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Technology Roadmap

Carbon Capture and Storage in Industrial Applications



International Energy Agency



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ABOUT THE IEA

The IEA is an autonomous body, which was established in November 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme.

The IEA carries out a comprehensive programme of energy co-operation among 28 of the 34 OECD countries. The basic aims of the IEA are:

- To maintain and improve systems for coping with oil supply disruptions.
- To promote rational energy policies in a global context through co-operative relations with non-member countries, industry and international organisations.
- To operate a permanent information system on international oil markets.
- To provide data on other aspects of international energy markets.
- To improve the world's energy supply and demand structure by developing alternative energy sources and increasing the efficiency of energy use.
- To promote international collaboration on energy technology.
- To assist in the integration of environmental and energy policies, including those relating to climate change.

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The United Nations Industrial Development Organization (UNIDO) is a specialized agency of the United Nations. Its mandate is to promote and accelerate sustainable industrial development in developing countries and economies in transition, and work towards improving living conditions in the world's poorest countries by drawing on its combined global resources and expertise.

In recent years, UNIDO has assumed an enhanced role in the global development agenda by focusing its activities on poverty reduction, inclusive globalisation and environmental sustainability. Our services are based on two core functions: as a global forum, we generate and disseminate industry-related knowledge; as a technical co-operation agency, we provide technical support and implement projects.

UNIDO focuses on three main thematic areas, in which it seeks to achieve long-term impact:

- poverty reduction through productive activities
- trade capacity-building
- energy and environment.

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Foreword

Current trends in energy supply and use are patently unsustainable – economically, environmentally and socially. Without decisive action, energy-related emissions of carbon dioxide (CO₂) will more than double by 2050 and increased oil demand will heighten concerns over the security of supplies. We can and must change our current path, but this will take an energy revolution and low-carbon energy technologies will have a crucial role to play. Energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment if we are to reach our greenhouse gas (GHG) emission goals. Every major country and sector of the economy must be involved. The task is also urgent if we are to make sure that investment decisions taken now do not saddle us with sub-optimal technologies in the long term.

Awareness is growing of the urgent need to turn political statements and analytical work into concrete action. To spark this movement, at the request of the G8, the International Energy Agency (IEA) is leading the development of a series of roadmaps for some of the most important technologies. By identifying the steps needed to accelerate the implementation of radical technology changes, these roadmaps will enable governments, industry and financial partners to make the right choices. This will in turn help societies make the right decisions.

No country has raised standards of living and wealth without significant industrial development. Industry promotes widespread structural change, creates jobs, generates income,

improves livelihoods and combats poverty. In the last 30 years, manufacturing output has been the mainstay for rapid economic growth and substantial poverty alleviation, particularly in East Asia. A historic shift of industry to developing countries seems to be well under way.

However, industrialisation has negative consequences for climate change. Current options of reducing CO₂ emissions from industrial sources will not be sufficient to achieve deep emissions reduction in industry, so new technologies are required. Recognising the importance of CCS, the IEA and the United Nations Industrial Development Organization (UNIDO) have collaborated to develop a technology roadmap for the application of CCS in industry.

This roadmap paves the way for low-carbon industrial growth in developed and developing countries by providing a vision of industrial CCS up to 2050. Its insights will help policy makers evaluate the benefits of CCS technology and hence make informed decisions. It also offers investors a much-needed assessment of the potential for CCS in industry, an application that has been neglected.

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Key Findings

- Carbon capture and storage (CCS) is a key cost-effective option for reducing carbon dioxide (CO₂) emissions from industrial applications. Whereas the power sector can take advantage of alternatives to fossil fuels, in several industries deep emission reductions can only be achieved through CCS.
- CCS could reduce CO₂ emissions by up to 4.0 gigatonnes (Gt) annually by 2050 in industrial applications, accounting for about 9% of the reductions needed to halve energy-related CO₂ emissions by 2050. To achieve this target, 20% to 40% of all facilities need to be equipped with CCS by 2050.
- High-purity sources¹ offer an early opportunity to demonstrate CCS. If this opportunity can be linked to enhanced oil recovery (EOR), costs could be lower than USD 10 per tonne of CO₂ (tCO₂), or even negative.
- As with CCS in general, incentives and regulatory measures will be required to facilitate industrial applications of CCS. The mechanisms should be selected according to the maturity of the technology, and should distribute funding for CCS demonstration programmes efficiently between power generation and industrial production processes.
- CCS in industry needs more specific support, including financial assistance for investing and operating CCS. Over time, however, incentives for CCS technologies should be linked primarily to their ability to reduce CO₂ emissions.
- Additional capital investments of about USD 256 billion would be required for industrial CCS between 2010 and 2030. Of this total, USD 172 billion will be needed in developing countries. This high additional capital cost is one of the main barriers to implementation.
- For developing countries, CCS could be part of a low-carbon industrial development strategy. If CCS can be implemented through the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM) or other new global climate mechanisms, the cost barrier could be partly overcome. It is likely that if CCS moves forward under the CDM, the first projects will be in industry.

1. The high-purity sources sector includes natural gas processing (onshore/offshore); hydrogen production from natural gas, coal or biomass; ethylene oxide production; coal-to-liquids (CTL); and ammonia production.

Key actions in the next 10 years

- Governments need to ensure adequate funding for CCS demonstration projects in major industrial and fuel transformation sectors such as ammonia, gas processing, biomass conversion, refineries, iron and steel, and cement manufacturing. By 2020, investment worth USD 27 billion will be needed to fund about 60 early large-scale projects. If additional operating cost, transportation and storage were included, the total additional cost would reach an estimated USD 45 billion.
- Governments and financiers need to ensure funding mechanisms are in place to support demonstration and deployment of CCS in developing countries, where the largest opportunities exist for CO₂ capture in industrial applications.
- To enable a deeper understanding of the potential for CCS in industrial applications, more data need to be made available on emissions, technologies, costs and projections. Governments need to review the opportunities for industrial CCS in their countries and ensure that industrial CCS is given prominence into the short term, especially in low-cost applications.
- Although industry will eventually need to implement the technology, public research and development (R&D) programmes on CCS in industrial applications is required to bring more information in the public domain.
- Best practices for CCS in industrial applications need to be developed and disseminated so that interested parties can learn faster how to apply the relevant technologies.
- CCS opportunities in industrial applications need to be mapped better and more consistently at the national and local level, including CO₂ storage opportunities in EOR operations.

Introduction

There is a pressing need to accelerate the development and deployment of advanced clean energy technologies in order to address the global challenges of energy security, climate change and sustainable development. Ministers from the G8 countries, and China, India and South Korea, in their meeting in June 2008 in Aomori, Japan, acknowledged this challenge when they declared the wish to have the International Energy Agency (IEA) prepare roadmaps to advance innovative energy technology.

“We will establish an international initiative with the support of the IEA to develop roadmaps for innovative technologies and co-operate upon existing and new partnerships, including carbon capture and storage (CCS) and advanced energy technologies. Reaffirming our Heiligendamm commitment to urgently develop, deploy and foster clean energy technologies, we recognise and encourage a wide range of policy instruments such as transparent regulatory frameworks, economic and fiscal incentives, and public/private partnerships to foster private sector investments in new technologies....”

To achieve this ambitious goal, the IEA has undertaken an effort to develop a series of global technology roadmaps. The roadmaps will enable governments, industry and financial partners to identify the steps needed and to implement measures to accelerate the required technology development and uptake.

The underlying objective of this roadmap is to advance the global uptake of low-carbon technologies in industrial applications, particularly by involving developing countries and transition economies.

This roadmap builds on the initial IEA roadmap on CCS (IEA, 2009), which outlined actions and milestones for CCS in the power, industry and fuel transformation sectors as a whole. It also draws on the technology roadmap for the cement sector developed by the IEA and the Cement Sustainability Initiative of the World Business Council for Sustainable Development (IEA/WBCSD, 2009).

Rationale for a roadmap on CCS in industry

The IEA projects that cutting CO₂ emissions to 50% of their 2005 levels – the target necessary to limit the global warming between 2°C and 3°C –

would require a reduction of 43 gigatonnes of CO₂ (GtCO₂). Total CCS in power generation and industrial applications is expected to contribute 19% to this reduction target in 2050 (IEA, 2010).

Much of the most promising short-term potential for CCS – and half of the global economic potential by 2050 – lie in industrial applications, particularly in the developing world (Zakkour *et al.*, 2008; Bakker *et al.*, 2009; IEA, 2009). In many industry sectors CCS is often the only technology, with the exception of energy-efficiency measures, that allows for deep reductions in CO₂ emissions.

CCS in industrial applications has so far received little attention. Most studies on the potential application of CCS have focused on the power sector (IPCC, 2005; IEA, 2009), even though all existing operational large-scale demonstrations of CCS are in industrial applications. If CCS is to achieve its full potential to reduce overall emissions, this imbalance needs to be corrected. The need to recognise the potential of CCS for industrial emission sources and to review demonstration opportunities was one of the conclusions of the April 2011 Clean Energy Ministerial meeting held in Abu Dhabi.

In their report to the 2010 Muskoka G8 Summit, the IEA and the Carbon Sequestration Leadership Forum (CSLF), in partnership with the Global CCS Institute (IEA/CSLF, 2010), called for the identification of a larger number of CCS projects in industrial sectors globally, as well as support for CCS in developing countries. If developing countries are to implement CCS in the short- to medium-term, each country needs to address its own specific requirements and take steps to increase awareness of the possibilities for CCS in industrial applications.

Roadmap objectives, scope and structure

This roadmap focuses on the challenges for capture of industrial CO₂. Full details on transport assessment and the technical aspects of storage, as well as barriers to the deployment of CCS in general (such as those related to legal frameworks and public perception), may be found in the IEA *Technology Roadmap: Carbon capture and storage* (IEA, 2009).

Table 1 Sectors and CO₂ production processes covered in this roadmap

Sector	Production process
High-purity CO ₂ sources	Natural gas processing (onshore/offshore); hydrogen production from natural gas, coal or biomass; ethylene oxide production; coal-to-liquids (CtL); ammonia production.
Biomass conversion	Biosynthetic gas; ethanol production; hydrogen production from biomass; biomass-to-liquids (BtL); black liquor processing in pulp and paper manufacturing.
Cement	Dry-process / suspension preheater rotary kiln with or without precalciner / grate cooler.
Iron and steel	Blast furnace (pig iron), direct reduced iron (DRI), FINEX and HIsarna.
Refineries	Hydrogen production – from natural gas steam methane reforming (SMR), gasification residues, fluidised catalytic cracking and process heat.

This roadmap has three objectives:

- To provide stakeholders with a vision for developing CCS in industrial applications up to 2050 and a set of milestones by which this vision can be achieved.
- To help policy makers evaluate the benefits of CCS technology and provide investors with an objective assessment of the potential for CCS in industrial applications.
- To strengthen the capacities of developing-country stakeholders with regard to industrial CCS, by disseminating knowledge and raising their awareness of key issues.

The roadmap aims to strengthen collaboration among energy-intensive industries in developed and developing countries.

The roadmap focuses on five main industrial sectors: high-purity CO₂ sources; biomass conversion; cement; iron and steel; and refineries (Table 1). The combined CO₂ emissions of the five sectors in 2008 were 7.4 GtCO₂, about 25% of total global emissions.

The sectors covered offer the most promising potential for the early and/or large-scale application of CCS. This analysis focuses on the abatement of direct CO₂ emissions from industrial processes.² Hence, the roadmap examines applications that:

- offer a prospect of easy capture of large volumes of CO₂;

- provide promising 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 industrial development strategies in developing countries.

This roadmap starts by discussing the status of the technologies covered. It continues with a review of current and future CO₂ emissions from industrial sources and then outlines a vision for global deployment of CCS in the five sectors covered, based on an update of the IEA *Energy Technology Perspectives 2010 (ETP 2010)* (IEA, 2010). The third section presents actions and milestones for technological development of CCS in industry, while section four focuses on actions and milestones for policy makers and financial partners. The fifth section explores the role of business and considers business models, taking into account the importance of matching sources and reservoirs, and of EOR. The roadmap concludes by outlining near-term actions for all stakeholders.

The technological assessments and the actions and milestones are based on seven sectoral assessments conducted for the development of the roadmap (UNIDO, 2010a; b; c; d; e and UNIDO, 2011a; b) and the technology synthesis report (UNIDO, 2010f); workshops in Abu Dhabi (United Arab Emirates), Amsterdam (the Netherlands) and Rio de Janeiro (Brazil); and an extensive expert review.

2. Some energy-intensive sectors, such as the production of aluminium, require substantial amounts of electricity, which could lead to significant indirect CO₂ emissions depending on the underlying power generation mix.

CCS in Industry Today

While some individual CCS technologies can be considered mature – such as transportation of CO₂ in pipelines, capture from high-purity sources and several storage options, in particular EOR³ – deployment of integrated, commercial-size CCS projects has been limited to a few industrial applications. Large-scale capture of CO₂ will soon be demonstrated in power generation and has been demonstrated in some industry sectors. CO₂ storage in oil and gas reservoirs is not likely to lead to technological difficulties, while saline aquifers may have more challenges. Some capture technologies, as well as several catalysts and alternative processes enabling CO₂ capture, are still in the development phase. In general, more large-scale demonstration projects are needed to overcome the current lack of experience with fully integrated capture, transport and storage.

Capture technologies for industry

The application of CCS depends on the costs and readiness of capture technologies. Several industrial processes remove CO₂ as part of the process itself, resulting in highly concentrated CO₂ vent streams. These processes, which are based on a variety of CO₂ separation technologies depending on the specific process conditions, are discussed in the high-purity CO₂ sections of this roadmap. They offer early opportunities to deploy CCS, if business models, transport and storage infrastructure and regulatory frameworks are developed. In many applications CO₂ from high-purity sources still requires additional purification or dehydration before compression, transport and storage.

Many other applications of CCS in industry – for example for boilers, turbines, iron and steel furnaces, direct iron reduction processes and cement kilns – require additional CO₂ separation technologies to concentrate dilute streams of CO₂ to a level that enables economic transportation and storage. In some cases, this capture step requires far-reaching process modifications. Separation technologies include chemical or physical absorption, adsorption, liquefaction or cryogenic separation, and membrane separation. Most involve partial oxidation or full combustion of hydrocarbons. They fall into three categories:

- **Removal from diluted streams**, similar to post-combustion capture in power generation applications: The low-pressure flue gases exiting an oxidation process are treated using chemical or physical sorbents to remove CO₂ selectively from the gas mixture. The sorbents are then regenerated – using steam, for example – to produce a concentrated CO₂ stream from a stripping column.
- **Removal from oxy-fired streams**, similar to oxyfuel combustion in power generation applications: Combustion or oxidation in a relatively pure oxygen/CO₂ environment results in streams with high concentrations of CO₂, which are suitable for transport and storage after particulate and contaminant removal, optional flue gas desulphurisation and water removal.
- **Pre-process removal**, similar to pre-combustion CO₂ capture in power generation applications: Carbon-containing fossil fuels or biomass can be gasified with partial oxidation to produce high-pressure synthetic gas mixtures (syngas), which are then typically subjected to a water-gas shift reaction and gas separation to produce hydrogen and CO₂. The CO₂ is thus available at a higher concentration and pressure which simplifies the CO₂ separation process prior to transport and storage.

In most industrial processes, CO₂ removal technologies are already available but are not yet mature for CCS, or are only at demonstration stage (Table 2).

3. It is important to note that EOR is not necessarily CO₂ storage; EOR must be accompanied by a comprehensive monitoring and verification plan to be considered storage.

Table 2 Sector and technological maturity for CCS in industry

<i>Sector</i>	<i>Technology</i>	<i>Estimated date of maturity for CO₂ capture</i>
High purity	Ammonia*	Currently mature
	Gas processing*	Currently mature
	Liquefied natural gas (LNG) production*	Currently mature
	Fischer-Tropsch (FT) – synthesis coal*	Currently mature
Biomass conversion	Ethanol*	Currently mature
	FT – synthesis biomass (including black liquor)*	2015
	Bio-synthetic gas*	2015
	Chemical absorption – kraft mills	2015-20
	Black liquor gasification	2015-20
Cement	Chemical absorption	2015-20
	Oxyfuel	2030
	Carbonate looping	2030
Iron and steel	Post-combustion blast furnace	2020
	Oxyfuel blast furnace	2020-30
	Gas DRI	2020
	FINEX steelmaking process	2020-30
	Hlsarna steelmaking process	2030
Refineries	Hydrogen from synthetic gas reforming (SGR)*	Currently mature
	Hydrogen gasification residues	2015-20
	Fluid catalytic cracker (FCC)	2020-30
	Process heat	2020

Note: * The CO₂ source has a high purity and only transport and storage need to be demonstrated. Often, these processes have also diluted flue gas combustion streams.

Status of CCS in industrial sectors

Capture from **high-purity CO₂ sources** entails fewer technological challenges, but the CO₂ still needs to be compressed, transported and stored. Five full-scale projects demonstrating CCS from high-purity sources that include sufficient measurement, monitoring and verification (MMV) systems and processes are operating. Three are natural gas processing projects with storage in saline formations (in Salah, Algeria; and Sleipner

and Snøhvit, Norway). The Rangely oil field in Colorado imports CO₂ for storage from the Shute Creek gas sweetening plant in Wyoming; and the Weyburn-Midale project stores CO₂ from a syngas plant in North Dakota in oil fields in Saskatchewan, Canada. In Western Australia, the Gorgon LNG project under construction by Chevron will store CO₂ in saline formations.

In the **biomass conversion** sector, a number of CCS projects are under way. At the Arkalon bio-ethanol plant in Liberal, Kansas, 170 kilotonnes of CO₂ (ktCO₂) to 180 ktCO₂ – about 60% of the total produced – is captured for transportation to an oil field near Booker, Texas, for EOR. A similar project in Illinois using CO₂ from the Archer Daniels Midland Company bio-ethanol plant in Decatur will involve the injection of 1 megatonne of CO₂ (MtCO₂) a year over three years in the Mount Simon Sandstone saline formation (MGSC, 2010). While the bio-ethanol plant is operating, the capture, transport and storage component is still in development. In São Paulo state, Brazil, the Global Environment Facility (GEF) awarded a grant for implementation of CCS at a sugar-based ethanol plant. A typical sugar mill in São Paulo state produces 25 million litres of ethanol per year, so this implies that 20 ktCO₂ per year will be stored in a local saline formation.

In the **cement** sector, CO₂ capture technologies are not expected to become commercially available before 2020, and CCS is likely to raise production costs by 40% to 90% (IEA/WBCSD, 2009). Oxyfuel technology seems to be the most promising, given probable efficiency gains in cement production, but still needs “extensive research to understand all potential impacts on the clinker burning process” (IEA/WBCSD, 2009). The only known planned, small-scale demonstration involved post-combustion capture. The project was planned by CEMEX with funding from the United States Department of Energy (DOE) to demonstrate post-combustion dry sorbent CO₂ capture technologies. CEMEX concluded that careful consideration must be given to mitigating the technological risk and high capital cost of CCS in a cement plant. Given the time restrictions of the DOE programme, the company decided not to pursue the construction and operation of an industrial-scale demonstration project.

In the **iron and steel** industry, CCS faces many uncertainties regarding cost, efficiency and technology choice. Direct CO₂ emissions of the iron and steel sector are very site-specific and depend on the iron and steel making process used.⁴ Some mining and steel companies in France, Germany, the Netherlands, Sweden and the United Arab Emirates are exploring options through small-scale

4. It is sometimes not straightforward to attribute the actual CO₂ emissions to specific process steps, e.g. if actual CO₂ emissions happen in downstream process steps (i.e. by use in a power plant, coke oven underfiring, hot stoves, etc.) after exporting carbon-rich fuel gas from a blast furnace.

demonstrations of CO₂ capture from processes such as HIsarna, top-gas recycling (TGR), oxyfuel and DRI⁵ (UNIDO, 2010a). In Europe, 48 companies and organisations, from 15 countries, have launched a co-operative R&D project under the Ultra-Low CO₂ Steelmaking (ULCOS) consortium.

Refineries have many CO₂ sources with different levels of purity. In Norway, Gassnova (on behalf of the Norwegian state), Statoil, Shell and Sasol are building two small-scale capture demonstration plants near Mongstad to test CO₂ capture from flue gas streams of a cogeneration⁶ power plant and a refinery cracker. Statoil also plans to develop a full-scale capture plant on the natural gas-fired cogeneration plant that supplies heat to the refinery, but the government has postponed the investment decision until 2016 to review the environmental impacts of by-products from the amine solvents. In Brazil, Petrobras is operating a demonstration project for CO₂ capture by oxy-firing fluidised catalytic cracking in a refinery. In Canada, the Alberta government financially supports the North West Upgrading bitumen refinery project, which will capture CO₂ from a gasification process used to produce hydrogen. In Rotterdam, the Netherlands, CO₂ from the Pernis refinery is captured, transported and used in nearby greenhouses. Plans to transport more CO₂ from the refinery and store it in the depleted Barendrecht gas field were cancelled because of public resistance to storage. Also in the Rotterdam area, an ethanol production facility is almost ready to capture and store CO₂. Since 2010, Total has been testing oxycombustion based capture at Lacq in southwest France at the countries’ largest production site of liquid hydrocarbons. Other planned projects are listed in Table 11.

5. These processes are explained in Table 8.

6. Cogeneration (also combined heat and power [CHP]) is the use of a heat engine or a power station to simultaneously generate both electricity and useful heat.

Vision for CCS in Industrial Applications

In 2008, global primary energy supply reached 12 267 million tonnes of oil equivalent (Mtoe) and the related emissions of CO₂ amounted to 29 Gt. Nearly one-third of global energy demand (4 254 Mtoe) and one-quarter of worldwide CO₂ emissions (7 GtCO₂) are attributable to total industry and fuel transformation. Within the industry and fuel transformation sectors, 31% of emissions are attributed to the production of iron and steel, 27% to cement production, 10% to petroleum refining and 7% to high-purity CO₂ sources (Figure 1). The other industries, not covered in this roadmap, accounted for 25% of the emissions from industry and fuel transformation. In general, biomass can be considered CO₂-emission free, as it absorbs in its growing phase the carbon emitted when it is combusted.⁷

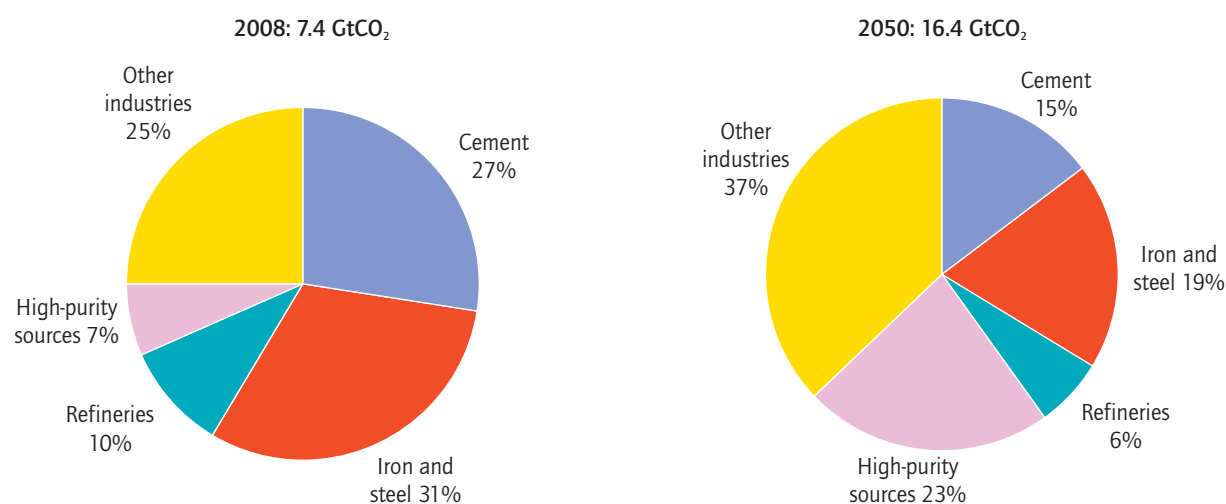
18% of total global energy-related CO₂ emissions in 2050. Reducing CO₂ emissions from these sectors is therefore an essential part of global action to prevent dangerous climate change.

To achieve the ambitious goal outlined in the ETP BLUE Map Scenario of cutting CO₂ emissions to 50% of 2005 levels by 2050 (Box 1), substantial deployment of CCS in industrial applications is necessary. Other options for reducing emissions – including improving energy efficiency through the application of best available technologies, fuel substitution, materials recycling and energy recovery – are not sufficient to reach this goal.

In the ETP Baseline Scenario, which assumes no new policies other than those currently in place, the CO₂ emissions of the five sectors discussed in this roadmap are projected to grow by 83% between 2008 and 2050, and would represent

7. This study does not attempt to make lifecycle analysis on the various types of biomass. Some types have practically 100% carbon-neutrality; others must account for CO₂ arising from cultivation practices or transformation processes.

Figure 1 Industrial CO₂ emission projections in the ETP Baseline Scenario



Note: Biomass conversion is not included in this figure.
Source: IEA analysis.

KEY POINT: By 2050, CO₂ emissions from total industry and fuel transformation sectors increase by 120% in the ETP Baseline Scenario.

Box 1 IEA ETP 2010 BLUE Map Scenario

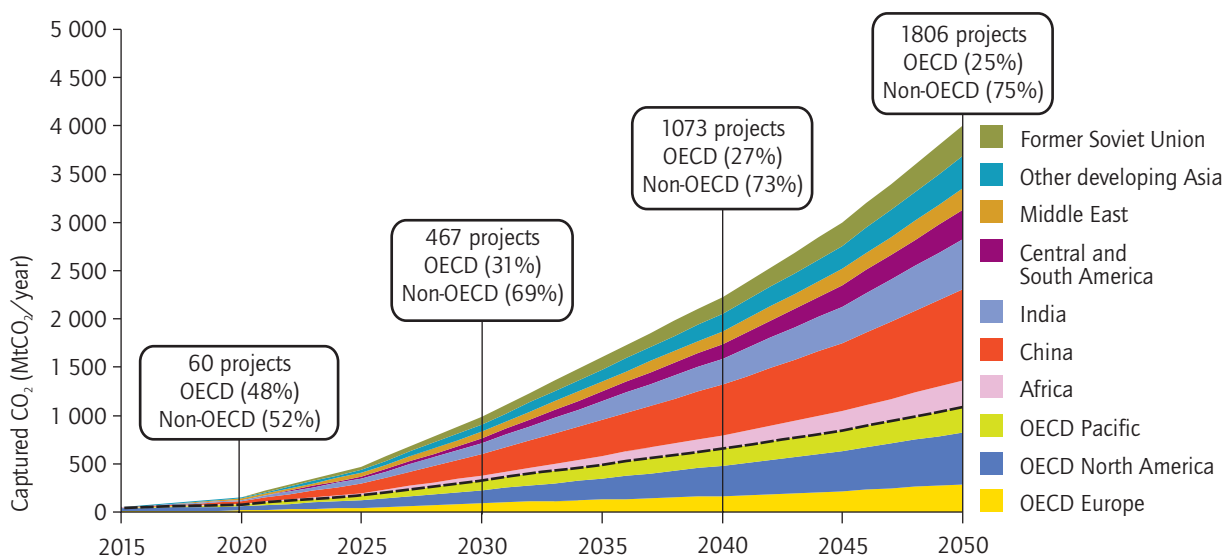
This roadmap outlines the deployment pathway needed to achieve the cost reductions and favourable conditions necessary for CCS in industry to reach the results of the *ETP 2010 BLUE Map Scenario*. This scenario sets out the technologies and policies necessary to reduce global energy-related CO₂ emissions to halve their 2005 levels by 2050. In addition, a Baseline Scenario, which assumes no new policies other than the existing ones today, is considered in order to illustrate the reduction efforts needed to reach the BLUE Map Scenario.

The ETP model is a bottom-up MARKAL model that uses cost optimisation to identify least-cost mixes of energy technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. In addition, the ETP model is supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors.

The BLUE Map Scenario reveals that an energy technology revolution is needed for deep emission reductions, involving a portfolio of solutions: greater energy efficiency, increased renewable energies and nuclear power, and the near-decarbonisation of fossil fuel-based power generation. A range of technologies, with a cost of up to USD 175/tCO₂ when fully commercialised, are necessary to halve CO₂ emissions by 2050.

According to the BLUE Map Scenario, widespread deployment of low-carbon technologies can reduce global oil, coal and gas demand to below current levels by 2050. Even so, it projects that fossil fuels will remain an important element of the world's energy supply for the foreseeable future.

Figure 2 Global deployment of CCS in industry by region



Note: The dashed line indicates separation of OECD/non-OECD groupings.
Source: IEA analysis.

KEY POINT: CCS is a key option in both OECD and non-OECD member countries; the share in non-OECD member countries increases continuously through 2050.

CO₂ reduction targets

The BLUE Map Scenario demonstrates the potential for CO₂ emissions for industry and fuel transformation to be 11 Gt lower in 2050 than under the Baseline Scenario. For the five sectors covered, the reductions achieved through the deployment of CCS reach 4 GtCO₂,⁸ accounting for 36% of the reductions. Over 1 800 projects are required in industry to achieve this goal. About three-quarters of the project in 2050 will be in non-OECD member countries (Figure 2). The application of CCS in these sectors represents about 9% of the total global CO₂ reductions envisaged in the BLUE Map Scenario.

In the BLUE Map Scenario, all regions need to apply CCS to new and existing industrial and fuel transformation plants to achieve deep reductions in emissions. This transition should start as soon as possible for new plants. As the technology matures and costs decline, existing plants need to

be retrofitted to maximise the potential of CCS.⁹ A large share of CCS projects are expected to be in non-OECD member countries (Figure 3),¹⁰ which contribute almost 80% of total industrial materials production by 2050, compared with 65% today.

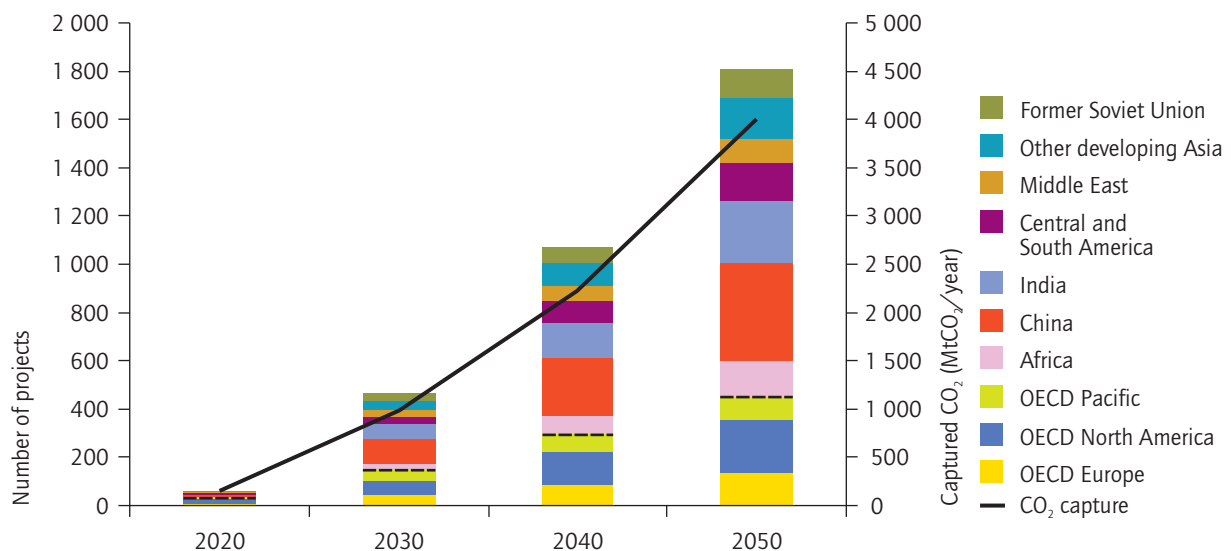
To achieve this level of CCS implementation in industrial applications, it is estimated that additional investments of USD 882 billion are required by 2050, over 75% of this in non-OECD member countries. Total cumulative additional costs, including additional investments, operation, transport and storage, would reach about USD 3 trillion by 2050.

8. This section presents the amount of CO₂ captured from CCS-equipped facilities taking into account CO₂ formation and capture efficiency. It does not present the CO₂ avoided, which reflects the level of emissions abatement achieved by CCS-equipped facilities relative to the emissions of an equivalent facility without CCS.

9. In some specific circumstance and for some industries (e.g. iron and steel), it may be more cost-effective to retrofit existing plants.

10. The practicable potential for CO₂ storage is not specifically modelled, but estimated storage potential is taken into account in modelling CCS in industry. Work is under way to improve the modelling and better reflect regional- or country-specific storage potential.

Figure 3 Global deployment of CCS in industrial sectors, 2020-50 (CO₂ captured and number of projects)



Note: The dashed line indicates separation of OECD/non-OECD groupings.
Source: IEA analysis.

KEY POINT: By 2050, 1 800 CCS projects are required in industry to capture 4 GtCO₂ annually.

The contribution of CCS differs in each of the five sectors analysed in this roadmap. Deployment depends on several factors, such as the projected growth in production for the sector (as it is often easier to implement CCS in new plants than to retrofit existing plants); the maturity of the capture technology to be applied; and availability of other low-cost options to reduce emissions.

The following sections examine the contribution of CCS in each sector and the number of projects required, as well as total costs of CCS and additional investments needed.

Deploying CCS in high-purity CO₂ sources

High-purity CO₂ sources include natural gas processing, new hydrogen and synfuels production, and ammonia production (if based on absorption processes for CO₂ separation). In this roadmap, about 753 MtCO₂ from high-purity sources would be captured in 2050 in the BLUE Map Scenario, accounting for 19% of the total capture in the five sectors analysed. Gas processing would account for 52% of high-purity capture in 2050; hydrogen and synfuels would make up 41%.

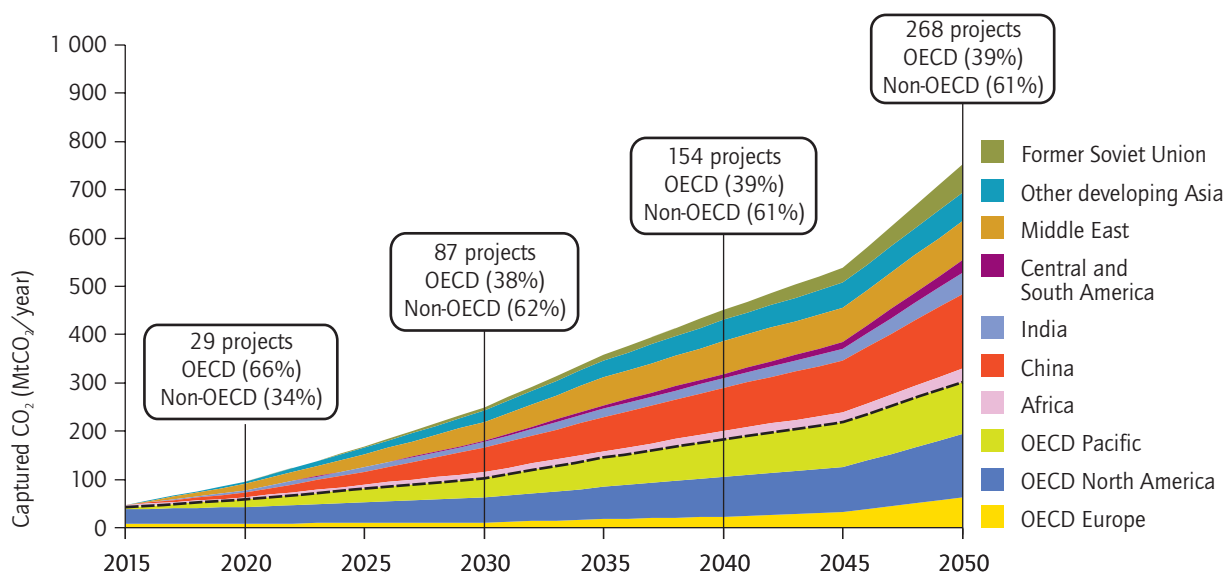
Under the BLUE Map Scenario, CCS from high-purity sources has to rapidly develop in the medium term in non-OECD member countries (Figure 4).

Five full-scale CCS projects including MMV are currently applied on high-purity sources (mostly gas processing plants). Given the state of research, development and demonstration (RD&D) in this sector, as well as the ease of capture from high-purity sources, costs and additional investments required are low. The additional investment to deploy 268 projects amounts to USD 56 billion from 2010 to 2050.

Deploying CCS in biomass conversion

Biomass is often considered a CO₂-free energy carrier, as it is assumed to absorb in its growing phase the carbon it emits when it is combusted. If the biomass is sustainably grown and used, the capture of CO₂ from biomass-based sources thus results in a net removal of CO₂ from the atmosphere.

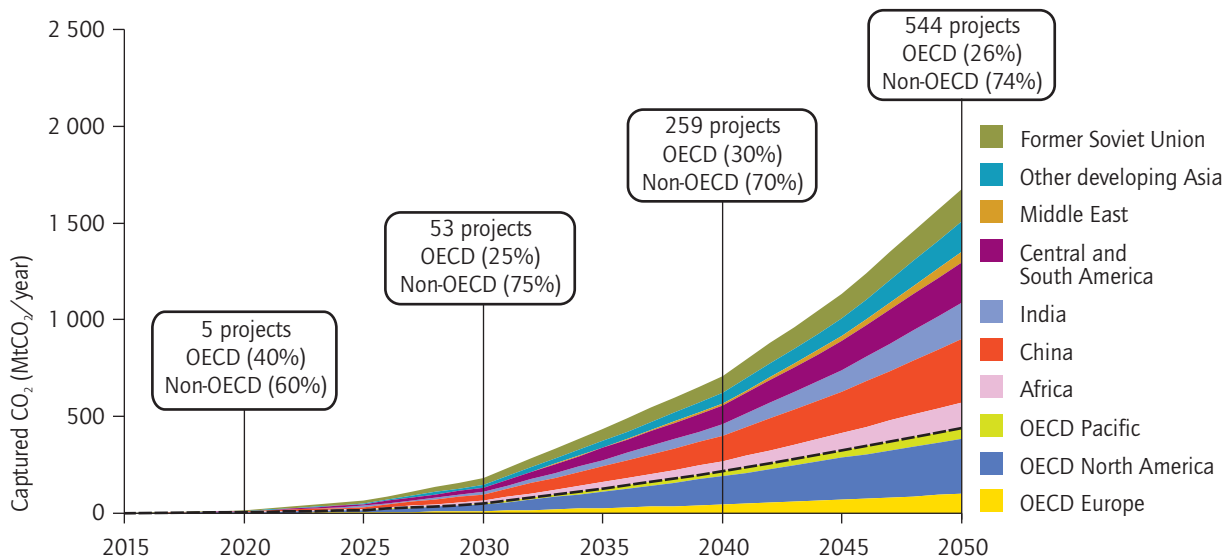
Figure 4 High-purity CO₂ sources: global deployment of CCS by region, 2015-50



Note: The dashed line indicates separation of OECD/non-OECD groupings.
Source: IEA analysis.

KEY POINT: North America and China would be major players in deploying CCS from high-purity CO₂ sources.

Figure 5 Biomass conversion sector: global deployment of CCS by region, 2015-50



Note: The dashed line indicates separation of OECD/non-OECD groupings.
Source: IEA analysis.

KEY POINT: The expected deployment of CCS and strong increase in the production of fuels from biomass results in a net removal of 1.7 GtCO₂ in 2050.

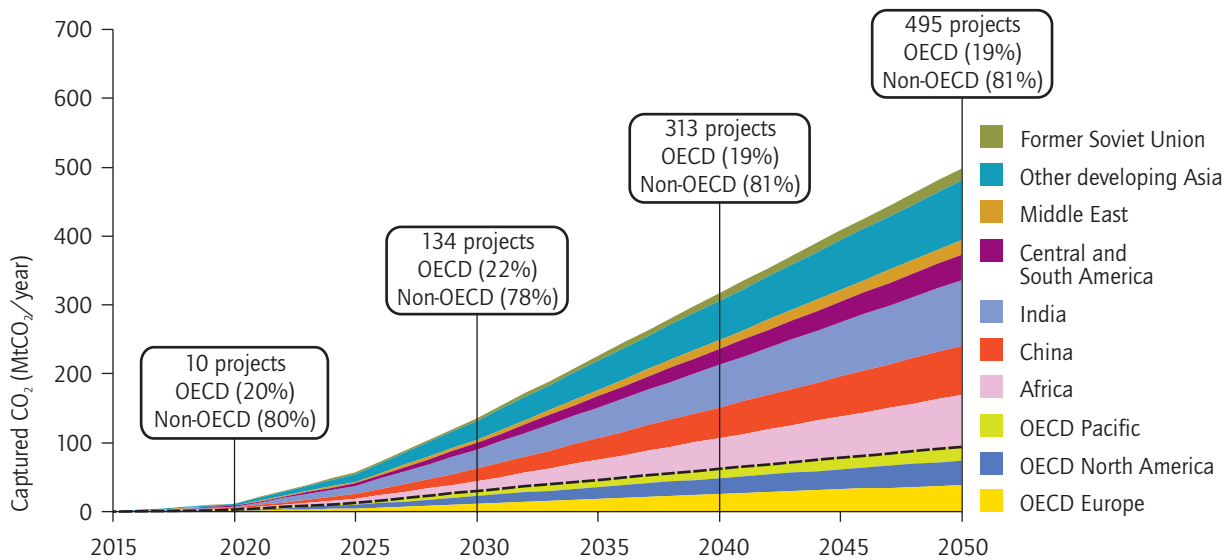
Deployment of CCS in biomass conversion sources is projected to start modestly. By 2020, 14 MtCO₂ could be captured, mostly from ethanol and hydrogen production. The production of biofuels is expected to increase dramatically in the medium to long term, notably in response to the growing demand from the transportation sector. CCS deployment in biomass is projected to rise sharply from 2030 (Figure 5) and would account for 42% of the emissions captured in the five sectors analysed by 2050. CCS in hydrogen and synfuel production would account for 70% of the carbon capture in this sector; synthetic natural gas (SNG) will account for 17% and ethanol production for 11%. North America and China are expected to play a key role in CCS deployment in biomass conversion.

Of the USD 212 billion of total additional investments required in this sector, USD 182 billion is required between 2030 and 2050 as the use of biofuels in the BLUE Map Scenario increases in the medium to long term.

Deploying CCS in the cement sector

The cement sector represents about 12% of the CO₂ captured in 2050 from the five sectors analysed in this roadmap. Overall CO₂ savings are expected to be small in the short term, given strong expected growth in demand, low capital stock turnover and the modest gains that can be achieved through energy-efficiency retrofits, but will accelerate after 2020 with CCS deployment. This deployment starts slowly but ramp up rapidly after 2030 as costs decline. Under the BLUE Map Scenario, about 500 MtCO₂ is captured in 2050 in the cement sector (Figure 6).

Figure 6 Cement sector: global deployment of CCS by region, 2015-50



Note: The dashed line indicates separation of OECD/non-OECD groupings.
Source: IEA analysis.

KEY POINT: In the next 20 years, about 130 projects are needed, a significant ramp-up given the current state of technologies applicable in the cement sector.

Under the BLUE Map Scenario, 495 CCS projects are required in the cement sector worldwide by 2050. About two-thirds of these are in Africa and developing Asia. Such deployment requires an estimated USD 300 billion in additional investments by 2050.

Deploying CCS in the iron and steel sector

By 2050, the iron and steel sector accounts for about 23% (914 MtCO₂) of the CO₂ captured from the sectors covered in this roadmap. Although OECD member countries play a key role in the demonstration and early deployment of CCS in this sector, their share of deployment in 2050 is significantly lower as their share of global production declines (Figure 7).

Non-OECD member countries, notably China and India, play the largest role in the global deployment of CCS in the iron and steel, given their expected strong production growth throughout the period to 2050.

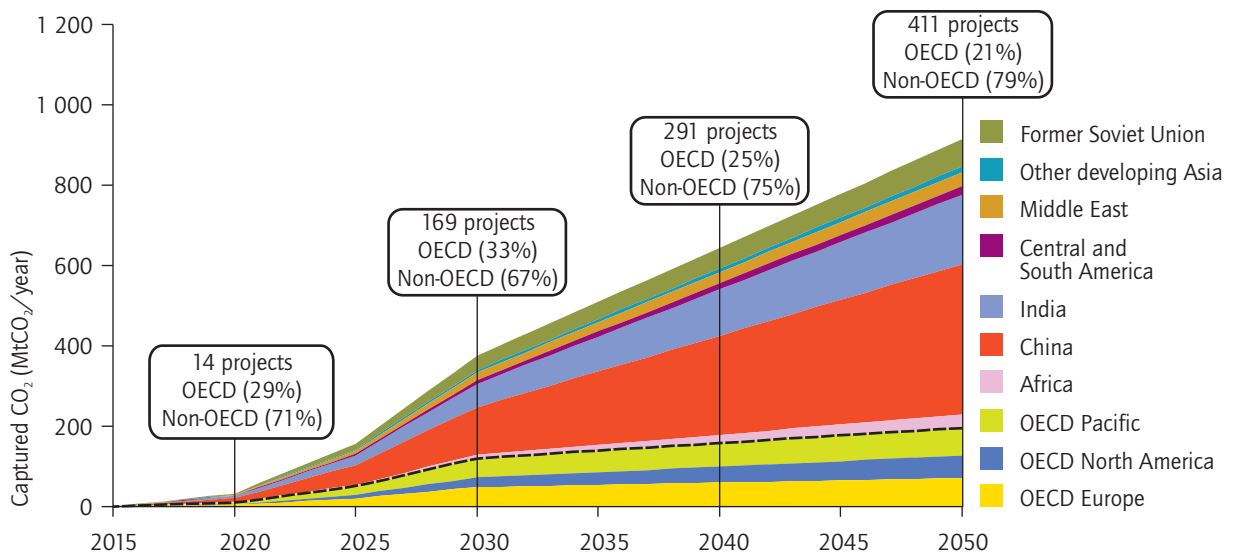
Reaching such ambitious levels of CCS requires about 14 projects to be implemented by 2020. The additional total investments over the 2010 to 2050 period amount to almost USD 260 billion.

Deploying CCS in refineries

Refineries account for about 4% of the capture from the sectors analysed in this roadmap in 2050. In contrast to the other sectors analysed, all refinery CCS projects are in OECD member countries before 2020, and OECD member countries account for a higher share than non-OECD member countries until 2030 (Figure 8).

The capture of 165 MtCO₂ in refineries by 2050 requires USD 57 billion of additional investments.

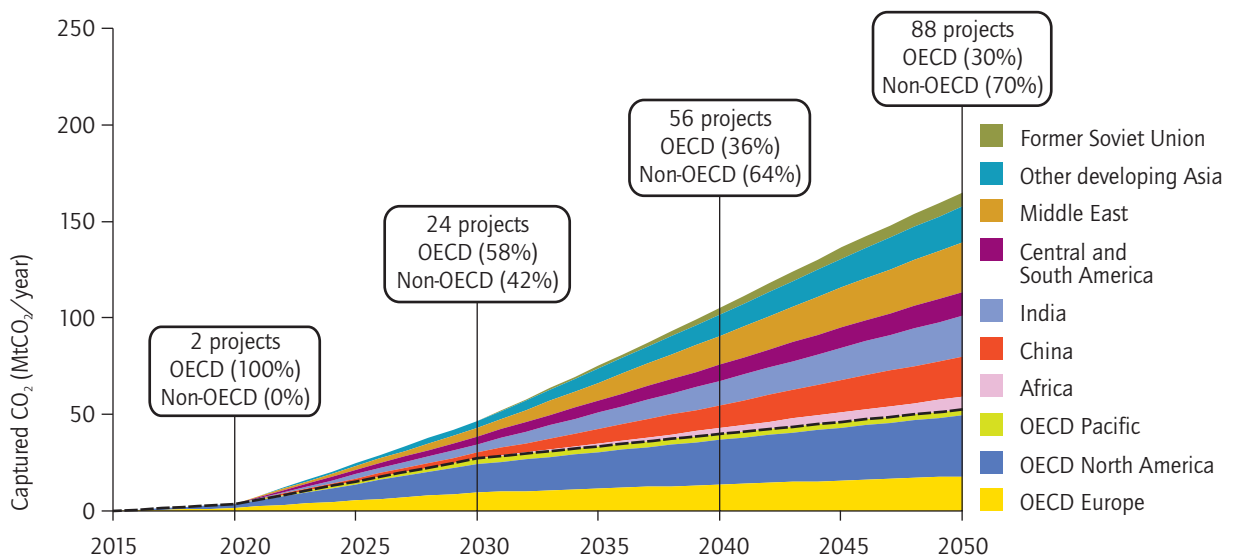
Figure 7 Iron and steel sector: global deployment of CCS by region, 2015-50



Note: The dashed line indicates separation of OECD/non-OECD groupings.
Source: IEA analysis.

KEY POINT: The strong growth in crude steel production in the next decades opens up opportunity for the deployment of CCS.

Figure 8 Refining sector: global deployment of CCS by region, 2015-50



Note: The dashed line indicates separation of OECD/non-OECD groupings.
Source: IEA analysis.

KEY POINT: OECD member countries continue to be an important player in the deployment of CCS with a share of 30% of the projects in 2050.

Additional investments needed and total additional costs

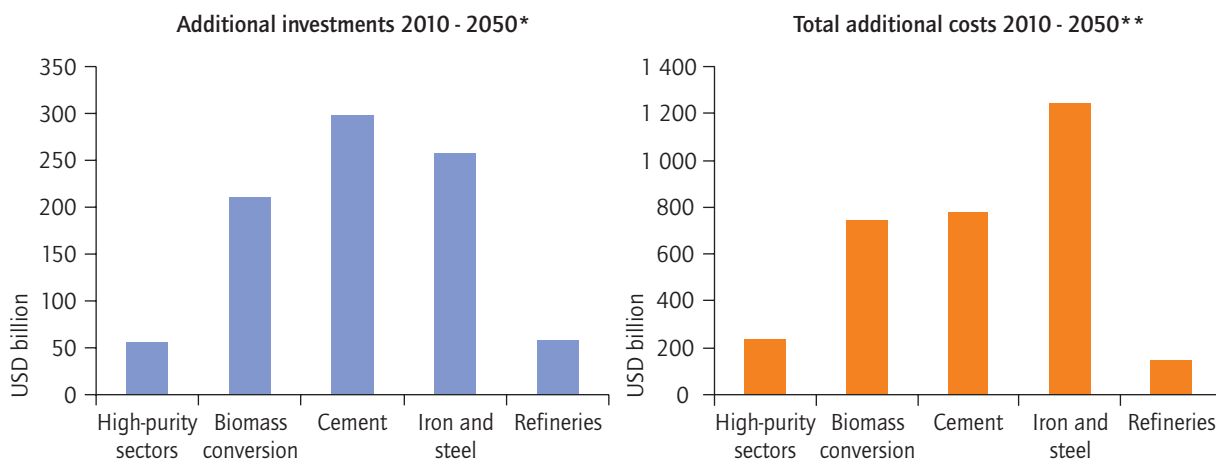
To achieve the deployment of CCS in industrial applications envisaged in this roadmap, additional investments for capture only over the period 2010 to 2050 would amount to USD 882 billion (Figure 9). This represents about 2% of the overall additional capital investment needed to achieve a 50% reduction in CO₂ emissions by 2050 as set out in the BLUE Map Scenario. The total additional costs, including capital expenditure, fuel and maintenance costs, and costs associated with CO₂ transport and storage, are estimated at about USD 3 trillion over the 2010 to 2050 period. Transport and storage amount to about one-third of the total additional costs.

The investment required varies across regions as patterns and rates of CCS deployment differ. In the short term, accelerated deployment of CCS in OECD member countries requires USD 12 billion of additional plant investments by 2020, over 40% of the additional investment required (Table 3).

Growth in materials production is expected to come mostly from non-OECD member countries. As it is often less costly to apply capture in new facilities than to add capture later, there are substantial opportunities to deploy CCS widely in these regions. By 2030, over 65% of total additional investments are expected to be in non-OECD member countries; by 2050, this share amounts to about 75%.

The abatement costs associated with CCS (USD/tCO₂ avoided) differ across regions and sectors, as shown by the range of estimates over the period 2010 to 2050 used for the BLUE Map Scenario analysis (Figure 10). The costs of capture technology are expected to fall as demonstration of integrated projects increases and technology costs decline, while optimisation of regional pipeline infrastructure reduces transport costs.

Figure 9 Additional investments and total additional costs by sector



Notes: *Does not include investment in transport and storage. **Includes cost of transport and storage.
Source: IEA analysis.

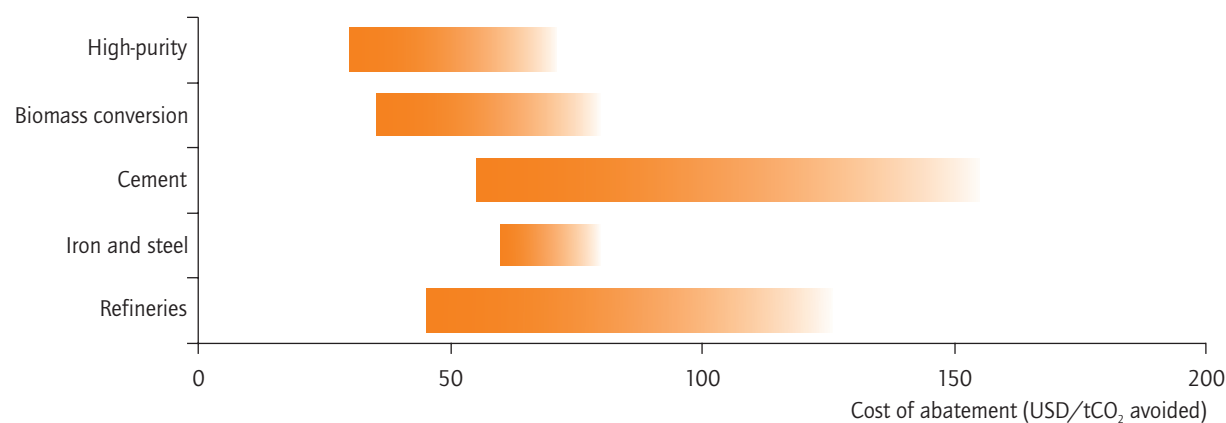
KEY POINT: The additional investment needs for CCS over the 2010 to 2050 period are about USD 882 billion; total additional costs are over USD 3 trillion.

Table 3 Additional investments and total additional costs by region

	<i>Additional investments* (USD billion)</i>				<i>Total additional costs** (USD billion)</i>
	<i>2010-20</i>	<i>2021-30</i>	<i>2031-50</i>	<i>Total 2010-50</i>	<i>Total 2010-50</i>
OECD member countries	12	73	130	214	872
OECD Europe	3	25	38	66	277
OECD North America	6	22	64	92	348
OECD Pacific	2	25	28	56	247
Non-OECD member countries	15	156	496	668	2 281
Africa	2	14	71	87	249
China	4	44	141	190	719
India	2	30	93	125	431
Central and South America	1	14	50	65	216
Middle East	2	13	31	46	160
Other Developing Asia	2	23	68	93	266
Former Soviet Union	2	17	42	61	240
World	27	229	626	882	3 153

Notes: *Does not include investment in transport and storage. **Includes cost of transport and storage.
Source: IEA analysis.

Figure 10 Ranges of CCS abatement costs used in this roadmap (USD/tCO₂)



Note: The costs shown above represent the range of abatement costs based on IEA, 2009, and the analysis compiled for this roadmap. These costs are therefore affected by the assumed level of CCS uptake in each sector. For sectors with a low uptake, the ranges above relate only to early-opportunity, lower-cost applications; for sectors in which uptake of CCS is high, the ranges are more representative of total sector CCS applications. These costs do not assume that storage generates revenues – *i.e.*, no EOR options are taken into account. They also represent a regional estimated average, meaning that cheaper options are possible.
Source: IEA analysis.

KEY POINT: Abatement costs range most widely between and within sectors.

CO₂ Capture Technologies: Actions and Milestones

The wide variety of industrial processes poses challenges but also opportunities for CCS in industrial applications. Only minor treatment of CO₂ streams from high-purity sources is required before compression, transport and storage. Capturing “process CO₂”, by contrast, can require the re-engineering of established and reliable production techniques, posing high costs, and is therefore at an early stage of development.

Specific technology gaps need to be bridged to achieve this roadmap’s ambitious growth pathway for CCS in industrial applications. This section discusses the maturity of industrial CCS technologies and summarises the specific action items identified for each sector.

As the technologies for capture in industrial applications have important elements in common with pre-combustion, post-combustion and oxyfuel technologies in power-sector CCS, significant cross-fertilisation with CCS in industrial applications is likely. Given the wide variety of

industrial emissions, however, tailored solutions are required for industry, specifically for the energy use of CO₂ capture plants.

Capture of CO₂ from high-purity sources

Several processes in industrial applications result in a high-purity, high-concentration CO₂ vent stream, which can be readily dehydrated, compressed, transported and stored, providing a lower-cost option for CCS.

CO₂ capture techniques for producing the high-concentration CO₂ vent streams include:

- Existing gas separation techniques such as: membrane separation; chemical absorption using amine solvents; hot potassium carbonate-based processes; physical sorbent-based processes; and pressure swing absorption (PSA).
- Cryogenic separation processes.

Table 4 High-purity CO₂ sources: key technological characteristics relevant to CCS

Process	Summary of key technological characteristics
Natural gas processing (onshore/offshore)	Natural gas typically undergoes processing before export to markets. Depending on the field conditions, raw natural gas may contain 2% to 70% CO ₂ by volume. This needs to be reduced to market or process specifications. Most current CO ₂ emissions sources are in the Middle East and Southeast Asia. Natural gas processing includes production of LNG, where removal of CO ₂ is a pre-requisite to the natural gas liquefaction process.
CtL	In CtL technology, coal is gasified to produce synthesis gas, which is then catalytically treated in a FT process to produce liquid fuels like gasoline and diesel. CtL is an energy-intensive process but can produce significant amounts of high-purity CO ₂ via a water-shift reaction and subsequent removal of CO ₂ . This indirect coal liquefaction method is used by Sasol in South Africa. A CtL plant in China is using direct coal liquefaction. In 2009, global CO ₂ emissions from the only two CtL plants operational (in China and South Africa) were 30 Mt.
Ethylene oxide production	Ethylene oxide, which has a range of uses in the chemical industry, is produced by direct oxidation of ethylene in the presence of a silver catalyst. CO ₂ , a by-product of the ethylene oxide process, can be partly re-used in the reactor feed, vented or used in commercial applications.
Ammonia production	Ammonia is primarily used for fertiliser production. The compound is produced through the Haber-Bosch process, which involves the synthesis of hydrogen with gaseous nitrogen using an iron- or ruthenium-enriched catalyst. The hydrogen used for the process is normally produced at the ammonia production site through steam reforming of natural gas (or sometimes coal). Depending on the exact design of the process, steam reformation can result in a near-pure stream of CO ₂ . About half of the CO ₂ resulting from ammonia production is used to produce urea; the rest is vented.

Selection of the appropriate process depends on factors including end use specification; gas inlet concentration and pressure; co-contaminants (like hydrogen sulphide [H₂S]); energy use and efficiency; and maintenance needs.

Although high-purity CO₂ streams resulting from these processes have much potential for accelerating CCS, notably by enabling cost-effective demonstration, significant technical uncertainties and challenges remain. To date, the processes have not been optimally designed to capture CO₂ for the purposes of transport, storage or EOR.

The first challenge is a lack of data on the distribution of different types of gasifiers, reformers and gas treatment technologies employed in high-purity CO₂ sources. To understand fully the potential for transporting and storing CO₂ from high-purity sources, it is essential to investigate any technical limitations within such a broad range of processes (Table 4). The use of PSA in ammonia production, for example, could have an impact on the availability of high-purity CO₂ where the tail gas is used for low-grade heat production (UNIDO, 2010d).

Second, the co-storage in natural gas processing of acid (CO₂) and sour (H₂S) gas, as is commonly done in some regions, could affect the deployment of CCS (Bachu *et al.*, 2008).

Other technological challenges include ducting of the large flue gas streams in confined areas, transport to a capture plant and energy use of the capture plant.

Technology actions for CCS in the high-purity sources sector

Although capture of CO₂ in high-purity sources is relatively straightforward, several short-term challenges need to be addressed:

- Compile an inventory of hydrogen, ammonia and ethylene oxide production technologies to verify their suitability for CCS.
- Identify key technical barriers to deployment of CCS in these processes, with reference to heat integration, the utilisation of CO₂ or the presence of co-contaminants (such as H₂S) in the CO₂ stream.

- Estimate the costs of any required CO₂ capture, gas conditioning, additional piping and compression of CO₂ stemming from high-purity CO₂ processes.
- Establish CO₂ transportation and storage demonstration projects involving hydrogen, ammonia and ethylene oxide production processes.
- Realise 29 gas processing, Ctl, ethylene oxide or ammonia production plants with CCS by 2020, and 87 plants by 2030.

Capture of CO₂ from biomass conversion

Given an expected increase in global demand for biofuels from 2.3 exajoules (EJ) today to 32 EJ in 2050 (IEA, 2011a), the potential to deploy CCS in the biomass sector is likely to increase significantly. To achieve substantial deployment, however, several challenges need to be met.

The two main routes for the industrial conversion of raw biomass feedstock into final energy products are gasification and biological processing (fermentation). Fermentation uses micro-organisms to break down the feedstock and produce liquid and gaseous fuels.

The application of CCS to biomass conversion could achieve a net removal of CO₂ from the atmosphere. These negative emissions may be required to meet ambitious CO₂ abatement targets such as those set out in the IEA BLUE Map Scenario. Negative emissions are only possible, however, if biomass production is sustainable, a condition that must be carefully considered by stakeholders (Box 2).¹¹

¹¹ For more details see the *Technology Roadmap Biofuels for Transport* (IEA, 2011a).

Box 2 Sustainability of biofuel production

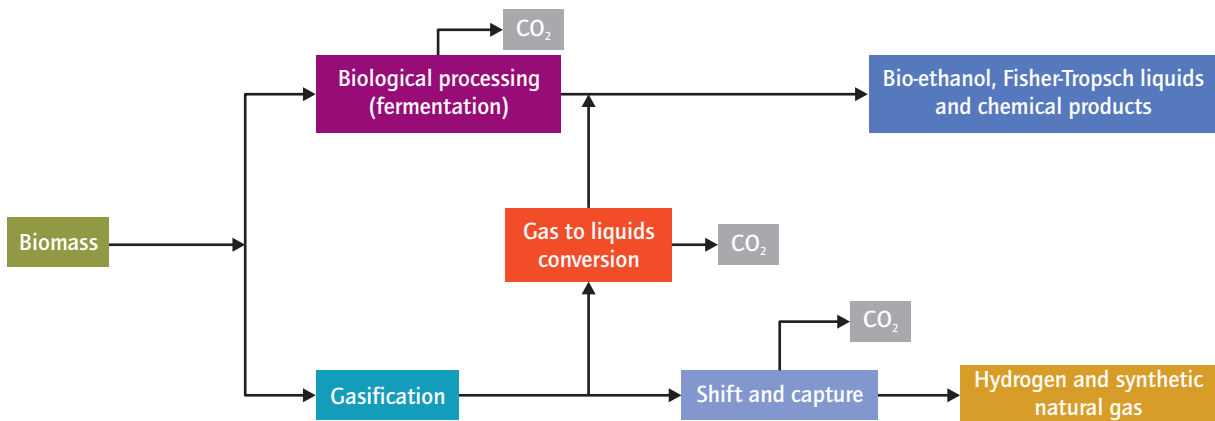
The anticipated demand for biofuels will require adequate policy to ensure that biomass feedstock is produced in a sustainable manner. Excessive demand for conventional biomass feedstocks (such as grain and sugar) could affect food and livestock prices, and contribute to greenhouse gas (GHG) emissions stemming from land-use change for biomass cultivation. It is important that policies promote the equitable distribution of proceeds from biofuel sales along the whole supply chain. R&D into biofuel production processes using advanced conversion processes and lignocellulosic biomass feedstocks can help achieve sustainability. In addition, adoption of sound sustainability certification for biofuel can ensure considerable life-cycle emission reductions. Bio-energy with carbon capture and storage (BECCS) could result in negative emissions, as well as promoting the sustainable production of biofuels along the whole supply chain.

For more detail on the sustainability of biofuel production, please refer to the *Biofuels for Transport Technology Roadmap* (IEA, 2011a).

In most biomass conversion processes, high CO₂ concentrations enable straightforward capture of CO₂ (Figure 11). Challenges arise from the small

scale of the CO₂ source and hence the economics of transport and storage.

Figure 11 Routes for biomass with CO₂ capture



Sources: UNIDO, 2010e. Adapted from Rhodes and Keith, 2005.

KEY POINT: The application of CCS to biomass conversion could achieve a net removal of CO₂ from the atmosphere.

Table 5 Biomass conversion: key technological characteristics relevant to CCS

<i>Process</i>	<i>Summary of key technological characteristics</i>
Hydrogen and SNG	Gasification of biomass results in a synthesis gas made up of carbon monoxide (CO), CO ₂ , hydrogen, methane and nitrogen. The synthesis gas then undergoes a water-gas shift reaction, to produce a stream rich in CO ₂ , CO and hydrogen. The CO ₂ is removed from the stream using pre-combustion capture technologies such as absorption by organic solvents, membrane separation or through the use of adsorption materials. The hydrogen can then be used to produce SNG through the process of methanation.
Ethanol production	A common conventional (first generation) process to produce bio-ethanol, is the fermentation of sugar and starches (sugar beet, corn, sugar cane or sweet sorghum), where a by-product of the reaction is a relatively pure stream of CO ₂ .
Black liquor processing in pulp and paper manufacturing	Approximately 60% of CO ₂ emissions in the pulp and paper industry are from biomass fuel combustion. Flue gases of pulp and paper mills contain 13% to 14% CO ₂ , and post-combustion capture of CO ₂ from these diluted streams is costly. Black liquor gasification can be applied for production of liquid fuels and allows for easier capture of CO ₂ using pre-combustion capture technologies.

Technology actions for CCS in the biomass conversion sector

- R&D into the removal of tars that result from the gasification of certain types of biomass and conversion of cellulose through chemical or biochemical routes.
- Continue research on the most suitable types of biomass fuels that can be produced in a sustainable manner.
- Further quantify the total amount of biomass that could be produced in a sustainable manner.
- Encourage R&D on combining the shift and CO₂ capture steps in a single reactor to lower capital costs, increase the CO₂ capture ratio and lower the energy penalty (the extra energy required for CO₂ capture).
- Realise six commercial-scale biomass conversion plants combining CO₂ compression, transport and storage by 2020, including an industrial-scale biomass gasification demonstration plant with CCS.

Capture of CO₂ in the cement sector

Cement production results in CO₂ emissions from fuel combustion to provide the process heat, and from limestone calcination, which contributes

more than half of total emissions. Post-combustion capture from diluted flue gas streams and oxyfuel combustion technologies can be used to capture CO₂ from cement production.¹²

Post-combustion technologies will not require fundamental changes in the clinker-burning process, and could be retrofitted to existing plants depending on space restrictions. Typically, they use amine-based solvents to separate CO₂ from flue gases in an absorption process. The CO₂-rich solvent is then regenerated in a stripping process by addition of low-temperature heat, typically low-pressure steam. The energy requirements for the regeneration of the amines used in the chemical absorption process are high and additional installations such as a cogeneration plant would need to be constructed. Other post-combustion capture techniques, including membranes and solid sorption processes, are in R&D and may lead to less energy-intensive capture options.

Post-combustion capture technology is a short-term option for CCS in the cement sector, given its maturity in other industrial sectors and the high level of attention it has received from the power industry. However, the high energy requirements for the regeneration of the capture solvents used

12. It should also be noted that oxygen enrichment is common practice to increase productivity of cement kiln. This process called de-bottlenecking was first developed in the 1990's to increase the capacity by reducing the nitrogen gas (N₂) content through replacing a part of the combustion air with oxygen.

Table 6 Cement production: key technological characteristics relevant to CCS

Process	Summary of key technological characteristics
Post-combustion	Planned pilot and demonstration projects for post-combustion capture both in industry and in the power sector are solely based on chemical absorption, mainly through the use of amine-based systems (ECRA, 2009).
Oxyfuel	Oxyfuel combustion, the use of oxygen instead of air in the cement production process, can generate an almost pure CO ₂ stream. Oxyfuel is not likely to be suitable for retrofitting as it requires significant modification to the cement producing process and equipment. Two options for oxyfuel technology in the cement industry have been proposed (ECRA, 2009): - partial capture in the pre-calciner, but not in the rotary kiln, and capture at an intermediary stage; and - total capture based on burning fuel in an oxygen/CO ₂ environment in both the pre-calciner and the rotary kiln to produce a nearly pure CO ₂ stream from the whole process.

in post-combustion capture warrant significant R&D into oxyfuel combustion, which has been successfully applied in other high-temperature processes.

Oxyfuel technologies have their own disadvantages, however. While they can avoid the high energy costs associated with all post-process capture techniques, the cost of oxygen gas (O₂) production is high. Moreover, many industrial processes are not designed to operate in oxygen-rich environments, so significant re-engineering may be needed to accommodate altered thermodynamics and material stress. Any impacts on product quality also need to be fully understood.

Technology actions for CCS in the cement sector

Post-combustion

- Conduct R&D for improving the economics and performance of capture techniques under flue gas conditions that are typical for the cement sector, in particular by further developing existing and new (such as aqueous ammonia) chemical absorption solvents to reduce energy requirements while minimizing any potential environmental and health impacts.
- Test the suitability of physical removal capture systems such as membranes and physisorption (physical adsorption). Study the potential of novel capture processes, such as anti-sublimation, and modification of current clinker processes, to produce a more concentrated CO₂ flue gas at the chimney stack.

- Encourage the development and use of mobile post-combustion test rigs or modular equipment that can be taken to existing cement kilns.
- Investigate the potential economic savings of sharing process equipment or capture-related support infrastructure through the co-location of cement plants and power plants, and potential synergies if calcium looping is used for CO₂ capture in the power plant (or both plants).
- Realise a pilot post-combustion cement plant before 2015.
- Demonstrate a full-scale post-combustion capture plant in the cement industry between 2015 and 2020.

Oxyfuel

- Investigate the influence of the O₂/CO₂ atmosphere on the design and operation of the pre-heater, pre-calciner and kiln; the impact of CO₂-rich atmosphere on the equilibrium of calcium reaction; the need for novel refractory materials; and how these may affect product quality.
- Undertake R&D effort in the heat transfer characteristics of O₂/CO₂/water environment in the cement pre-calciner and kiln.
- Undertake further research on refractories to enable them to withstand higher operation temperatures.
- Evaluate the impact of air ingress to the downstream CO₂ processing.

- Pilot-scale pre-calciner and cement kiln operating under oxyfuel combustion must be built to gain insight and confidence in this technology.
- Support R&D in methods to improve the energy efficiency of air separation, such as ion transport membranes, to reduce the energy penalty of oxyfuel processes.
- By 2020, develop a pilot oxyfuelled cement plant to assess the impact of the process re-design on the composition of the cement product.
- Demonstrate a full-scale oxyfuelled cement plant between 2025 and 2030.

The mainstream blast furnace production process can be equipped with CO₂ capture. There are also several alternatives to blast furnace technology, including advanced smelting technologies – Hlsarna and FINEX – and DRI. Research is under way to identify the most energy-efficient capture technique for removing CO₂ from the gas recycling system.

Biomass-based DRI processes are in research phases and could become an important iron production pathway (Hallin, 2010). A Hlsarna pilot plant is under construction in IJmuiden, the Netherlands, with the first results expected in 2011 (Meijer, 2010).

Capture of CO₂ in the iron and steel sector

In the iron and steel sector, the main sources of CO₂ emissions are power production, iron ore reduction in either a blast furnace or a DRI plant, and coke and sinter plants. Selection of capture equipment will depend on factors including CO₂ capture rate, possible requirements for secondary gas treatment, energy consumption, reliability and operational and capital costs.

Table 7 Technology options for CO₂ separation and capture from blast furnace gas from oxygen blast furnace applications

	<i>Unit</i>	<i>PSA</i>	<i>Vacuum pressure swing adsorption (VPSA)</i>	<i>VPSA + compression and cryogenic flash</i>	<i>Amines + compression</i>	<i>PSA + cryogenic distillation + compression</i>
CO ₂ yield	% vol	79.7	87.2	96.3	100	100
Total energy consumption	gigajoules (GJ)/tCO ₂	0.36	0.38	1.05	3.81	1.12

Note: Results based on the input gas with the approximate composition of the top gas recycling blast furnace gas (CO = 45% vol; CO₂ = 37% vol; N₂ = 10% vol; hydrogen gas = 8% vol).

Source: UNIDO, 2010a.

Table 8 Iron and steel production: key technological characteristics relevant to CCS

<i>Process</i>	<i>Summary of key technological characteristics</i>
Blast furnace (pig iron)	Blast furnaces are the largest source of direct CO ₂ emissions in the steel-making process, and CCS currently represents the only technological option to drastically cut these emissions. Top gas recycling (TGR) or oxyfuel blast furnaces are ways to increase the CO ₂ concentration in the off-gas. PSA is an option to capture CO ₂ .
DRI	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 CO. CO ₂ capture is already widely applied in the DRI process to enhance the flue gas quality. DRI facilities are normally concentrated in a few countries that have access to inexpensive gas reserves, such as parts of Latin America and the Middle East. Capture of CO ₂ can be done through pre-combustion (gasification) and PSA, VPSA or chemical absorption.
FINEX process	The FINEX process is an advanced smelting technology, an energy-efficient alternative to the blast furnace. In the FINEX process, part of the CO ₂ is removed from the recirculation gas. This is currently vented because of the lack of suitable storage sites. With some process redesign, all the CO ₂ could be captured with no efficiency penalty to the FINEX process itself.
Hlsarna process	The Hlsarna process combines twin screw reactors, smelting and cyclone converter furnace technologies. It operates using pure oxygen instead of air, resulting in a top gas that is nitrogen-free and has a high concentration of CO ₂ . Hlsarna equipped with CCS could capture approximately 80% of the CO ₂ process from producing liquid iron from iron ore and coal. Capture technologies are PSA or VPSA.

Technology actions for CCS in the iron and steel sector

In the short term, top-gas recycling blast furnaces (TGR-BF) seem to offer a viable approach to CCS in the sector since TGR can be retrofitted on existing blast furnaces. The suitability for CCS of new iron and steel production processes, such as DRI and smelting technologies, increases the potential for CCS in the sector. Given that there is no clear technology winner at this point, investment and R&D remains necessary.

This roadmap recommends the following actions:

- Stimulate further research into the most cost-effective and energy-efficient capture techniques to use on TGR-BF.
- Optimise process by using heat from other on-site processes to regenerate capture solvents.
- Realise a full scale TGR-BF demonstration by 2016.
- By 2020, smelting technology to achieve 2 million tonnes per year production per furnace.

- By 2035, smelting technology to contribute about 2% to 5% of overall steel production.
- Equip 75% of new large blast furnaces and DRI units in OECD member countries with CCS by 2030, and 50% in non-OECD member countries.

Capture of CO₂ in the refining sector

Many CO₂ point sources are typically dispersed across each refinery complex. The greatest CO₂ emissions stem from process heaters, utilities and FCC, and from hydrogen manufacture. Given this diversity of processes, all three key capture routes – pre-combustion (pre-process) capture from syngases, post-combustion from diluted flue gas streams and oxyfuel combustion for concentrating CO₂ in flue gases – could be relevant.

Table 9 Major CO₂ emission sources at a typical refinery complex

CO ₂ emitter	Description	% of total refinery emissions	% concentration of CO ₂ stream
Furnaces	Heat required for the separation of liquid feed and to provide heat of reaction to refinery processes such as reforming and cracking.	30-60	8-10
Utilities (including boilers)	CO ₂ from the production of electricity and steam at a refinery.	20-50	4 (cogeneration turbine gas)
FCC	Process used to upgrade a low-hydrogen feed to more valuable products.	20-50	10-20
Hydrogen production	For numerous processes, refineries require hydrogen. Most refineries produce this hydrogen on-site, for example via SMR or with a gasifier.	5-20	20-99

Source: Straelen, J. van *et al.*, 2010.

A refinery may contain pure CO₂ sources that allow easy capture at low cost, as well as sources where CO₂ is more diluted. Hurst and Walker (2005) suggest ducting the gases from dispersed process heaters to a central location where CO₂ could be

separated and compressed. For deep CO₂ emission avoidance, fuel gas could be decarbonised in the central fuel gas processing plant and then distributed to process heaters (Lindsay *et al.*, 2010).

Table 10 Refineries: key technological characteristics relevant to CCS

Process	Summary of key technological characteristics
Hydrogen production – natural gas SMR	Between 5% and 20% of refinery CO ₂ emissions are linked to the production of hydrogen. Hydrogen is most commonly produced through SMR. The hydrogen produced in this process needs to be separated from by-products that end up in the syngas, including CO ₂ . Traditionally, hydrogen produced in SMR plants was purified using chemical adsorbents, resulting in high-purity CO ₂ . More recently, however, the use of PSA is becoming more common, which results in lower-concentration CO ₂ streams, making the gas suitable for reuse in fuelling the SMR furnace but increasing the cost of CO ₂ capture.
Hydrogen production – gasification residues	Residues are gasified to syngas from which hydrogen is separated. With different technologies, a pure stream of CO ₂ can be produced.
FCC	Catalytic cracking is the process of breaking down heavy oil into lighter oil products such as gasoline and naphtha. The FCC can account for 20% to 50% of the total CO ₂ emissions from a refinery. Oxyfuel technology could be applied to new FCC, and when large on-site heaters and boilers are replaced. Small-scale testing has shown that it is technically feasible to maintain stable operation of a FCC in oxy-firing mode.
Process heat	Retrofitting process heaters in a refinery with post-process capture technologies is limited by the wide distribution of heating units within a refinery complex. Solutions for this are being proposed but the feasibility of these solutions is contested.

Technology actions for CCS in the refining sector

Several companies are developing and commercialising oxyfuel burners for refinery applications. Shortcomings remain, however, including the heat flux that could induce fouling in some heaters. The energy efficiency of air separation units for the production of oxygen also needs to be improved. Another key challenge, particularly for retrofitting of any type of capture equipment at a refinery, is finding the space required for the infrastructure, including CO₂ ducts and oxygen pipelines.

This roadmap recommends the following actions:

- Investigate autonomous technological developments in the refinery sector, including advanced gas conversion catalyst development, and their consequences for CO₂ emissions and the application of CCS, including the greater use of PSA.
- For pre-process capture from syngases, encourage R&D on combining the shift and CO₂ capture steps in a single reactor to lower capital costs, increase the CO₂ capture ratio and lower the energy penalty (the extra energy required for CO₂ capture).
- Assess the potential for using waste heat from various refinery processes in solvent regeneration and capture processes that can utilise low-grade heat.
- Implement CCS as soon as possible on hydrogen production facilities that emit high-purity CO₂.
- Develop an industrial scale oxyfuelled fluid catalytic converter demonstration project by 2020.

Policy, Finance and International Collaboration: Actions and Milestones

Many regions and countries have recently put in place policies to reduce emissions from industrial sources. While some policies are voluntary (*e.g.* sectoral voluntary agreements), others are binding, such as emissions trading mechanisms. Emission reductions in industrial sectors are typically sought by changing fuels, improving energy efficiency and using more renewable energy. For deep emission cuts, however, policies will need to incorporate CCS.

Industrial CCS, which is currently limited in its number of application, could become technologically mature in most sectors in the next decade (Global CCS Institute, 2011). To realise the deployment scenarios outlined in this roadmap, however, many barriers need to be overcome. Barriers faced by CCS in general, such as those related to legal frameworks and public perception, are discussed in the initial IEA Technology Roadmap on CCS (IEA, 2009). This roadmap discusses areas particularly important for the wider deployment of CCS in industry.

Policy strategy for CCS in industry

Unless governments and relevant authorities analyse the potential of CCS and provide explicit recognition of the role it can play in a country's energy future, CCS projects are unlikely to be developed. Governments should establish an overall policy strategy and pathway for CCS in industry, incorporating the necessary RD&D priorities, incentive policy mechanisms and enabling legal frameworks. Governments should also play a role in raising awareness of CCS as a whole. This is particularly the case for industrial applications of CCS, as the awareness of these opportunities is in general lower than for power-related CCS. Governments and industry should together pursue large-scale demonstration for CCS in industry in national or regional demonstration programmes.

Incentive mechanisms for CCS in industry

Industry will not adopt CCS without incentives and regulatory mechanisms, which governments should tailor to the maturity of the technology and its development over time. Governments should clearly state what incentive policies are intended to achieve, and when. For immature technologies, incentives need to be directed towards technology

learning, whereas incentives for mature technologies can be more generic and should aim to achieve CO₂ emission cuts. Good government policy would outline a pathway for policy evolution. Further analysis is required of the suitability of various incentive mechanisms for given sectors. IEA (2011b) provides a comprehensive analysis of incentive policies and outlines an overarching policy architecture to deliver CCS.

Financial support mechanisms and tax credits

Several countries have announced or are implementing measures to fund CCS demonstration in industrial applications. Such mechanisms include direct financial support to cover additional upfront investment costs, tax credits, CO₂ price guarantees and government loan guarantees. One estimate shows that around USD 26 billion has been committed by developed countries to subsidise a first group of CCS projects (IEA/CSLF, 2010).

Carbon prices or taxes

The most commonly considered policy incentive for CCS is a sufficiently high and stable global price for carbon emissions. Carbon prices can be created through emissions trading schemes, which involve setting a cap on CO₂ emissions, or by imposing carbon taxes. In the long term, carbon markets are expected to deliver the required reductions at lowest cost to society, but it has not been demonstrated that they will provide enough incentives to encourage the deployment of new, more expensive technology in the short term. Other support mechanisms will therefore be needed in the medium term.

Norway's strong, economy-wide carbon tax is one of the few existing examples. In 1991, the Norwegian government decided to tax CO₂ emissions from its offshore oil and gas industry at a rate of around USD 35/tCO₂ emitted. The tax is now around USD 50/tCO₂. The Norwegian petroleum sector is also included in the European Union Emission Trading Scheme (EU ETS). Both the Sleipner and Snøhvit industrial CCS projects have been strongly incentivised by the CO₂ taxation. Another example of a support mechanism has been recently proposed by the United Kingdom government (United Kingdom, 2010). A proposal to introduce a "carbon price floor" has been put forward, by which a price differential will be added

Box 3 Providing incentives for negative emissions – biomass and CCS

Capturing CO₂ from biomass-based processes has the potential to achieve negative emissions. Even though the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National GHG Inventories allow for negative emissions to be allocated in national GHG inventories (IPCC, 2006), the concept has yet to be transposed into current policy frameworks. For example, in the third phase of the EU ETS between 2013 and 2020, installations that exclusively use biomass as process input stream are excluded. The policy does not recognise the potential of achieving negative emissions by combining CCS with biomass conversion processes. In order to provide incentives for CCS in biomass-based industries, operators that capture and store CO₂ must be effectively credited for doing so.

to the EU Emission Allowances¹³ (EUA) value to ensure a minimum price for traded emissions in the EU ETS. The price differential aims to reach GBP 30/tCO₂ by 2020 and GBP 70/tCO₂ by 2030.

Mandates and standards

Regulatory instruments such as technology mandates and standards could also be used to provide incentives for CCS in industrial applications. Governments could, for example, require CCS in certain installations or industries as a condition for granting an operating license. Governments could also consider prohibiting CO₂ venting from natural gas processing plants or from large, high-purity point sources of CO₂. Sectoral GHG emission intensity standards or GHG emissions limits are further options. But a balance will have to be struck between mechanisms that are specific to technologies or facilities, and more general market-based mechanisms, which provide more flexibility to the operator and result in lower

costs of GHG mitigation to society. Mandates and standards are also unlikely to provide a practical option before technologies are commercially available and could therefore be counterproductive if not implemented carefully.

Carbon financing in developing countries

The CDM of the Kyoto Protocol is currently the only financial incentive to attract investment in projects that reduce CO₂ emissions in developing countries. After a prolonged debate on the suitability of CCS for the CDM, it was recognised by the UNFCCC as a CDM project activity in late 2010. However, a set of modalities and procedures must be established before the first CCS projects under the CDM can be implemented. Other international mechanisms that may attract funding for CCS include the Green Climate Fund and the Nationally Appropriate Mitigation Action (NAMA) architecture, both agreed at the United Nations (UN) climate change conference in Copenhagen in 2009.

13. Credits that are allocated to the companies covered by the EU ETS. Each one represents the right to emit one tonne of carbon dioxide.

Box 4 Best practice: R&D on CCS in Brazil

Brazil has set a tax of 1% on oil revenues that is being invested in R&D (ANP ORDINANCE 10/99). The surge in oil prices and the rise in domestic oil production in Brazil over the past year has resulted in significant R&D investments, both within the national oil company, Petrobras, and in several university departments.

For instance, Petrobras and the Pontifical Catholic University of Rio Grande do Sul have co-founded the Carbon Storage Research Centre in Brazil (CEPAC), a group of 40 researchers working on several CCS related areas:

- geological and mineralogical characterisation of storage reservoirs, and their interaction with the injected CO₂, by means of laboratory experiments and numerical modelling;
- conventional and unconventional energy-providing uses of coal, such as coal bed methane (CBM), enhanced coal bed methane (ECBM), and coal-derived syngas via underground coal gasification (UCG);
- integrity and durability of CO₂ injection wells, with focus on materials – cement, iron and interfaces – and procedures employed in their construction; and
- site selection using source-sink matching methodology.

Actions for policy

Governments should:

- Review opportunities for industrial CCS, or encourage industry to undertake such a review, and ensure that CCS in industrial applications is given the required attention in government scenarios and policy.
- Set up programmes to raise public awareness and understanding of the need for CCS, so that it can become part of a low-carbon industrial development strategy.
- Implement demonstration programmes that include industrial CCS and ensure that funding for CCS demonstration is distributed efficiently between power generation and industrial production, given that the potential for reducing CO₂ emissions in industry is large, and that there are few alternatives to CCS for making significant reductions.
- Design policy frameworks and provide incentives that accelerate commercial-scale CCS deployment in industry beyond the demonstration phase. Incentive policies should be analysed and then adapted to meet the specific needs of different industry sectors, and economy-wide policies and technology-specific policies should be compatible with each other. Without such incentive policies, CCS projects will not be able to attract financing from capital markets. Such action should be taken immediately in OECD member countries and should follow without undue delay in non-OECD member countries.
- Explore sector-based approaches, including technology transfer and mandates, for CCS policies in appropriate specific sectors, *e.g.* steel and some high-purity sources.
- Start developing a mechanism that rewards industry for achieving negative emissions through the use of biomass and CCS.

Governments and industry should:

- Explore consumer-based strategies in the field of biofuels, such as making it possible to purchase fuels and products that stem from a sustainable biomass industry that captures and stores its CO₂.

Actions for finance

Governments should:

- Support and urgently finalise the process of including CCS in the CDM.

Governments and industry should:

- Raise awareness of industrial CCS in the financing community and with international development banks, as CCS needs to be part of their low-carbon industrialisation strategies.

The financing community should:

- Develop dedicated products that finance only the incremental CCS investment in an industry project. Government and financiers should form public-private partnerships to enable these products.

Governments and the financing community should:

- Consider requiring CCS readiness when providing finance to new conventional industry projects.
- Investigate the viability of an international financial mechanism for demonstrating industrial CCS in developing countries. Subsequently, they should implement a mechanism that allows for sufficient capital to be made available commercially for non-OECD member countries to deploy CCS in industry, given possibilities in the CDM and other relevant international frameworks.

International collaboration actions and milestones

International climate negotiations

New instruments for international collaboration were approved at the UN climate change meeting in Cancun in 2010 but have not yet been implemented. A few developing countries, such as Botswana, have included CCS in their submissions to the UNFCCC on NAMAs. All developing countries with significant oil and gas industries and large current or future industrial CO₂ emissions could consider CCS as part of their industrial development strategy. They could include this in low-emission development national plans and NAMAs. Properly supported NAMAs would be an appropriate vehicle to finance CCS in developing countries.

The Cancun agreements also contain stronger provisions for measuring, reporting and verifying (MRV) emission reductions. These new rules could be used to improve the availability of data on CO₂ emissions in industry, particularly in developing countries.

The UNFCCC also aims to advance technologies through collaborative R&D and technology transfer in its Technology Mechanism. The inclusion of CCS in these activities could enable developing countries to build capacity on CCS, for example through twinning arrangements with developed country institutions and co-operative technology R&D programmes. Solving intellectual property (IP) issues will be an important step in making such approaches effective. All new mechanisms will only succeed if sufficient financial resources are provided.

Preventing carbon leakage¹⁴

For industrial sectors exposed to trade, such as cement, steel production and refineries, production could shift to countries or regions with less stringent emission reduction policies. This so-called carbon leakage could undermine national efforts to provide incentives for CCS through pricing of CO₂ emissions or mandating CCS. The need to provide a “level playing field” to prevent carbon leakage, raised repeatedly by industrial stakeholders, cannot be ignored by

policy makers considering options for accelerating the deployment of CCS in industry. Reducing the potential for carbon leakage will require a global dialogue between governments and industry. Sectoral agreements or additional emissions allowances can be used to create level playing fields (Box 5). Installations in sectors at risk of carbon leakage that meet efficiency benchmarks will in principle receive all the emissions allowances they need. Installations that do not meet the benchmarks can either lower their emissions (*e.g.* through engaging in abatement) or purchase additional allowances to cover their excess emissions.

Each industrial sector has unique global market dynamics which means that a “one size fits all” policy to prevent carbon leakage in industry is unlikely to work. For instance, many iron and steel and refinery products are traded globally, whereas cement is traded at a more regional scale. Governments should undertake a thorough assessment of optimal policy mechanisms.

14. Carbon leakage is defined as the increase in CO₂ emissions in one country (A) that result from emissions reduction in another country (B) with more stringent constraints. It often reflects cost associated with emissions reduction: as constraints drive up costs of production in country B, companies may opt to produce the same goods in country A, where lighter restrictions help keep costs lower.

Box 5 Avoiding carbon leakage: allocation of industrial emission allowances in the third phase of the EU ETS (2013-20)

Through an amendment to the EU ETS Directive in 2008, the European Commission was required to identify industrial sectors at risk of carbon leakage. Sectors classified as being at risk represent about a third of European Union (EU) emissions, including cement, ceramics, coke, glass, refineries, basic iron and steel, and aluminium. These sectors are not exempt from the emissions trading scheme but will be allocated more free allowances than other sectors in the third phase.

The amount of free allowances provided to producers will be calculated with reference to a product-specific (rather than sector-specific) emission intensity benchmark based on the average of the 10% most efficient installations, multiplied by each producers historical production figure. Even though industries exposed to risk will be allowed 100% of the benchmark emissions level, the stringency of these product-specific benchmarks should encourage investment in GHG abatement. Furthermore, total pool of allowances allocated for free to industry will decline in line with the overall EU ETS cap, providing a further incentive for emission reductions.

Box 6 Avoiding carbon leakage: border tax adjustments

Adjusting for carbon cost at the border (sometimes called border levelling) can level the playing field by adjusting the costs of commodities such as steel and cement imported into a region that exerts a carbon penalty on industry. This results in a system whereby all commodities consumed in the region are exposed to a carbon cost irrespective of origin.

Border carbon adjustments have technical, legal and political ramifications. They may not be compatible with World Trade Organisation agreements, and they may harm emerging markets in developing countries. To overcome the latter issue, it has been suggested that part of the revenue generated through border carbon adjustment could be used for international benefit (Grubb and Counsell, 2010).

Sectoral agreements

Agreements to co-ordinate GHG emissions reductions in a given sector could take many forms, include a variety of stakeholders (*e.g.* manufacturing industry or their equipment suppliers) and be based on multilateral agreements between governments. Alternatively, industry actors within a sector could agree to implement best practice, short of imposing binding and costly constraints, and could promote domestic policy that favours their actions on emission reductions and energy savings, where barriers exist. Industry agreements may be most promising in developing countries, where policy sometimes lags behind industrial practice. Sectors could also work together on R&D co-ordination, provided actors do not have immediate competitive stakes in the results.

International transboundary transport of CO₂

Offshore geological storage of CO₂ is likely to be important for the deployment of CCS at the scale required, with a significant number of projects using such storage options for domestic and internationally sourced CO₂. While amendments have been made to the London Protocol on the prevention of marine pollution to allow cross-border transportation of CO₂ for offshore CO₂ storage, and to the related OSPAR Convention on protecting the marine environment of the northeast Atlantic, to allow key configurations of CO₂ storage offshore in relevant regions, both amendments require ratification by a sufficient number of parties to enter into force. Not all parties to these protocols are currently interested in offshore CO₂ storage, making ratification of these amendments a low priority. The amendment

to the London Protocol requires ratification by two-thirds of parties (approximately 27 parties) and thus far only one party has ratified it. This means that CO₂ cannot be exported by a country that is a party to the London Protocol if the storage will be offshore.

To facilitate global CCS deployment, all countries are encouraged to consider ratifying these amendments, even if the specific issue is not a high priority for a country. In many cases this will require raising awareness of the issue among the relevant government ministries and authorities, which may not be the ones that deal with energy and industry issues.

Overcoming knowledge and awareness barriers – international capacity development

Awareness of industrial CCS applications is generally low, so governments and industry need to familiarise policy makers, regulators and other stakeholders with the technologies and their challenges, as well as educating students and engineers, and gaining practical experience.

If the potential of CCS in industrial applications is to be fully realised, governments and industry decision-makers in both developed and developing countries should make use of existing international knowledge-sharing practices (such as those established under IEA, CSLF, Global CCS Institute and Asia-Pacific Economic Cooperation [APEC]) and form relevant international and/or regional networks if necessary. Governments should also ensure including CCS in curricula for universities and technical schools, and consider undertaking or funding activities that develop the capacity for CCS.

Regional networks could serve to exchange knowledge and experience across similar economic, political, cultural and geographical contexts. Countries within regions with many similar high-purity CO₂ sources or significant potential for EOR could learn from each other, and should make bilateral sources of finance available for this.

Actions for international collaboration

Governments should:

- Pursue international agreements for trade-sensitive industrial sectors that specifically include CCS in the absence of a global carbon price.
- Ratify the 2009 London Protocol amendment to allow transboundary movement of CO₂ for storage, and the 2007 OSPAR Convention amendment to allow the sub-seabed injection of CO₂ for storage.
- Encourage the development of capacity building and education programmes at universities and technical schools, particularly in developing countries and in economies in transition.

Governments and industry should:

- Collect and register emissions data in industry globally and provide assistance to regions that lack the capacity to do so, respecting the Cancun Agreements on MRV.

- Continue to address potential problems concerning IP in CCS in industrial applications.
- Set up industry-specific awareness and capacity development programmes, focusing on sectors where CCS can be cost-effective, such as gas processing, biofuel production, refineries, ethylene oxide, ammonia plants and Ctl facilities.
- Develop and disseminate best practices for CCS in industry to enable faster learning about the application of the relevant technologies in practice. Governments should also encourage industrial CCS in demonstration programmes.

Governments and relevant stakeholders should:

- Develop appropriate rules and modalities under the UNFCCC to make sure the CDM applies to CCS, as well as encourage the use of new instruments in the Cancun Agreements, such as NAMAs and the Technology Mechanism, to help implement national actions on CCS in industry.
- Develop the national capacities required to implement CCS projects from the policy, technical and financial perspectives.

Governments, relevant international organisations and industry should:

- Develop and utilise existing regional networks and knowledge circles in countries and regions, involving multilateral banks, donors, industry, government departments and civil society.

Business Opportunities for Industrial CCS

CCS development can create value for a business or organisation in several ways. In a carbon-constrained setting, CCS primarily creates value by meeting requirements to reduce GHG emissions; similarly, it allows a business to remain viable by continuing to use affordable and accessible fossil fuels. This value is directly realized by avoiding the payment of a CO₂ tax or the price of an emission credit, or by the sale of unneeded credits. CCS can be considered as a way to hedge the risk of a high price on carbon.

CCS can also create value when injected and stored CO₂ enhances the recovery of hydrocarbons. In regions where industrial agglomerations enable synergies such as the sharing of infrastructure, economies of scale can make CCS viable even if the carbon price is too low for individual project-by-project CCS. Business opportunities also exist to market and sell new CCS technologies or expertise.

This section explores the ways CCS can create value in conjunction with EOR, in industrial agglomerations and in the CCS supply chain.¹⁵

Industrial CCS projects with EOR

Injection of gases such as CO₂ can enhance the recovery of oil from more mature reservoirs by mixing with oil trapped in reservoir rock and driving it towards production wells. Most CO₂ used for CO₂-EOR originates from natural underground accumulations of CO₂. When this natural underground CO₂ is replaced with CO₂ from human activities (anthropogenic CO₂), emissions can be reduced. Not all reservoirs are suitable for CO₂-EOR, so detailed assessment is needed to evaluate their actual potential.

The use of CO₂ in EOR is taking place in several countries, preeminently in the United States. Globally 47 MtCO₂ from natural underground reservoirs are used for EOR operations (UNIDO, 2011b).¹⁶ Most CO₂-EOR projects have been designed to minimize the amount of CO₂ injected because of the cost of CO₂. If EOR is to be used for storing CO₂, operators will need to inject more CO₂ and change the way they recycle, store and monitor it in the reservoir in the long term.

15. The business opportunities listed in this chapter are not unique to industrial sectors, but also relate to the power sector, or CCS in general.

16. CO₂-EOR operations do not store 100% of the injected CO₂, a fraction is produced with additional oil.

At least half a dozen projects use anthropogenic CO₂ exclusively, including Weyburn in Canada, and the Rangely, Sharon Ridge, Enid Fertilizer and Salt Creek projects in the United States. Until 2004, the supply of CO₂ in the United States exceeded demand, and CO₂ for EOR was traded at low prices. The current price paid for CO₂ used for EOR, about USD 40/tCO₂, could support early capture opportunities. While the storage potential for EOR in the long term is uncertain, it could help early demonstration projects to get off the ground, paving the way for large-scale CCS deployment.

EOR in combination with high-purity CO₂ sources may be particularly attractive for developing countries that produce oil. Currently EOR is often carried out with natural gas, but companies are increasingly aware of the opportunity of exporting natural gas instead of using it for EOR. Developing countries have few other incentives to reduce CO₂ emissions, so sustaining oil production through CO₂-EOR can not only support national energy security, but also familiarise authorities, industry and policy makers with the process of injecting CO₂ into geological formations. This would also require the development of regulatory frameworks that can accommodate both EOR and conventional CO₂ storage.

One high-level study estimated that if state-of-the-art technology were implemented in the world's 50 largest oil basins,¹⁷ the fields could have a theoretical potential to produce 470 billion barrels of additional oil and store 140 GtCO₂ (UNIDO, 2011b).

Regional focus and potential projects

In the short term, EOR efforts should focus on countries where all the conditions for EOR implementation are met: mature, well characterised oil fields, sources of CO₂, political will, human capacity and companies that can implement EOR (Table 11).

Stakeholders in the Middle East and Southeast Asia, in particular, have identified projects that could reduce emissions through EOR. MASDAR in the United Arab Emirates is searching for effective source/sink combinations to use CO₂ for EOR and then permanent storage. EOR has also been tested in developing countries and transition economies,

17. Fields representing 1.5 billion barrels of oil (UNIDO, 2011b) have reservoirs amenable to the application of miscible CO₂-EOR.

Table 11 A selection of ongoing or proposed CO₂-EOR projects making use of CO₂ from industrial sources

<i>Project</i>	<i>Location</i>	<i>CO₂ source(s)</i>	<i>Technology</i>	<i>Status</i>	<i>MtCO₂ injected per year</i>
Rangely Weber sand unit CO ₂ injection project	Colorado, United States	Gas processing	High-purity	Started 1986	1.0
Air Liquide	Rotterdam, the Netherlands	Hydrogen production	Pre-combustion	Planned 2012	Not specified
Enid fertilizer plant	Oklahoma, United States	Ammonia production	Pre-combustion	Started 2003	0.68
Emirates Steel Industries	Abu Dhabi, United Arab Emirates	Steel plant	Other	Planned 2015	0.8
Air Products steam methane reformer and EOR project	Texas, United States	Hydrogen production at refinery	Pre-combustion	Planned 2015	1.0
Leucadia Energy capture project	Mississippi, United States	Petcoke to SNG plant	Pre-combustion	Planned 2014	4.0
Occidental gas processing plant	Texas, United States	Natural gas processing plant	Gas processing	Planned 2011	9.0
Coffeyville Gasification Plant	Kansas, United States	Fertiliser plant	Pre-combustion	Planned 2013	0.585

Note: For an extensive list please see The Global Status of CCS: 2010 (Global CCS Institute, 2011).
Source: Global CCS Institute, 2011.

for example in the Buracica project in Brazil, which re-injected CO₂ from 1991 to 2009, and the Jilin Oilfield in China, from 2000 to 2003.

Actions and milestones for EOR

The use of anthropogenic CO₂ for EOR can present business opportunities if market conditions are favourable, regulatory frameworks are in place and CO₂ sources are close enough to suitable oil fields. Action is needed to overcome bottlenecks and accelerate deployment.

Governments should:

- Clarify whether and how EOR may be eligible for the CDM or other new climate instruments and identify accounting rules to prove the net environmental benefit.
- Stimulate dialogue and promote agreements between the oil industry and industry sectors with high CO₂ emissions to facilitate business models that benefit both sides.
- Ensure that regulatory frameworks allow CO₂ storage through EOR and are comparable to those governing storage in saline aquifers and other geological formations.

- Develop methods for transparent reporting and verification of CO₂-EOR activities.

Governments and industry should:

- Conduct detailed regional analyses matching CO₂ sources and reservoirs, with a focus on EOR. In particular, industry should explore areas with EOR potential to overcome the dynamic difference between the declining CO₂ demand in an oil field using EOR and the continuous supply of CO₂ from an industry source.
- Enable dedicated capacity building and training in EOR to identify oil reservoirs that are suitable for permanent storage of CO₂.
- Develop methods and regulations that optimise EOR for CO₂ injection, maximising the volume of CO₂ stored. Current EOR activities are generally optimised for oil recovery. More experience is needed to determine how this would work in practice.

Industry should:

- Analyse how reservoirs currently optimised for EOR could be transformed into CO₂ storage reservoirs after production ceases. Industry should also clarify to what extent existing infrastructure such as oil and gas platforms and injection sites can be re-used for CO₂-EOR.

Industry and academia should:

- Conduct research on CO₂ stream composition requirements for CO₂-EOR.

Industrial agglomerations

While costs for a single CCS project may be high, a cluster of CO₂ sources could achieve considerable economies of scale by sharing transport and storage infrastructure, enabling smaller sources, such as biomass conversion, to be included in a CCS programme. Industrial agglomerations can also have advantages in terms of planning requirements and legal procedures (McKinsey & Company, 2008). A concentration of low-carbon industries within a region could also create industrial hubs of CCS expertise. Several propositions for industrial collaborations on CCS, notably in Europe, seek to exploit these opportunities, some of them integrating CCS in the power sector with CCS in industry (Table 12).

The proposed CCS cluster in the Port of Rotterdam in the Netherlands is probably the most advanced of these. In 2007, as part of the Rotterdam Climate Initiative, a roadmap was devised to deploy several CCS demonstration installations in the region before 2025, in both the power and industry sectors, capable of capturing 20 MtCO₂ a year at full deployment (DCMR, 2009).

A proposed power generation CCS cluster in the Teesside region in the northeast of the United Kingdom would capture 7.5 MtCO₂ a year, with the possibility of including other industries to double this to 15 MtCO₂ a year. As well as reducing CO₂ emissions, such development could safeguard jobs and stimulate further employment, but its implementation depends on United Kingdom government funding.

In southern Scandinavia, a cluster of CCS opportunities in the Skagerrak-Kattegat region is being studied. The aim of this project is to link potential sinks, or reservoirs, to CO₂ sources above 0.5 Mt per year in the region. Total emissions from these plants could contribute 25% of the national CO₂ reduction targets of Denmark, Norway and Sweden. The potential sinks identified in the region include onshore and offshore aquifers, as well as oil and gas fields in the North Sea.

Local focus and potential projects

Major industrial agglomerations with a mix of industries (in particular oil and gas operations, refineries, biomass conversion and biofuel production, and certain cement and iron and steel processes), can often be found in locations with good water and road transportation networks. Large industrial agglomerations can be found all over the world, in particular in emerging economies and developed countries.

Table 12 A selection of industrial agglomerations considering CCS

<i>Project</i>	<i>Location</i>	<i>Source(s)</i>	<i>Technology</i>	<i>Status</i>	<i>CO₂ abatement per year</i>
Kattegat/ Skagerrak	Sweden, Norway, Denmark	3 power plants 3 refineries 2 cement plants petrochemical plant paper mill (recycled paper based) ammonia plant ethylene plant	various	under consideration	12 Mt
Masdar CCS project	Abu Dhabi, United Arab Emirates	gas-fired power plant aluminium smelter steel mill	2 capture plants using amine-based solvents	planned 2015	5 Mt
Rotterdam Climate Initiative	Rotterdam, the Netherlands	5 power plants 2 hydrogen plants furnace in crude distillation unit waste heat incinerator biomass plants	various	first phase 2011-12: final investment decision for power plants; ethanol plant to be coupled to the CO ₂ grid second phase 2015	1.4 Mt (Phase I) up to 15 Mt (Phase II) potential scaling up to 25 Mt
North East CCS Cluster	Middlesbrough, United Kingdom	2 integrated gasification combined cycle power plants UCG 2 gas-fired power stations	various	under consideration	7.5 Mt scaling up to 15 Mt
Mongstad CCS	Mongstad, Norway	cogeneration power plant refinery	post-combustion capture	2018-20	initial 1.3 Mt
Collie South West Hub CCS	Western Australia	fertiliser plant power plants alumina plant	pre-combustion and post-combustion	2020	2.5 Mt to 7.5 Mt
Thames Cluster	Thames and Medway Estuaries, United Kingdom	9 existing and future power plants refinery	various	2020	16 Mt scaling up to potential 28 Mt
Alberta Carbon Trunkline (ACTL)/ Integrated CO ₂ Network (ICO ₂ N)	Alberta, Canada	existing fertiliser plant and a planned oil refinery	various	construction planned for 2013	1.8 Mt scaling up to potential 14.6 Mt

Note: For an extensive list please see The Global Status of CCS: 2010 (Global CCS Institute, 2011).
Source: Global CCS Institute, 2011.

Box 7 Matching sources and reservoirs: the key to CCS

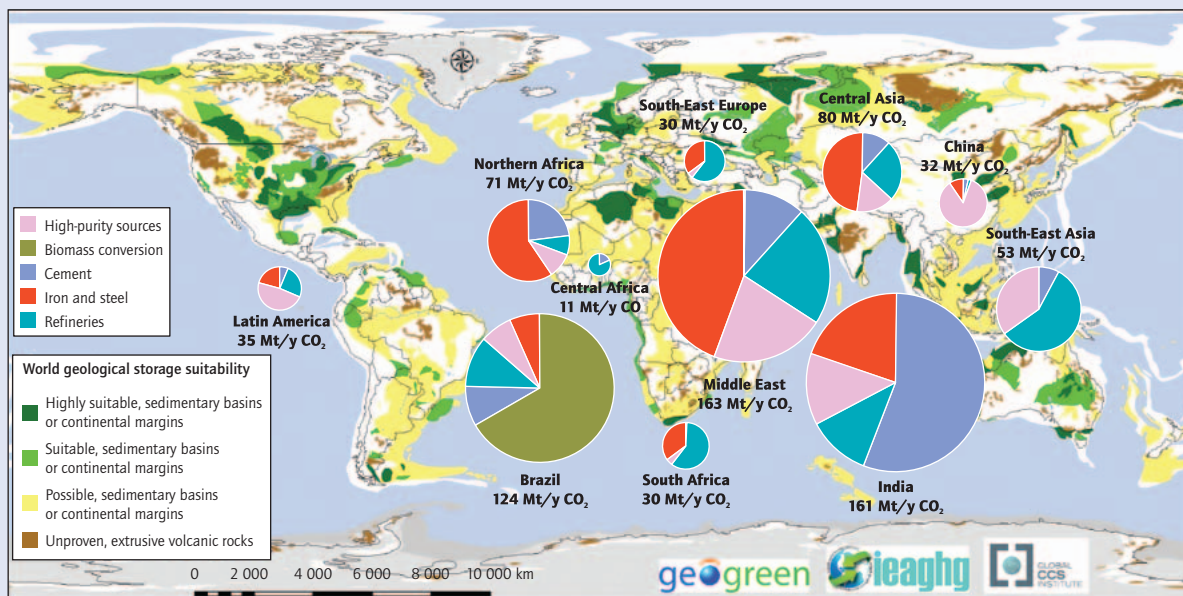
Matching CO₂ sources and sinks lies at the core of CCS feasibility, as deployment depends on the proximity of potential reservoirs to large point sources, and the terrain to traverse. Vast pipeline infrastructure to transport CO₂ over large distances would drive the cost up significantly and could raise other problems, notably with regard to safety.

The proximity of industrial CO₂ sources to potential sinks was assessed for this roadmap, to indicate whether regional storage resources are sufficient for storing regional industrial CO₂ emissions, especially the high-purity emissions that are cost-effective and feasible in the short term. The assessment focused on non-OECD member countries (Figure 12). Its main limitation is the lack of publicly available storage data and uncertainties on the volumes of CO₂ emitted.

Some conclusions drawn from the assessment were that:

- Certain regions have excess storage, such as Northern and Central Africa, the Middle East and Central Asia, but storage is limited in other areas, such as India (due to geological limitations) and Brazil.
- Regions with short-term potential for early technical opportunities (low-cost capture from industrial sources and storage nearby) include Brazil, China, the Middle East, Northern Africa and Southeast Asia. There is limited number of early opportunities in most regions because of the lack of storage resources near industry clusters.
- As storage is limited, competition with the power industry for storage space is likely.

Figure 12 Developing region estimates of industrial emissions and geological storage suitability for 2050



Note: The study used datasets developed for the Global CCS Institute and the IEA GHG IA 'Global Storage Resource Gap Analysis for Policy makers' project.
Source: UNIDO, 2011a.

Actions and milestones for industrial agglomerations

Governments should:

- Identify whether special administrative arrangements are needed, for example a “regional superintendent” with the authority to prepare and make decisions on the availability of storage reservoirs and the build-up of the regional pipeline or shipping infrastructure.

Governments and industry should:

- Raise awareness and interest with branch organisations and authorities in existing industrial agglomerations and create a dialogue on possible co-operative actions.
- Identify regional storage locations, possible routes for CO₂ pipelines, and locations for pipeline infrastructure and intermittent CO₂ storage facilities early to overcome planning issues.
- Explore potential public-private business models, discussing contractual, risk and financing possibilities.

Innovation and the CCS supply chain

Although CCS represents an additional cost to sectors in industry that emit CO₂, industries taking a long-term view and considering the potential of a carbon-constrained future may want to invest in CCS. Companies providing capture, transport and storage equipment and expertise could benefit by exporting their products, and conventional industries that invest in CCS demonstration have an advantage in operational knowledge once CCS becomes a necessity.

CCS will require specialist vendors and a more extensive and complex supply chain than is present in most countries. Established technology providers and equipment manufacturers, as well as their up-and-coming competitors in emerging economies, should be encouraged to form innovation and demonstration partnerships with industries that are currently CO₂ sources. In addition, further exploration and production expertise and equipment is needed to find and develop safe storage locations.

Actions and milestones for innovation

Many actions for companies in the CCS value chain have been listed elsewhere in this roadmap, but the following specific actions can be identified:

- Encourage innovative technology providers and equipment suppliers to develop CO₂ capture technology specifically for industry.
- Encourage CCS partnerships and demonstrations between technology providers and equipment suppliers, and CO₂-emitting industries, keeping in mind the barriers to collaboration between these parties.
- Raise awareness with equipment suppliers, *e.g.* kiln makers, who generally have a low awareness of and interest in developing CO₂ capture installations.

Conclusion: Near-term Actions for Stakeholders

This roadmap has been designed with milestones that the international community can use to ensure that CCS development in industry is on track to achieve the emission reductions required by 2050 to limit the long-term global average temperature rise to between 2.0°C and 3.0°C. As such, the IEA and UNIDO, together with government, industry and other key stakeholders, such as the Global CCS Institute and CSLF, will report regularly on

the progress that has been achieved toward this roadmap vision. Recommended actions by key stakeholders are summarised below, presented to indicate who should take the lead in such efforts. In most cases, a broad range of actors will need to participate in each action.

Summary of actions led by stakeholders

Lead stakeholder	Actions
Industry	<ul style="list-style-type: none"> • Compile an inventory of the hydrogen, ammonia and ethylene oxide production technologies employed in industry to determine whether such processes can be combined with CCS. • Stimulate further research into the most cost-effective and energy-efficient capture techniques. • Raise awareness and interest with branch organisations and authorities in existing industrial agglomerations and create a dialogue on possible co-operative actions. • Enable dedicated capacity building and training in EOR to identify oil reservoirs that are suitable for the permanent storage of CO₂. • Conduct detailed regional matching of CO₂ sources to reservoirs, with a focus on EOR.
Governments	<ul style="list-style-type: none"> • Identify regional storage locations, possible routes for CO₂ pipelines, and locations for pipeline infrastructure and intermittent CO₂ storage facilities early to overcome planning issues. • Review national opportunities for industrial CCS and ensure that it is given the necessary prominence. • Implement demonstration programmes that include industrial CCS projects, ensuring that funding for demonstration projects is distributed efficiently between power generation and industrial production processes. • Develop and disseminate best practices for CCS in industry to enable faster learning about the application of the relevant technologies. Industry participation in the development of these best practices is essential. • Design and implement enabling policies and legal and regulatory frameworks, and provide incentives that accelerate commercial-scale CCS deployment in industry beyond the demonstration phase. • Develop methods and regulation that optimise EOR activities for CO₂ injection. • Develop dedicated financial products to fund the incremental CCS investment in an industry project. Form public-private partnerships between government and financiers to enable these products. • Encourage innovative equipment suppliers to develop CO₂ capture technology specifically for industry. • Explore sector-based approaches, including technology transfer and mandates, for CCS policies in appropriate specific sectors, <i>e.g.</i> steel and some high-purity sources.

<i>Lead stakeholder</i>	<i>Actions</i>
Universities and other research institutions	<ul style="list-style-type: none"> ● Develop capacity building and education programmes at universities and technical schools, particularly in developing countries and in economies in transition. ● Conduct R&D on improving existing solvents and developing new solvents. ● Support R&D in methods to improve the energy efficiency of air separation, such as ion transport membranes, to reduce the energy penalty of oxyfuel processes. ● Develop advanced materials for use in industrial boilers, process heaters and gas turbines, which can withstand the combustion temperatures associated with oxyfuel combustion. ● Conduct R&D into the removal of tars that result from the gasification of certain types of biomass.
International governmental organisations and multilateral development agencies	<ul style="list-style-type: none"> ● Raise awareness on CCS in various industrial sectors in the financing industry and with international development banks, which needs to make CCS part of their low-carbon industrialisation strategies. ● Assist governments in developing the national capacities required to implement CCS projects from the policy, technical and financial perspectives. ● International financial institutions should implement a mechanism that allows sufficient capital to be made available commercially for developing countries to deploy CCS in industry. ● Develop and utilise existing regional networks and knowledge circles in countries and regions, in involving multilateral banks and donors and other main actors: industry, government departments and civil society. ● Collect and register emissions data in industry globally and provide assistance to regions that lack the capacity to do so.

Abbreviations, Acronyms and Units of Measure

Abbreviations and acronyms

APEC	Asia-Pacific Economic Cooperation
BECCS	bio-energy with carbon capture and storage
BtL	biomass-to-liquids
CBM	coal bed methane
CCS	carbon capture and storage
CDM	clean development mechanism
CHP	combined heat and power
CO	carbon monoxide
CO ₂	carbon dioxide
CSLF	Carbon Sequestration Leadership Forum
CtL	coal-to-liquids
DOE	United States Department of Energy
DRI	direct reduced iron
ECBM	enhanced coal bed methane
EOR	enhanced oil recovery
ETP	Energy Technology Perspectives
EU	European Union
EUA	EU Emission Allowances
EU ETS	European Union Emission Trading System
FCC	fluid catalytic cracker
FT	Fischer-Tropsch
GBP	British pound sterling
GEF	Global Environment Facility
GHG	greenhouse gas
H ₂ S	hydrogen sulphide
IEA	International Energy Agency
IP	intellectual property
IPCC	Intergovernmental Panel on Climate Change
LNG	liquefied natural gas
MMV	measurement, monitoring and verification
MRV	measuring, reporting and verifying

N ₂	Nitrogen gas
NAMA	Nationally Appropriate Mitigation Action
O ₂	oxygen gas
OECD	Organisation for Economic Co-operation and Development
PSA	pressure swing absorption
R&D	research and development
RD&D	research, development and demonstration
SGR	synthetic gas reforming
SMR	steam methane reforming
SNG	synthetic natural gas
TGR	top-gas recycling
TGR-BF	top-gas recycling blast furnace
UCG	underground coal gasification
ULCOS	Ultra-Low CO ₂ Steelmaking
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
USD	United States dollar
VPSA	vacuum pressure swing adsorption
WBCSD	World Business Council for Sustainable Development

Units of measure

EJ	exajoules
GJ	gigajoules
Gt	gigatonne
kt	kilotonne
Mt	megatonne
Mtoe	million tonnes of oil equivalent
t	tonne

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Sectoral assessments

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United Nations Industrial Development Organisations (UNIDO) (2010a), *Sectoral assessment for the iron and steel sector*, Jean-Pierre Birat (ArcelorMittal), United Nations Industrial Development Organisation, Vienna, Austria.

UNIDO (2010b), *Sectoral Assessment for the cement sector*, Duncan Barker (Mott MacDonald), United Nations Industrial Development Organisation, Vienna, Austria.

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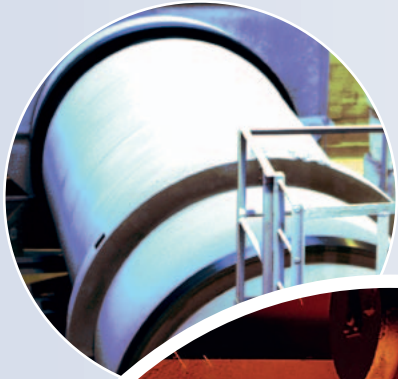
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