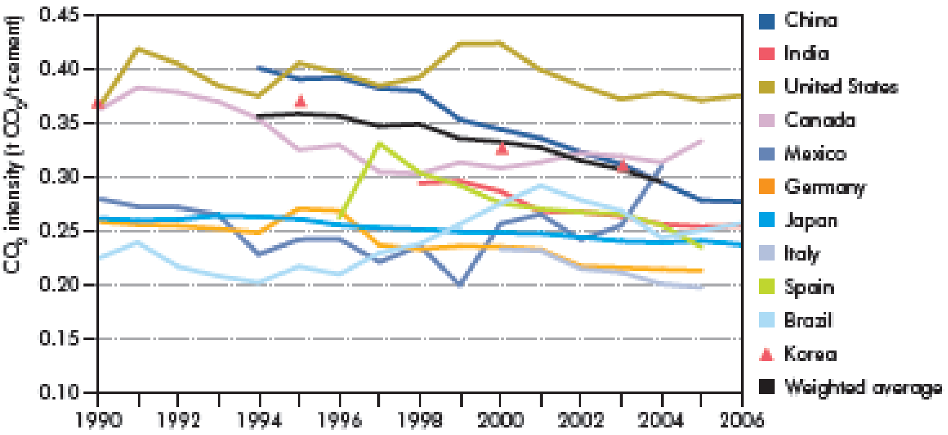

Figure 5: Thermal fuel CO_2 emissions per tonne of cement by country 1990 to 2006 (IEA 2009a) These figures exclude upstream CO_2 emissions from electricity use and process emission.

Cement production is an energy intensive process, and generates a substantial amount of CO_2 emissions. The most energy intensive component in the production of cement is generally referred to as clinker burning. This process involves gradually heating calcium carbonate (Ca_2CO_3) with small amounts of additives in a kiln. At approximately 900ºC, calcination occurs and CO_2 is released from the calcium carbonate. As the reaction reaches its peak temperature of around 1450ºC, clinkerisation starts, whereby the calcium oxide reacts and agglomerates with silica, alumina and ferrous oxide, forming cement clinker (IEA, 2007). After cooling, the resultant hard substance is then ground with a small amount of gypsum to form a powder.

The average world carbon intensity of carbon emissions in cement production is 0.81 kg CO2/kg. India has the most carbon intensive cement, (0.93 kg CO2/kg), followed by North America (0.89 kg CO2/kg), and China (0.88 kg CO2/kg) (Hendriks et al., 2008). Almost all of the CO_2 emissions from the cement manufacturing process stem from the clinker burning process (Rootzen et al. 2009). Unlike other industrial processes such as steel manufacturing, the burning of fuels to heat the process does not account for the largest proportion of total CO_2 emissions. Generally 60% of the CO_2 emissions are released during calcination, termed 'process CO_2', with 'fuel CO_2' accounting for the remainder (MPA Cement, 2009). Within the cement production process, the CO_2 emissions relating to calcination are largely unavoidable, and this restricts the potential impact that energy efficiency and alternative fuel use measures could have on CO_2 abatement. As such, CCS is viewed as a key technology to achieve ambitious CO_2 reductions in the cement industry.

There are possibilities to capture CO_2 from the cement process, although such technologies are yet to be deployed. The CO_2 content of exhaust gases from cement plants is between 14% and 33% (Liu and Gallagher, 2010). Technologies to capture CO_2 would resemble post combustion technologies similar to the types being developed for coal-fired power plants. It has been estimated that 77% of the CO_2 emissions could be abated using post combustion capture, however the energy efficiency of the process would be reduced considerably due the steam required to regenerate the capture solvent (IEA GHG, 2008), posing energy security and cost challenges. Although the abatement potential of post combustion applications on a cement plant is substantial, the IEA GHG (2008) expect that the cost for a plant incorporating post-combustion capture would be in the region of EUR 580 million, more than twice the cost of a non-CCS equivalent[5].

Oxy-fuel combustion with CO_2 capture could also be applied within a cement plant (either in the precalciner or in the kiln). By feeding the process with oxygen instead of ambient air, the CO_2 concentration in the flue gas can be increased, leading to more efficient capture. Compared to post-combustion capture, the abatement potential is reduced to 52%, however the cost for a cement plant utilizing oxy-fuel technology is considerably lower at €327 million, roughly 25% above the cost of a non-CCS equivalent (IEA GHG, 2008). While cheaper, the oxy-fuel approach is currently at an earlier stage of development, and there are a number of technical issues relating to the burning of raw materials in an oxygen rich environment. Furthermore, oxy-fuel will require a fundamental re-design of the incumbent cement process, and the potential for retrofitting is lower than with post combustion applications (MPA Cement, 2009).

3.3 Iron and steel

According to the World Steel Association[6] (2009), in 2008 world crude steel production totalled 1,327 Mt. Since the turn of the century the sector's output has risen significantly, with average growth rates per annum of 6.2% between 2000 and 2005, and 5.8% between 2005 and 2008. China is by far the largest steel manufacturer, producing 500 Mt in 2008, followed by Japan (119 Mt). With reference to 2008 production data, other developing countries with notable steel production capacity includes India (55 Mt), South Korea (54 Mt) and Brazil (34 Mt) (World Steel Association 2009). ArcelorMittal is the largest steel producer, with a market share of around 8%.

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[5] Based on a plant with an annual output of 1Mt of final product, (910,000 tonnes of clinker).

[6] The World Steel Association is an industry organization with company members representing around 85% of global steel production.

The production of iron and steel is an energy intensive process, and is the third largest contributor of CO_2 emissions after cement production and refining (IPCC, 2005). Global CO_2 emission data is at present underdeveloped, however in 2005 an estimated 649 Mt of CO_2 was released from 269 global sources (IPCC 2005). More recently, the IEA (2009a) estimated that the potential for reducing CO_2 emissions from iron and steel production could be up to 1.5 Gt per year. The iron and steel sector has a complex industrial structure, but two routes dominate the global production (Rootzen 2009; IPCC, 2005):

1. Integrated steel plants are the most common production route. Involves a series of interconnected production units (coke ovens, sinter plants, palletising plant, blast furnaces/basic oxygen furnaces (BOF), continuous casting units). Processing iron ore and scrap to crude steel. Coke, derived from coal, function both as fuel and reducing agent.
2. Mini-mills are plants where scrap, direct reduced iron and cast iron is processed in electrical arc furnaces to produce crude steel.

The integrated steel plant route accounts for 58% of steel production in the EU27, 90% in China, and 67% globally (World Steel Association 2009). It is also within this route where carbon capture and storage (CCS) technologies could be used to reduce direct emissions from the iron and steel industry, primarily through modifications to the blast furnace process. Between 65% and 75% of the CO_2 emissions come directly from the use of charcoal or coke as a fuel and reductant for the blast furnace, the core process where iron ore is smelted to produce intermediary material for commercial iron and steel manufacture (Rootzen 2009; IEA 2009a). Blast furnaces emit between 1.5 to 2.0 tCO_2/t of iron produced (IEA 2009e). Blast furnace gases are rich in carbon monoxide and CO_2, and if this gas is reformed[7], a CO_2 concentration of up to 60% can be achieved. Blast-furnace gas reforming and post-combustion capture are being investigated in Japan, Korea and China (IEA 2009a).

Another appropriate technique to capture CO_2 from the blast furnace, is to inject oxygen into the blast furnace to increase the concentration of the CO_2 in the off-gas. By scrubbing the CO_2 from the off-gas, CCS could reduce 85% to 95% of the CO_2 emissions from the core process (IEA 2009d). New increased-efficiency smelting technologies such as the FINEX process, developed by Siemens and South Korean company POSCO, already use oxygen and are well suited to CCS. The IEA (2009a) highlight that within current applications of the FINEX process, part of the CO_2 is removed from the gas re-circulation system. The CO_2 is merely vented, but could be captured with no efficiency penalty, reducing the CO_2 emissions from the process by almost 50%.

The HIsmelt (high-intensity smelting) process at demonstration phase, and the Hisarna process currently under development, could also be integrated with CCS to achieve a CO_2 abatement of roughly 70%. It has been estimated that CCS applied to blast furnaces could cost in the order of between 40 and 60 USD/tCO_2, with retrofits incurring a higher marginal cost than new builds (IEA 2009a). At present, the bulk of the research aimed at combining innovative steel making processes with CCS is being conducted by ULCOS (Ultra Low CO_2 Stealmaking), a consortium of 48 European companies and organizations with the goal of reducing CO_2 emission from the steel industry by 50% (ULCOS 2009).

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

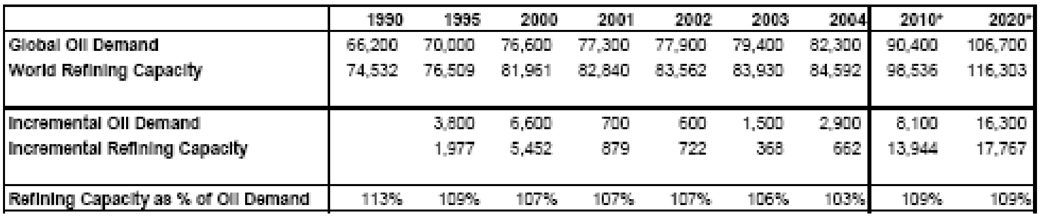
The gas-based direct reduced iron (DRI) process is also well suited for CCS (IEA 2009). The DRI process involves the conversion of iron ore to iron through the use of a reduction gas, normally natural gas which is chemically converted to hydrogen and carbon monoxide. CO_2 capture is already widely applied in DRI process in order to enhance the flue gas quality. It is during the recycling of the reduction gas that CO_2 is removed from the process. Gas-based DRI with CCS could be implemented at a relatively low cost of USD 25/tCO_2, however due to the high cost of natural gas, such facilities are concentrated in few countries such as the Middle East and Latin America. CCS combined with DRI has so far received limited attention (IEA 2009a). To reduce the cost of DRI, the gasification of fuel oil, naphtha, coal, petroleum coke or biomass for production of the reducing gas has been explored (Cheeley, 2000; Beurgler and Donato, 2008).

3.4 Refineries

Mineral refineries are responsible for the separation and processing of crude oil to make more valuable petroleum products such as naphtha, gasoline, diesel fuel and liquid petroleum gas (LPG). Modern refineries have a range of integrated processes such as distillation, reforming, cracking and conversion, all of which require significant heat input via fuel combustion. The furnaces and boilers that enable the process are fuelled by a mix of petroleum coke, still gas, petroleum fuels and natural gas (Rootzen et al. 2009).

The mineral refining process produces transport fuels and fundamental chemicals for the petrochemical industry. With reference to Table 2 below, it can be seen that as the global oil demand has risen since 1990, global refining capacity has also increased, albeit at a slower rate. It can be expected that oil demand and oil refining capacity will continue to grow, particularly in rapidly industrializing countries.

Table 1: Global oil demand and refining capacity (M bbl/d) (ICF Consulting, 2005)



	1990	1995	2000	2001	2002	2003	2004	2010*	2020*
Global Oil Demand	66,200	70,000	76,600	77,300	77,900	79,400	82,300	90,400	106,700
World Refining Capacity	74,532	76,509	81,961	82,840	83,562	83,930	84,592	98,536	116,303
Incremental Oil Demand		3,800	6,600	700	600	1,500	2,900	8,100	16,300
Incremental Refining Capacity		1,977	5,452	879	722	368	662	13,944	17,767
Refining Capacity as % of Oil Demand	113%	109%	107%	107%	107%	106%	103%	109%	109%

*2010-2020 Refining Capacity is estimated as the capacity required to make the refining capacity to Oil demand ratio at 109%. This was the average ratio from 1990 till 2000.

CO_2 emissions from refineries account for about 4% of global CO_2 emissions, almost 1 billion tones of CO_2 per year. According to van Straelen et al. (2009) a typical world-scale 300,000 barrel per day refinery will produce between 0.8 up to 4.2 million tons of CO_2 per year. Energy use and CO_2 emissions vary depending on what type of crude oil is being processed and on the mix and quality of the final products (Rootzen et al. 2009). The various streams of CO_2 from a refinery are described in Table 2.

Table 2: An overview of major CO_2 emission sources at a typical refinery complex (van Straelen et al. 2009)

Furnaces and boilers	Heat required for the separation of liquid feed and to provide heat of reaction to refinery processes such as reforming and cracking
Utilities	CO_2 from the production of electricity and steam at a refinery.

Fluid catalytic cracker	Process used to upgrade a low hydrogen feed to more valuable products
Hydrogen manufacturing	For numerous processes, refineries require hydrogen. Most refineries produce this hydrogen on site.

Process heating through the use of furnaces and boilers account for approximately 50% of the emissions from refining (Phillips 2002)[8]. The application of post-combustion CO_2 capture technology on process heating installations is potentially difficult, as these installations maybe scattered around the complex making deployment of capture equipment impractical and expensive (Phillips 2002). Although post-combustion capture is technically feasible, the concentration of CO_2 in the flue gases is between 4 and 12%, with capture costs increasing considerably at lower concentrations (van Straelen et al. 2009). In order to increase the concentration of CO_2 in the flue gases, oxygen from an air separation unit (ASU) could be injected into boilers or furnaces leading to oxyfuel combustion of the heater fuel (IEA GHG 2000). There are no examples of either post-combustion capture nor oxyfuel combustion in refineries to date.

Between 5% and 20% of CO_2 emissions from a refinery are linked to the production of hydrogen (H_2). Hydrogen rich fuel gas instead of fuel oil is used at refineries due to the required reduction of sulphur in transport fuels, and also in the processing of cheaper high sulphur crudes. Hydrogen is produced either through steam methane reforming of natural gas or gasification of heavy residues. Approximately 10 tonnes of CO_2 per tonne of hydrogen is produced, however the process results in a concentrated stream of CO_2 often at a high pressure (Phillips 2002). This is understood to be the lowest cost option for CCS deployment in refineries (van Straelen 2009). CO_2 capture from hydrogen production at refineries will be specifically covered in the high-purity CO_2 sources section (see Section 3.1).

Within the oil refining industry, there are also opportunities for the use of CCS during the processing of heavy crudes and/or low value residuals from the distillation process. A thermal cracking process known as flexi-coking licensed to ExxonMobil, includes the gasification of petroleum coke into higher value fuels and syngas. The CO_2 emissions from flexi-coking are very high, amounting to more than 20 kilograms of CO_2 per GJ of fuel processed (Gielen, 2003).

3.5 Biomass-based industrial CO_2 sources

The biomass conversion industry involves a range of processes that convert raw biomass feedstock into final energy products. Biomass conversion combined with carbon capture and storage has the potential to generate useful energy products such as bioethanol, substitute natural gas (bio-methane) and hydrogen, while removing CO_2 from the natural carbon cycle for geological timescales (Rhodes and Keith 2003). Observing data from the IPCC (2005), the contribution of bio-energy and bioethanol activities to global CO_2 emissions is slight (91 Mt CO_2/yr) when compared to the cement (932 MtCO_2/yr), refining (798 MtCO_2/yr) or iron and steel industries (646 Mt CO_2/yr).

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[8] In many modern installations, heat is provided by combined heat and power (CHP) installations, in which case CCS would be achieved through applying CCS on the power plant, which is outside of the scope of this roadmap.

The application of CCS to biomass conversion processes has the potential to achieve a net removal of CO_2 from the atmosphere, in contrary to fossil fuel conversion with CCS which typically mitigates 80 to 90% of CO_2 emissions (IPCC, 2005). The rationale for the inclusion of the biomass conversion industry in this roadmap is not based on current emissions, but the potential expansion of the industry to deliver sustainable energy products throughout society. The extent of the expansion will in part depend on the de-carbonization of the transport sector, with fossil-fuelled vehicles being replaced by bio-fuelled and hydrogen fuel cell vehicles. The replacement of natural gas with biologically derived substitute natural gas (SNG), and an increase demand of hydrogen for heat and power may also stimulate a growth of the biomass conversion industry. The recent IEA (2009c) technological roadmap for CCS based on a strongly bio-based transport sector scenario, estimated that the biomass industry would account for 47% of total CCS deployment in industry by 2050.

There are a number of routes to convert biomass into final energy products (see Figure 6). For this roadmap, because of the focus on CCS applications in industry, only the gasification and biological processing routes will covered.

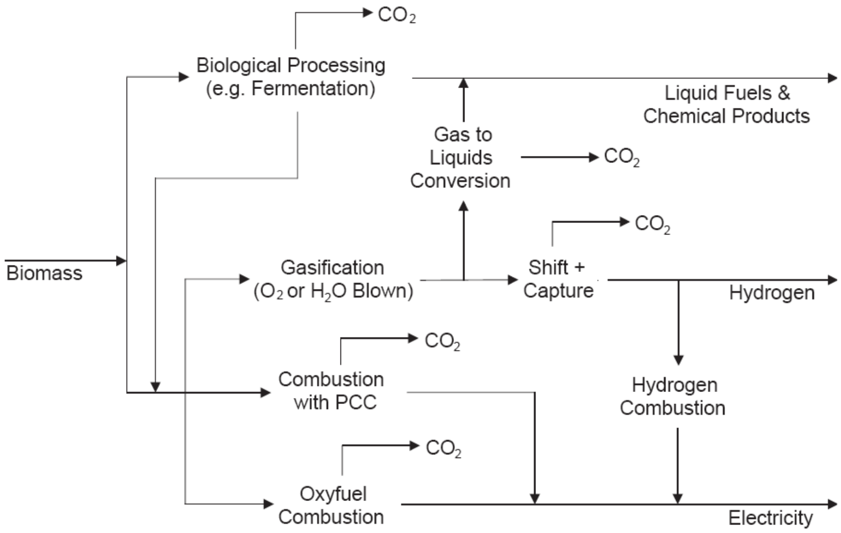

Figure 6: Routes to biomass with CO_2 capture (Rhodes and Keith, 2005)

Biological processing, for example fermentation, uses living micro-organisms to breakdown the feedstock and produce liquid and gaseous fuels. A common 1st generation process to produce bio-ethanol, is the fermentation of sugar beet, where a by-product of the reaction is a relatively pure stream of CO_2. To abate this CO_2, no capture equipment is required, although it is necessary to compress the off-gases from the fermentation tanks to facilitate transport and storage. On a bio-ethanol plant with a net output of 235 million litres/yr, the addition of compression equipment leads to a 0.9% increase in capital costs (Rhodes and Keith, 2003). CO_2 capture from biological processing will be specifically covered in high-purity CO_2 sources section (see Section 3.1).

The gasification of biomass is a thermal treatment which results in a high production of gaseous products and a small amount of char and/or ash (Demirbas, 2002). During gasification, the biomass is converted into gases by means of partial oxidation carried out at high temperatures of between 875-1275 K, using a gasifying agent which can be air, steam, steam-oxygen, air-steam or oxygen-enriched air (Gao et al., 2008). Dependant on a number of variables such as feedstock characteristics, temperature and gasifying agent, the resulting product gas includes carbon monoxide, carbon dioxide, hydrogen, methane, nitrogen, as well as the non-gaseous by-products of char and tars. At temperatures above 1275 K the resulting product consists primarily of hydrogen and carbon monoxide, called syngas. The gasification of biomass can lead to a number of products, most suitably represented in Figure 7 (Smit, 2009). Carbon dioxide is a by-product during all synthesis processes enclosed in the red quadrate.

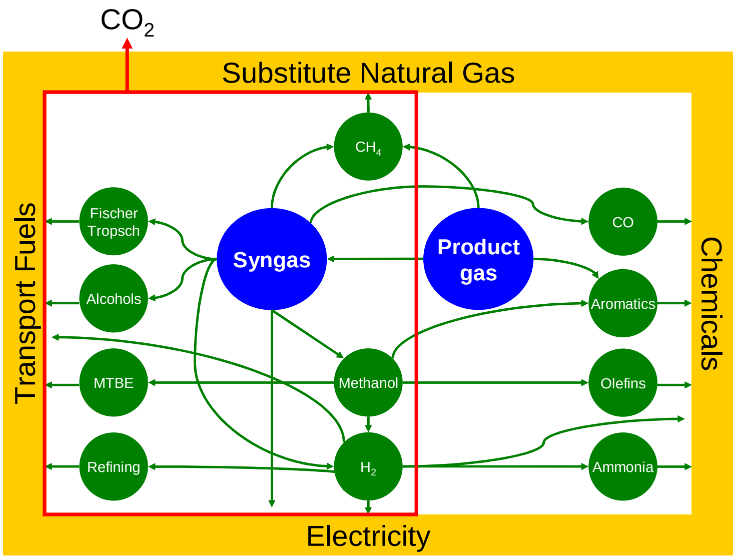

Figure 7: Products from the gasification of biomass (Smit, 2009).

The stream of carbon dioxide from the gasification process can be captured and stored, utilizing pre-combustion CCS technologies similar to proposed applications in integrated gasification combined cycle (IGCC) coal-fired power plants. Such technologies increase the CO_2 content of the bio-syngas by using a water-gas shift reaction, to produce a stream rich in CO_2, CO and H_2. The CO_2 is removed from the stream through either absorption by organic solvents, membrane separation or through the use of adsorption materials (Balat et al., 2009).

4. Content of sectoral assessments

The sectoral assessments are intended to give an educated but uninformed audience of decision-makers and industry stakeholders essential information to enable following through the actions and milestones that are recommended in the roadmap. The sectoral assessments should enhance a deeper understanding of the issues around the industrial sector and the technical and economic CO_2 capture possibilities.

The sectoral assessments should at least contain the following information about the sector and answer the annotated questions:

- Current and projected emissions: What is the amount of emissions in the sector at present and what are the projections (and assumptions for growth/decline) for the future? What are the most important regions and countries in terms of value added in the sector, currently and in the future, as well as for energy use and emissions?
- Technical overview of capture options: This is the first section going into the CCS aspects of industry. What are the mitigation options in general and the CO_2 capture options specifically in the sector (including integration into current and new processes)?

- Energy requirements and emission reductions for CO_2 capture: What would be the consequences for the energy requirements in the process and in the sector? What would be the consequences for upstream emissions, such as those relating to coal mining or transport? What are the potential CCS-related emission reductions in the sector?
- Current activities and projections on role of CCS: What are the research programmes going on in the sector? Are they privately or publicly funded? What are the current experiments and (if applicable) larger-scale demonstration of CO_2 capture in the sector? What role do optimisation models indicate CCS would play in the sector and what are the main assumptions behind those projections?
- Estimated investments and costs: What are the costs of applying CO_2 capture to the industry? How do the cost differ for new plants and retrofits? Costs should in any case be expressed as costs of CO_2 captured (or maybe avoided) and if possible in added costs per unit of product and upfront investment costs. What are the assumptions behind the costs? It is important to indicate whether costs are dependent on energy prices or other resource costs, such as steel prices. If there is readily available information, what might be the cost reduction as a consequence of learning and economies of scale in the sector; what does the learning curve look like?
- Characterisation of the industry: What industries are involved in the sector? What are the dominant companies? Does the sector consist of many smaller companies or is the global picture dominated by a limited number of players? Is the industry risk-averse or risk-seeking; innovative or conservative; globally active or primarily supplying a domestic market; heavily regulated or fully free?
- Current environmental legislation and pressures: How is the industry regulated in which regions, for greenhouse gases or (if relevant) for other environmental pressures?
- Major gaps and barriers to implementation: Based on the above and in those categories, what are the major gaps and barriers to deployment of CO_2 capture in the sector? This section will be the basis of the actions and milestones of different actors and stakeholders in the later sections of the roadmap. The following areas should be considered when addressing this: technical, policy, legal, financial, and market and organizational requirements.

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