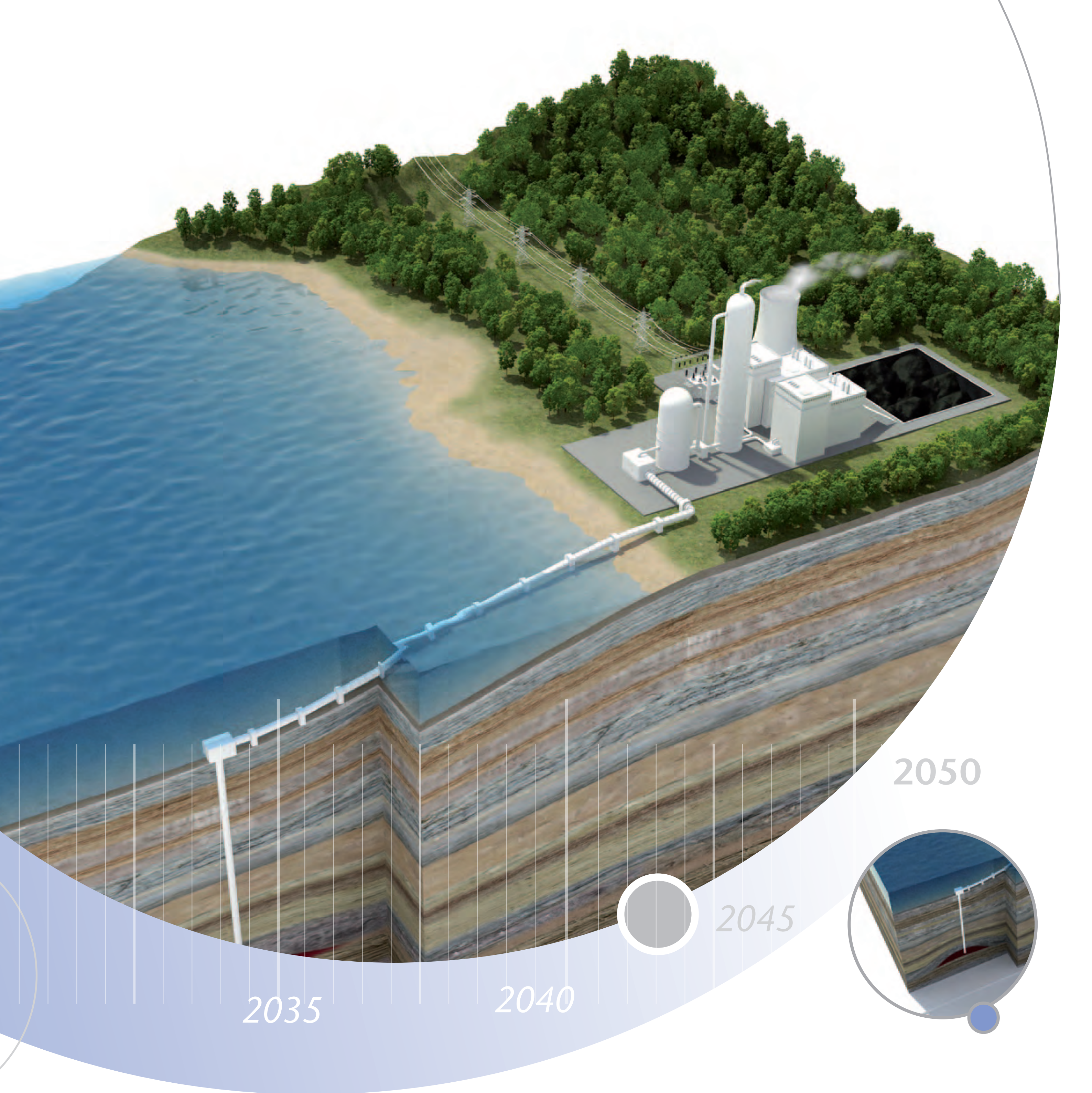

Technology Roadmap

Carbon capture and storage

International Energy Agency

DISCLAIMER

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 30 OECD member 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.

The OECD is a unique forum where the governments of 30 countries work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The OECD provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

Foreword

Current trends in energy supply and use are patently unsustainable – economically, environmentally and socially. Without decisive action, energy-related emissions of CO_2 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 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.

There is a growing awareness 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 developing a series of roadmaps for some of the most important technologies. These roadmaps provide solid analytical footing that enables the international community to move forward on specific technologies. Each roadmap develops a growth path for a particular technology from today to 2050, and identifies technology, financing, policy and public engagement milestones that need to be achieved to realise the technology's full potential. Roadmaps also include special focus on technology development and diffusion to emerging economies. International collaboration will be critical to achieve these goals.

This roadmap on CCS identifies, for the first time, a detailed scenario for the technology's growth from a handful of large-scale projects today to over three thousand projects by 2050. It finds that the next decade is a key "make or break" period for CCS; governments, industry and public stakeholders must act rapidly to demonstrate CCS at scale around the world in a variety of settings. The roadmap concludes with a set of near-term actions that stakeholders will need to take to achieve the roadmap's vision. The IEA presents this roadmap not only to provide additional focus and urgency to the international discussions about the importance of CCS as a technology solution, but to chart the course to make CCS a reality worldwide.

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Executive Director, IEA

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Key Findings

- Carbon capture and storage (CCS) is an important part of the lowest-cost greenhouse gas (GHG) mitigation portfolio. IEA analysis suggests that without CCS, overall costs to reduce emissions to 2005 levels by 2050 increase by 70%. This roadmap includes an ambitious CCS growth path in order to achieve this GHG mitigation potential, envisioning 100 projects globally by 2020 and over 3 000 projects by 2050.

- This roadmap's level of project development requires an additional investment of over USD 2.5-3 trillion from 2010 to 2050, which is about 6% of the overall investment needed to achieve a 50% reduction in GHG emissions by 2050. OECD governments will need to increase funding for CCS demonstration projects to an average annual level of USD 3.5 to 4 billion (bn) from 2010 to 2020. In addition, mechanisms need to be established to incentivise commercialisation beyond 2020 in the form of mandates, GHG reduction incentives, tax rebates or other financing mechanisms.

- Although the developed world must lead the CCS effort in the next decade, CCS technology must also spread rapidly to the developing world. This growth will require expanded international collaboration and financing for CCS demonstration in developing countries at an average annual level of USD 1.5 to 2.5 bn from 2010 to 2020. To provide this funding, CCS needs to be approved in the Clean Development Mechanism or an alternative financing mechanism.

- CCS is more than a strategy for "clean coal." CCS technology must also be adopted by biomass and gas power plants; in the fuel transformation and gas processing sectors; and in emissions-intensive industrial sectors like cement, iron and steel, chemicals, and pulp and paper.

- CO_2 capture technology is commercially available today, but the associated costs need to be lowered and the technology still needs to be demonstrated at commercial scale. Additional research and development is also needed, particularly to address different CO_2 streams from industrial sources and to test biomass and hydrogen production with CCS.

- CO_2 transport via pipeline has been proven; the challenge for the future of transport technology is to develop long-term strategies for CO_2 source clusters and CO_2 pipeline networks that optimise source-to-sink transmission of CO_2. To address this challenge, governments need to initiate regional planning exercises and develop incentives for the creation of CO_2 transport hubs.

- There is an urgent need to advance the state of global knowledge of CO_2 storage prospectivity. While depleted oil and gas fields are well mapped and offer promising low-cost opportunities, deep saline formations are the most viable option for the long-term. However, only a few regions have adequately mapped the CO_2 storage potential of these formations. There is also a need for common international methods for CO_2 storage site selection, monitoring and verification, and risk assessment.

- While some regions have made important progress in developing dedicated legal and regulatory frameworks for CCS, most countries still have issues to address before significant progress can be achieved. There is a need to develop near-term regulatory approaches to facilitate CCS demonstration efforts, while working at the same time to develop comprehensive approaches for the large-scale commercial deployment of CCS.

- Local communities have legitimate concerns about CCS that must be addressed. Governments need to take the lead on developing community-tailored CCS public engagement strategies, starting with providing resources for this critical activity and then ensuring early provision of information about the costs and benefits of planned CCS projects compared to other GHG mitigation options.

- Due to the short timeframe and investments required, this roadmap's vision will only be possible via expanded international collaboration. In particular, new efforts to provide developing country CCS capacity building and knowledge/technology transfer are needed. Industry sectors with a global reach should also expand their CCS collaborative efforts.

Introduction

The development of advanced clean energy technologies must be accelerated to address the global challenges of energy security, climate change and sustainable development. This pressing need was acknowledged by the Ministers from G8 countries (Canada, France, Germany, Italy, Japan, Russia, the United Kingdom and the United States) at their meeting in June 2008 in Aomori, Japan, where they asked the IEA to 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 cooperate 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 covering 19 demand- and supply-side technologies. The IEA is leading the process under international guidance and in close consultation with industry. The overall aim of this effort is to advance the global development and uptake of key technologies to reach a 50% emissions reduction by 2050. The roadmaps will enable governments, industry and financial partners to identify steps needed and to implement measures to accelerate required technology development and uptake.

The process starts with providing a clear definition of the elements needed for each roadmap. The IEA has defined its global technology roadmap accordingly:

> *... a dynamic set of technical, policy, legal, financial, market and organizational requirements identified by the stakeholders involved in its development. The effort shall lead to improved and enhanced sharing and collaboration of all related technology-specific research, development, demonstration and deployment (RDD&D) information among participants. The goal is to accelerate the overall RDD&D process in order to deliver an earlier uptake of the specific technology into the marketplace.*

Each roadmap identifies major barriers, opportunities and policy measures for policy makers, industry and financial partners to accelerate RDD&D efforts for specific clean technologies at both a national and international level.

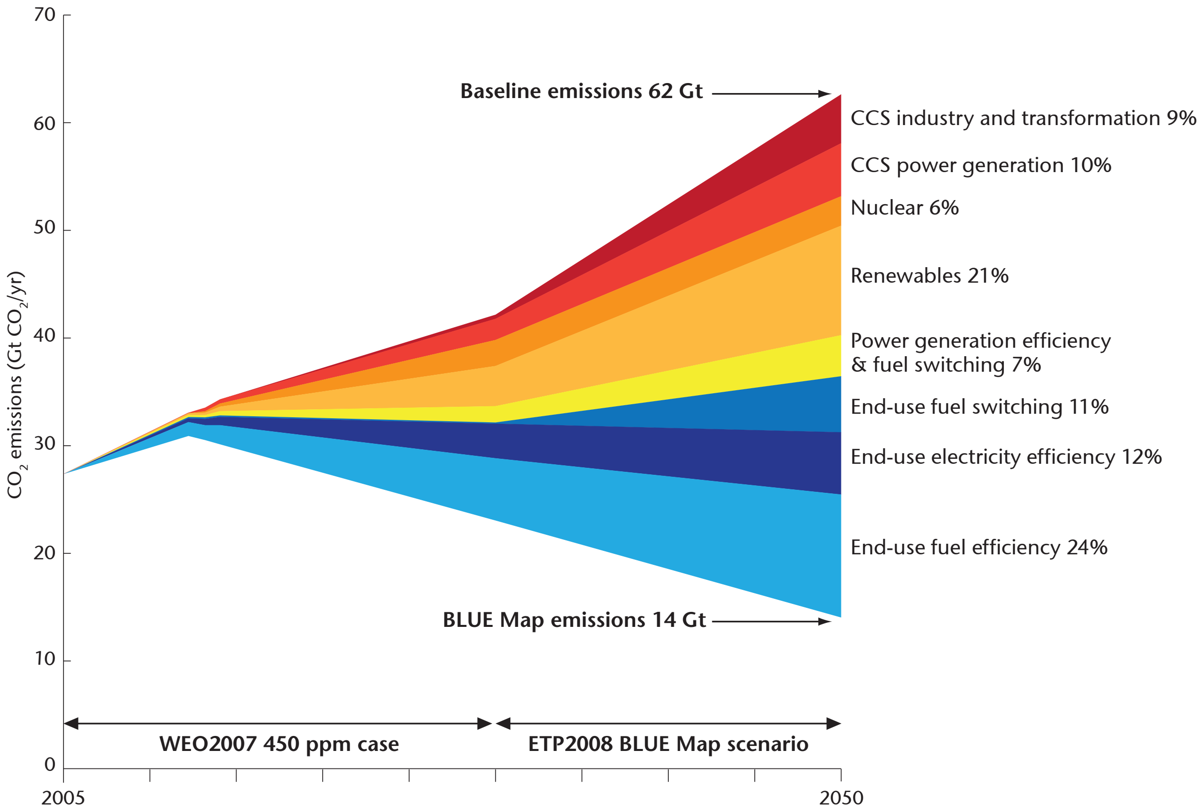
The rationale for CCS

The analysis in *Energy Technology Perspectives 2008* (ETP) projects that energy sector CO_2 emissions will increase by 130% above 2005 levels by 2050 in the absence of new policies or from supply constraints resulting from increased fossil fuel usage (IEA, 2008a). Addressing this increase will require an energy technology revolution involving a portfolio of solutions: greater energy efficiency, increased renewable energies and nuclear power, and the near-decarbonisation of fossil fuel-based power generation. CCS is the only technology available to mitigate greenhouse gas (GHG) emissions from large-scale fossil fuel usage in fuel transformation, industry and power generation. The ETP BLUE Map scenario, which assessed strategies for reducing GHG emissions by 50% by 2050, concluded that CCS will need to contribute one-fifth of the necessary emissions reductions to achieve stabilisation of GHG concentrations in the most cost-effective manner (see Figure 1).

The BLUE Map results revealed that if CCS technologies are not available, the overall cost to achieve a 50% reduction in CO_2 emissions by 2050 will increase by 70% (IEA, 2008a).[1] CCS is therefore an essential part of the portfolio of technologies that is needed to achieve substantial global emissions reductions.

1 The Intergovernmental Panel on Climate Change's (IPCC) CCS *Special Report* found that CCS would provide 15% to 55% of the cumulative mitigation effort up to 2100 (IPCC, 2005). The Stern Review found that omitting CCS would, on average, increase overall GHG abatement costs (Stern Review, 2007).

Figure 1: CCS delivers one-fifth of the lowest-cost GHG reduction solution in 2050



Source: IEA, *Energy Technology Perspectives* (2008a).

***KEY POINT:** Without CCS, overall costs to halve CO_2 emissions levels by 2050 increase by 70%.*

The purpose of the roadmap

This level of CCS deployment amounts to a tremendous global challenge. At present, there are only four fully integrated, commercial-scale CCS projects in operation. While these projects offer evidence that CCS technologies are viable at scale, nearly 100 additional commercial-scale demonstration projects are needed in a number of countries and settings. These projects will involve power generation and industrial sectors like cement, iron and steel, chemical production, and gas processing. The challenges of technology integration and scale-up can only be met through the experience of building and operating commercial-scale CCS facilities in a variety of settings. Governments are beginning to address this gap, which is evident through several recent announcements of funding for large-scale demonstration. However, more work needs to be done to successfully deploy commercial-scale CCS projects. To achieve the ambitious targets included in this roadmap, governments, industry and public stakeholders must successfully address all of the following challenges:

- financing large-scale demonstration projects and integration of CCS into GHG policies;
- addressing the higher cost and efficiency penalty of CCS through accelerated CCS research and demonstration;
- exploring, developing and financing adequate CO_2 storage capacity and infrastructure;

- developing appropriate legal and regulatory frameworks to enable projects to proceed that ensure safe, permanent CO_2 storage;
- ensuring appropriate funding is provided for public communication efforts about CCS, with a priority on public engagement at planned projects;
- fostering expanded international collaboration, particularly via expanding capacity and awareness in developing economies with large fossil fuel use.

This roadmap was developed to provide a vision for addressing the above challenges. The process started with a review and assessment of existing efforts by IEA member countries; international collaborative efforts like the Carbon Sequestration Leadership Forum (CSLF), the Global Carbon Capture and Storage Institute (GCCSI), the IEA Implementing Agreements Greenhouse Gas R&D Programme (IEA GHG) and Clean Coal Centre, and the IEA Working Party on Fossil Fuels; and efforts by other government, industrial and non-governmental organisations. Existing recommendations, such as those from a series of IEA/CSLF workshops in 2007 to 2008, were used as a starting point.[2] The process then engaged groups of experts from a broad variety of disciplines with the objective to develop a draft roadmap that focuses on the technical, legal, policy, financial and public engagement issues need to be addressed to move CCS from today's early demonstration projects to full-scale commercialisation.
This resulting roadmap is designed to be a living document and will be updated regularly to address new developments.[3]

2 For the list of IEA/CSLF Early Opportunities recommendations, see http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/fichier/80583/g8_rec_calgary07.pdf.

3 See www.iea.org/Textbase/subjectqueries/ccs/ccs_roadmap.asp.

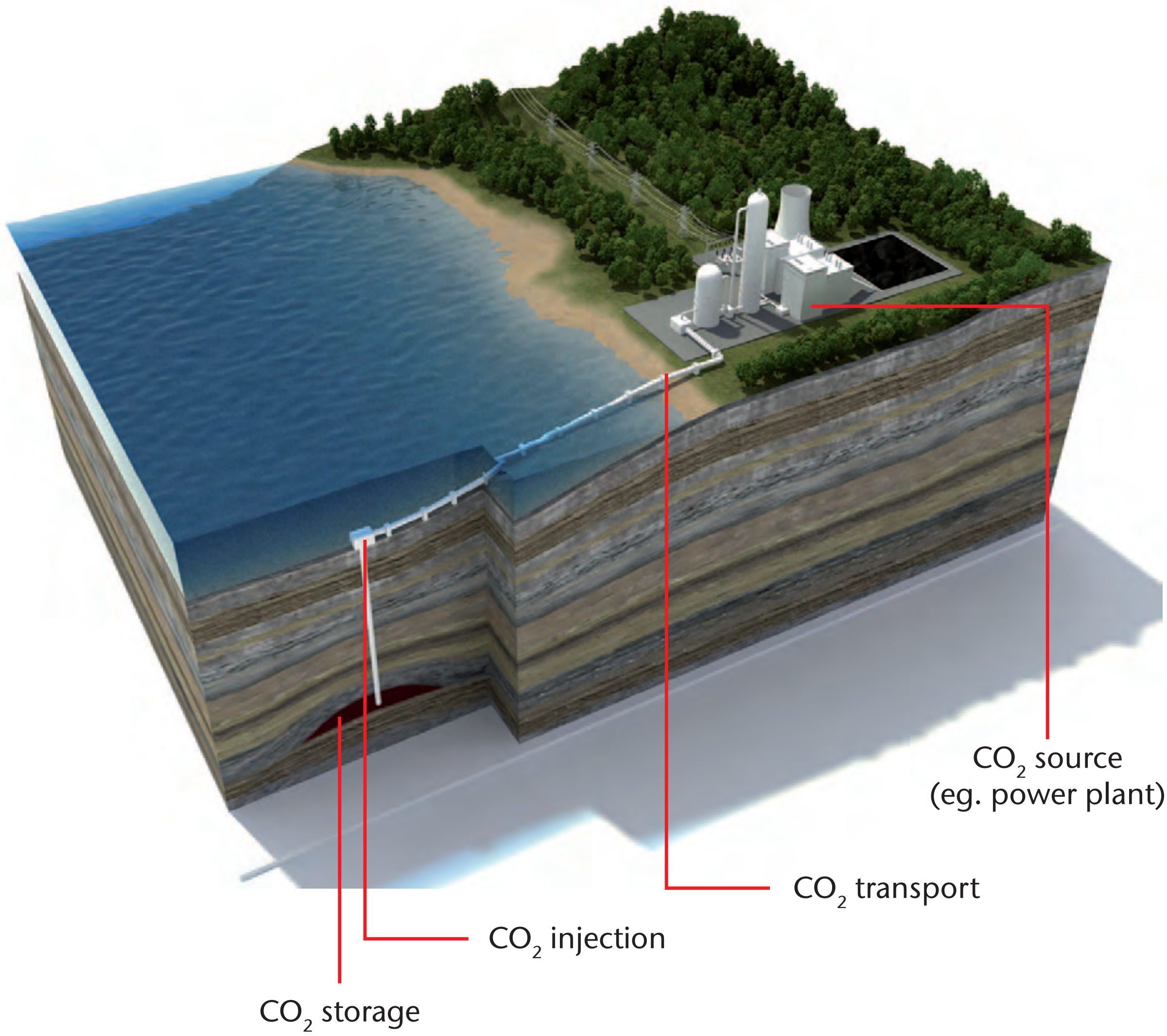
CCS Status Today

This section provides a brief overview of the current situation in CCS technology, financing, regulation and public engagement, to provide a baseline for this roadmap's milestones and actions for the coming decades.

Technology development and demonstration

For this roadmap, CCS is defined as a system of technologies that integrates three stages: CO_2 capture, transport and geologic storage (see Figure 2). Each stage of CCS is technically available and has been used commercially for many years (IEA, 2008b). However, various technologies with different degrees of maturity are currently competing to be the low-cost solution for each stage of the CCS value chain.

Figure 2: The CCS process



Source: Bellona Foundation.

CO_2 capture technologies have long been used by industry to remove CO_2 from gas streams where it is not wanted or to separate CO_2 as a product gas. There are currently three primary methods for CO_2 capture: post-combustion, pre-combustion and oxy-fuel. Post-combustion involves scrubbing the CO_2 out of flue gases from combustion process. Oxyfuel involves combusting fuel in recycled flue gas enriched with oxygen to produce a CO_2-rich gas. Pre-combustion uses a gasification process followed by CO_2 separation to yield a hydrogen fuel gas. Of these methods, post-combustion CO_2 capture using solvent scrubbing is one of the more established for CO_2 capture, and there are currently several facilities at which amine solvents are used to capture significant flows of CO_2 from flue gas streams. Oxy-fuel combustion has been demonstrated in the steel manufacturing industry at plants up to 250 MW in capacity, and the related oxy-coal combustion method is currently being demonstrated. Pre-combustion CO_2 capture from an integrated gasification combined cycle (IGCC) power plant has yet to be demonstrated; however, elements of the pre-combustion capture technology have already been proven in other industrial processes (IPCC, 2005; Henderson et al., 2009).

CO_2 transport has been utilised for over 30 years in North America; over 30 metric tonnes (Mt) CO_2 from natural and anthropogenic sources are transported per year through 6 200 km of CO_2 pipelines in the USA and Canada.[4] CO_2 is transported predominantly via high-pressure pipeline networks, which present a number of regulatory, access, public acceptance and planning challenges for different regions. Ships, trucks and trains have also been used for CO_2 transport in early demonstration projects and in regions with inadequate storage.

CO_2 storage involves the injection of CO_2 into a geologic formation to enhance carbon recovery. The three options for geological CO_2 storage are saline formations, oil and gas reservoirs, and deep unminable coal seams (IEA, 2008b).[5] Of the three, it is expected that saline formations will provide the opportunity to store the greatest quantities of CO_2, followed by oil and gas reservoirs. Monitoring data from projects involving injection into depleted oil and gas fields and saline formations has shown that the CO_2 performs as anticipated after injection with no observable leakage (IPCC, 2005). A number of other projects involving the injection of CO_2 into oil reservoirs have also been conducted, primarily in the USA and Canada. Most of these projects use the CO_2 for enhanced oil recovery (EOR), but some also intentionally store and monitor CO_2 concurrently with EOR operations. The practices in respect to CO_2 injection are well-known; however, more experience is needed to improve predictions of CO_2 behaviour at commercial scale. Exploration programmes are also needed to locate and characterise suitable storage sites, particularly deep saline formations.

4 Carbon Sequestration Leadership Forum (CSLF) (2009), Technology Roadmap(forthcoming); IEA GHG (2009), *What Have We Learnt From Demonstration Projects* (forthcoming).

5 CO_2 storage in basalt formations is also a potentially important option for regions like the Indian subcontinent.

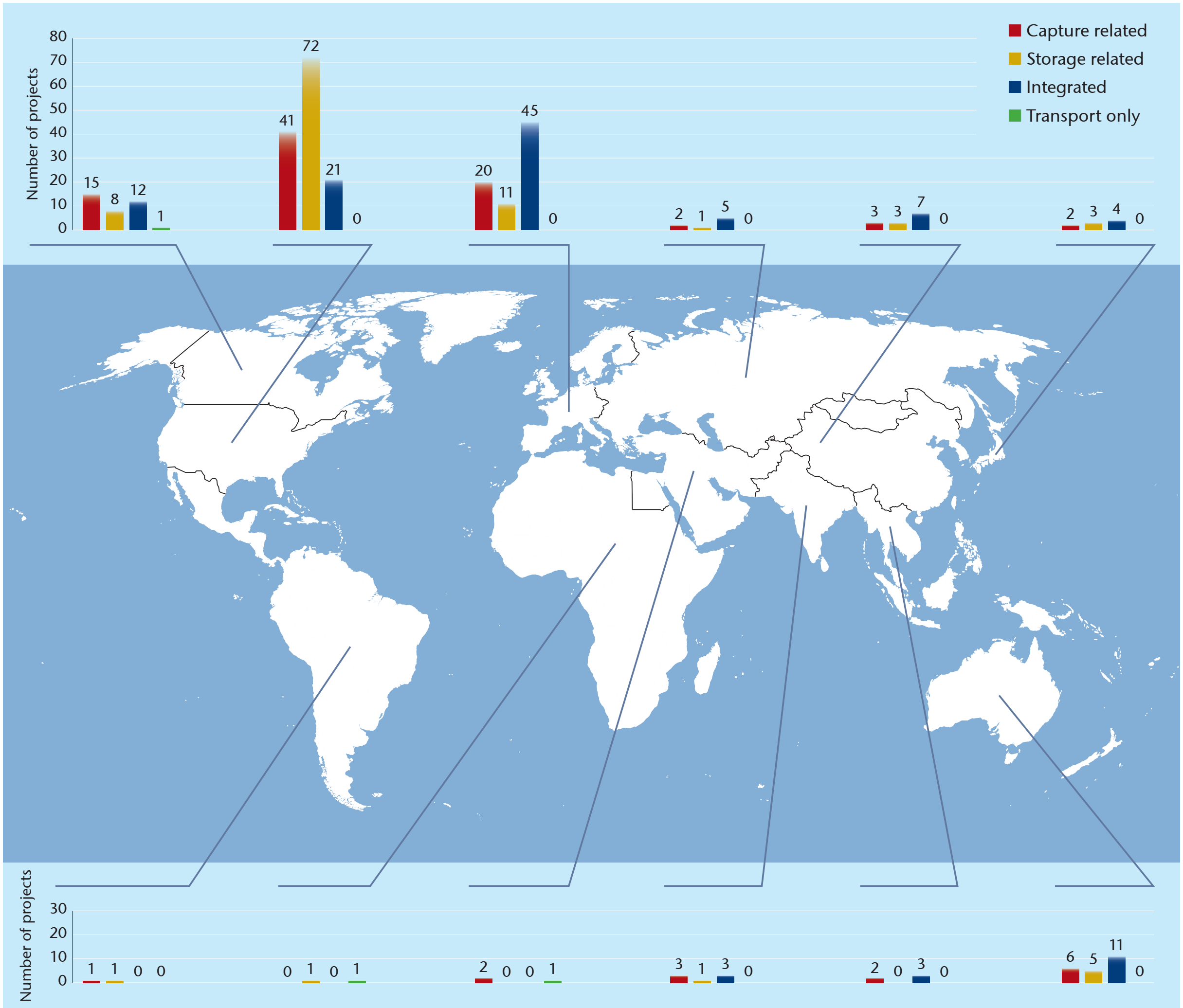
CO_2 storage exploration: a pressing priority

Current knowledge of global storage prospectivity and resources is based almost exclusively on oil and gas exploration data. Targeted exploration is required to locate suitable storage sites in saline aquifers, and more intensive site characterisation exploration is then required to elevate the technical assurance of prospective sites to the level required for project investment. Early CCS projects may therefore be largely restricted to depleted oil and gas fields for their storage capacity. Major, long-term CO_2 storage exploration programmes are required to locate, characterise and develop the large-scale storage resources required for commercial-scale deployment of CCS. To date, there has been very little storage-specific exploration undertaken worldwide, particularly in saline formations, and there is an urgent need for regional and site-specific data to underpin CCS development.

Integration and scale-up of technologies

While it is clear that the individual stages of CCS are technically viable, the challenges of integrating and scaling up these technologies can only be met through the experience of building and operating commercial-scale CCS facilities in a variety of settings. At present, there are five fully integrated, commercial-scale CCS projects in operation. The Sleipner and Snøhvit (Norway) and In Salah (Algeria) projects involve CCS where the CO_2 content of the extracted natural gas is too high. To achieve commercial-grade quality natural gas, the CO_2 is stripped, collected and stored securely in underground geological formations. The Rangely project, also in North America, also uses CO_2 from natural gas processing at a plant in Wyoming, but uses the CO_2 for enhanced oil recovery (EOR) and storage at the Rangely field in Colorado. Finally, the Weyburn-Midale project in North America involves the capture of CO_2 from a coal-based synfuels plant in North Dakota. The captured CO_2 is compressed and sent via pipeline to an oil field in Canada, where it is also used for EOR as well as storage. Currently, over 5 Mt CO_2/year is stored from these plants. In addition to these projects, there are a number of other projects in planning stages across the world. Figure 3 is a global snapshot of planned and operational large-scale CCS projects by project type and region.

Figure 3: Planned and operational large-scale (>1 MtCO_2/year) CCS projects



Source: *Strategic Analysis of the Global Status of Carbon Capture and Storage: Report 1 Project Status* (forthcoming), prepared for the Global CCS Institute by WorleyParsons Services Pty Ltd. (2009).

***KEY POINT:** There are over 100 planned and five operational large-scale CCS projects worldwide.*

Financing projects

In the current regulatory and fiscal environment, commercial power plants and industrial facilities will not invest in CCS because it reduces efficiency, adds cost and lowers energy output. While some regions have enacted carbon regulations that create a price for CO_2, the benefits of reducing emissions are not yet sufficient to outweigh the costs of deploying CCS. As a result, there is a need to fund near-term demonstration projects and to also provide additional financial incentives for CCS in the medium- to long-term. Governments are already addressing the demonstration funding gap, as indicated by a strong increase in announcements of funding for such projects in the past year. In addition, the European Union has also taken steps to link CCS to GHG regulation by recognising the technology in the Emissions Trading Scheme and setting aside allowances for CCS project development. Major announcements from countries around the world include:[6]

- **Australia** – The Australian government has committed AUD 2 bn (USD 1.65 bn) in funding for large-scale CCS demonstrations in Australia. In addition, Australia has committed AUD 100 million (m) a year for three years for the formation of the Global CCS Institute.
- **Canada** – The Canadian federal government has announced financial support of CAD 1.3 bn (USD 1.2 bn) for research and development (R&D), mapping and demonstration project support. In addition, the Province of Alberta has assigned CAD 2 bn (USD 1.8 bn) in funding to support CCS deployment.
- **European Union** – The European Union (EU) has set aside the revenue from the auctioning of 300 m credits within their Emissions Trading Scheme for the support of CCS and renewable energy. The EU has also allocated EUR 1.05 bn (USD 1.5 bn) from their economic recovery energy programme for the support of seven CCS projects.
- **Japan** – The Japanese government has budgeted JPY 10.8 bn (USD 116 m) for study on large-scale CCS demonstration since fiscal year 2008 (FY 2008).
- **Norway** – Since 1991, Norwegian authorities have had an offshore CO_2 tax for oil and gas operations; this tax is currently NOK 230 (USD 40)/MtCO_2. Norway has also announced the allocation of NOK 1.2 bn (USD 205 m) for CCS projects.
- **United Kingdom** – In addition to the broader EU funding, the United Kingdom (UK) has announced funding for up to four CCS projects. The first of these projects will be selected from projects via the CCS competition. The winner will have the additional costs of CCS covered by a government capital grant. The UK has recently announced that the remaining projects will be funded through a levy on electricity suppliers, to take effect in 2011.
- **United States** – The recent Economic Recovery Act includes USD 3.4 bn in funding for clean coal and CCS technology development. USD 1.0 bn has been allocated for developing and testing new ways to produce energy from coal. USD 800 m will augment funds for the Clean Coal Power Initiative with a focus on carbon capture, and USD 1.52 bn will fund industrial CO_2 capture projects, including a small allocation for the beneficial reuse of CO_2.

These announcements and funding allocations serve as the beginning of needed CCS investments; however, there are many fossil-based economies that require substantial additional funding if they are to achieve the levels of investment required for commercial-scale CCS integration.

6 This list does not include all national CCS announcements due to space limitations.

Legal and regulatory frameworks

The expansion of CCS will involve a number of legal and regulatory issues associated with protecting public health, safety and the environment, as well as ensuring stewardship for permanent CO_2 storage. There is also a need to provide flexible, adaptive regulations for the first set of demonstration projects. To address these issues, governments are amending existing resource extraction or environmental impact frameworks to allow the first demonstration projects to move forward, while at the same time developing dedicated legal frameworks to fund or facilitate CCS commercialisation for the longer-term. In some cases, project-specific regulations may be needed.

In recent years, the international community has amended legal instruments to advance CCS development. The London Protocol was amended in 2006 to allow for offshore CO_2 storage; in 2007, the Convention for the Protection of the Marine Environment of the North-East Atlantic (known as the OSPAR Convention) adopted similar provisions.[7] The United Nations Framework Convention on Climate Change does not include a firm commitment for parties with regard to CCS; however, in 2006, the Intergovernmental Panel on Climate Change released the revised *Guidelines for National Greenhouse Gas Inventories*, which are used for calculating and reporting national GHG emissions and removals. Although not yet officially sanctioned for use, the guidelines include a complete methodology for the treatment of CCS in an Annex I (industrialised) country and form a basis for future emissions reporting. For non-Annex I (developing) countries, a suitable international mechanism to finance CCS emissions reductions does not currently exist.

In parallel, many countries are developing comprehensive domestic regulatory frameworks for CCS. Dedicated legal frameworks enable CCS activities either through licensing regimes or by providing regulatory support for the financing of demonstration projects. The European Commission's 2008 CCS Directive establishes a regulatory framework for the geological storage of CO_2. Australia has also enacted comprehensive state and national CCS regulatory frameworks for CO_2 storage. Additionally, regulations are currently being pursued in the United States, Canada, Norway and Japan.

7 Note that the OSPAR amendments have not yet entered into force. In addition, the London Protocol does not currently allow transboundary transport of CO_2; this is an issue that still needs to be resolved.

Public engagement and education

As a relatively new and unknown technology that proposes placing CO_2 into natural systems, CCS is exposed to public scrutiny and potentially prone to controversy. Local communities have legitimate concerns about planned CCS projects that must be addressed in a timely, transparent manner; projects that have failed to do so have been postponed or cancelled. Therefore, it is clear that public engagement and education on CCS is an important priority that requires additional government resources. Given the rapid growth of the need for CCS demonstration projects in the next decade, it will be critical to create tools and model approaches that can be used to effectively engage the public in this debate.

It will also be important to provide public access to clear and reliable information about CCS, its role in global emissions reduction, and the costs and benefits of a proposed project for the local community. In addition to making information about the technology available, government and other agencies must establish engagement mechanisms that enable constituencies to raise their concerns. This input from stakeholders must also be carefully considered and addressed. The development of early demonstration projects will require substantial investments of public funds, making it particularly important that the public understands and supports the rationale for these investments.

CCS Deployment Requirements in the IEA BLUE Map Scenario

The CCS Roadmap outlines the deployment pathway that will be needed to achieve the cost reductions and favourable conditions necessary for CCS to achieve the results of the IEA ETP BLUE Map scenario (see box). It includes a number of aspects of CCS deployment, including levels of CO_2 captured and stored, the evolution of project numbers and sizes, and the financial aspects of CCS development, including costs and investment needs from 2010 to 2050.

Guide to the analysis in this roadmap

This roadmap outlines a set of quantitative measures and qualitative actions that define one global pathway for CCS deployment to 2050. This roadmap starts with the IEA Energy Technology Perspectives (ETP) BLUE Map scenario, which describes how energy technologies may be transformed by 2050 to achieve the global goal of reducing annual CO_2 emissions to half that of 2005 levels. The 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. The ETP model is a global fifteen-region model that permits the analysis of fuel and technology choices throughout the energy system. The model's detailed representation of technology options includes about 1 000 individual technologies. The model has been developed over a number of years and has been used in many analyses of the global energy sector. In addition, the ETP model was supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors. There are a number of terms that are used consistently throughout the ETP model:

Tonnes (t)CO_2 captured: the amount of CO_2 captured from CCS equipped facilities, taking into account CO_2 formation and capture efficiency. It is a rate function that describes the amount of CO_2 that will be captured, transported and injected in a given period, typically a year (tonnes (t) CO_2 captured/year).

tCO_2 stored: the amount of CO_2 stored in geological storage sites. It is a cumulative function of tCO_2 captured, describing the amount of storage capacity needed/used at a future point in time (tCO_2 stored in year X).

tCO_2 avoided: the level of emissions abatement achieved by CCS-equipped facilities relative to the emissions of an equivalent facility (i.e., with the same output) without CCS. It reflects the energy penalty associated with CCS equipment, and is derived as:

$$\text{Avoided } CO_2 = \text{captured } CO_2 / CE * [effnew / effold - 1 + CE]$$

where CE = capture efficiency (fraction captured); effold = energy efficiency of plant without capture (%); effnew = energy efficiency of plant with capture(%) (IEA, 2008b).

Project numbers: a translation of the mitigation contribution of CCS in the BLUE Map scenario (in Gt [gigatonnes] CO_2 captured) into real-world numbers of CCS projects. It is derived from ranges of typical project sizes within each sub-sector analysed. These range from small pilot CCS projects within the power sector to larger CO_2 reinjection projects being employed at high-CO_2 natural gas field facilities.

Total Investment: the amount of financial capital needed to build complete CCS facilities.

Additional Investment: the amount of financial capital needed to build just the CO_2 capture equipment.

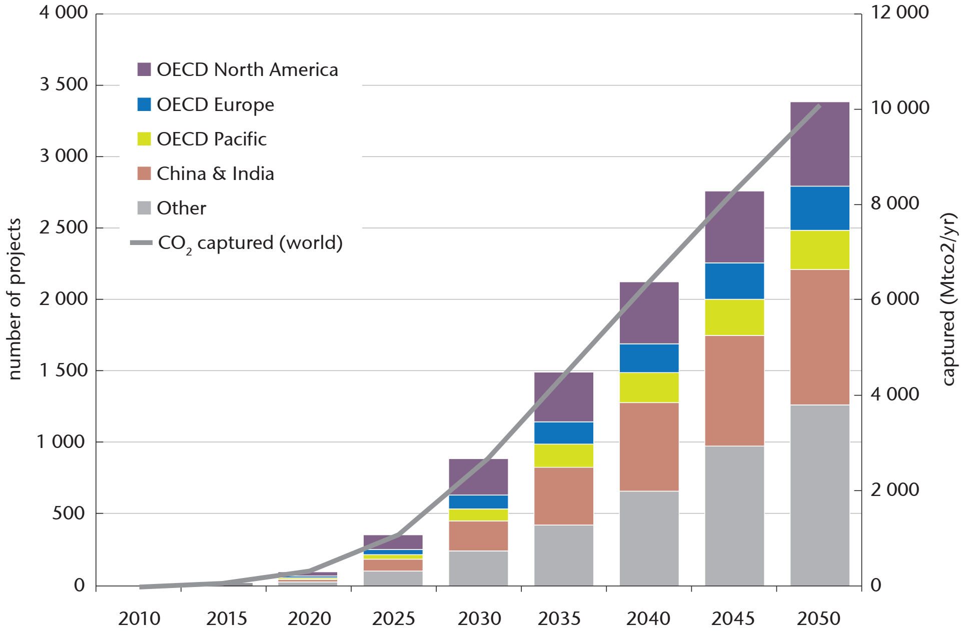
Total Costs: the annualised expenditures for a complete CCS-equipped facility. It includes capital repayments, fuel and maintenance costs, and cost associated with CO_2 transport and storage. It reflects the costs for operators in building, operating and maintaining facilities.

Additional Costs: the annualised expenditures for just the CCS part of a facility. It reflects the incremental costs for operators relative to operating an equivalent facility without CCS.

CO_2 reduction targets

Under the BLUE Map scenario, global deployment of CCS is projected to capture over 10 gigatonnes (Gt) of CO_2 emissions in 2050, with a cumulative storage of around 145 $GtCO_2$ from 2010 to 2050. Capture from power generation represents 5.5 $GtCO_2$/year (or 55% of the total CO_2 captured) in 2050. Capture from industry accounts for 1.7 $GtCO_2$/year (16%), and upstream capture (e.g., gas processing and fuels transformation) accounts for 2.9 $GtCO_2$/year (29%) of the total in 2050 (see Figures 4 and 5).

Figure 4: Global deployment of CCS 2010–2050 (CO_2 captured and number of projects)



	Number of projects in 2020	Number of projects in 2050	Additional cost 2010-2020 (USD bn)*	Additional cost 2010-2050 (USD bn)*	Total invest. 2010-2020 (USD bn)**	Total invest. 2010-2050 (USD bn)**
OECD NA	29	590	23.6	1 635	61.7	1 130
OECD Europe	14	320	6.8	590	15.8	475
OECD Pacific	7	280	5.9	645	14.1	530
China & India	21	950	7.6	1 315	19.0	1 170
Non-OECD	29	1 260	9.7	1 625	19.8	1 765
World	**100**	**3 400**	**54**	**5 810**	**130**	**5 070**

* *Includes cost of transport and storage*

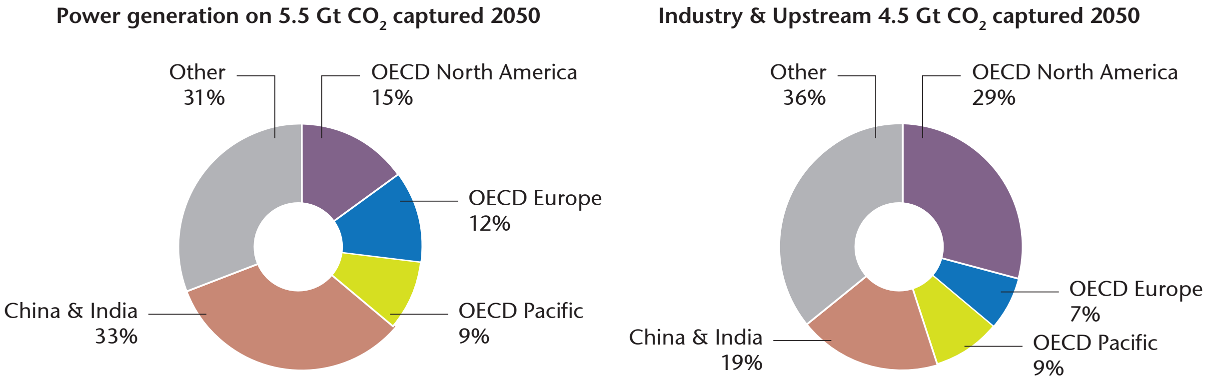
** *Does not include investment in transport and storage*

Notes: OECD NA = USA, Canada, Mexico; OECD Europe = Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, UK; OECD Pacific = Australia, Japan, New Zealand, South Korea; Non-OECD = the rest of the world.

***KEY POINT:** There is an ambitious growth path for CCS from 2010 to 2050.*

The BLUE Map scenario analysis estimates that growth in both demonstration and commercial-scale CCS projects within the OECD region will account for around two-thirds of the total CO_2 captured by 2020. However, the widespread deployment of CCS within power generation and industry in emerging economies will effectively decrease this share to 47% of the cumulative CO_2 stored by 2050. Within non-OECD regions, China and India will account for around 26% of the total cumulative amounts of CO_2 capture required (see Figures 5 and 6).

Figure 5: Global deployment of CCS 2010–50



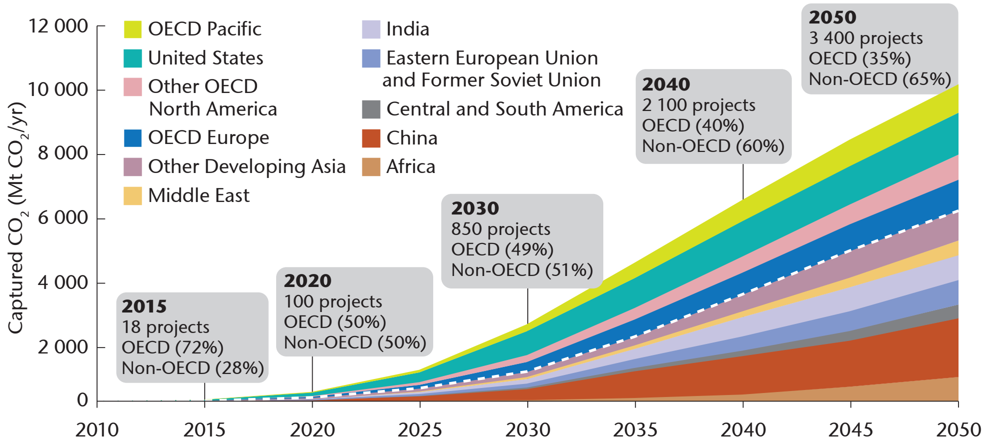
	Global deployment share 2050	Additional CCS cost 2010-2050* (USD bn)	Additional invest. 2010-2050** (USD bn)	Global deployment share 2050	Additional CCS cost 2010-2050 (USD bn)	Additional invest. 2010-2050 (USD bn)
OECD NA	16%	600	85	29%	1 035	187
OECD Europe	12%	350	71	7%	240	49
OECD Pacific	9%	225	54	9%	420	75
China & India	32%	700	166	19%	615	121
Non-OECD	31%	565	218	36%	1 060	260
World	**100%**	**2 440**	**594**	**100%**	**3 370**	**691**

* *Includes cost of transport and storage*

** *Does not include investment in transport and storage*

***KEY POINT:** CCS development will start in the industrialized countries but is expected to rapidly shift to developing regions after 2020.*

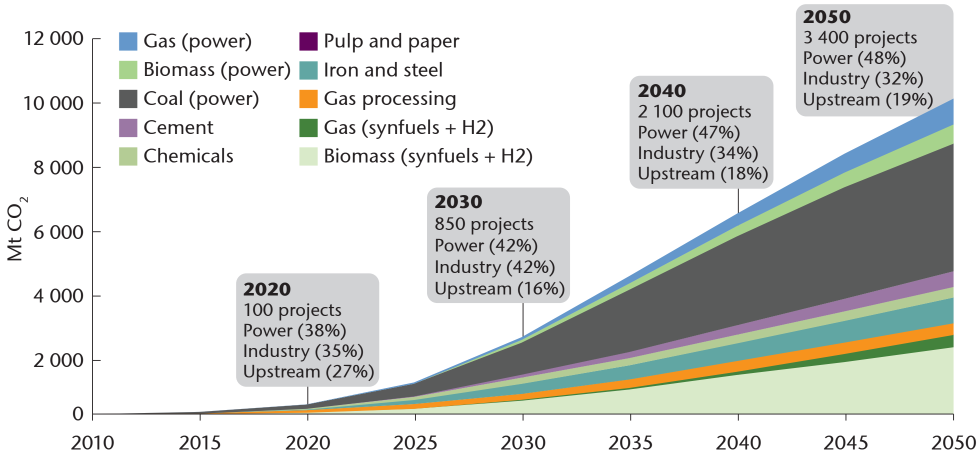
Figure 6: Global deployment of CCS 2010–50 by region ($MtCO_2$ captured/year)



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

***KEY POINT:** To achieve the BLUE Map targets, OECD regions must lead in the demonstration phase but then CCS technology must spread rapidly to the rest of the world.*

Figure 7: Global deployment of CCS 2010-50 by sector



***KEY POINT:** CCS is not just about cleaner coal: a number of sectors will need to develop CCS to achieve the BLUE Map scenario's emissions targets.*

CCS project deployment

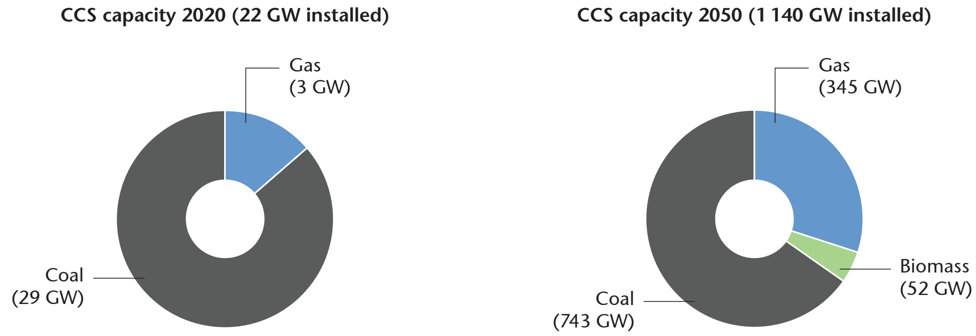
To meet the CO_2 savings achieved from CCS deployment under the BLUE Map scenario, around 3 400 projects will be required worldwide by the year 2050. Nearly half of this total number of projects will be required by the power sector (Figure 7). The capture of emissions from industrial sources will account for over 1 000 projects by 2050, with over 600 of these projects located in upstream sectors. Within the next ten years, about 100 projects are needed, a significant ramp-up from today's levels of CCS deployment.[8] Of the 100 projects, around 38% will be in the power sector and 62% from industry and upstream sources across a range of activities. These ambitious levels of deployment will require an average building rate of ten projects each year over the next ten years. From the full period (i.e., 2010 to 2050), it will require 85 projects each year.

Power generation

The BLUE Map scenario estimates that power generation will account for around 55% (5.5 $GtCO_2$/year) of worldwide CCS deployment by 2050. Demonstration of capture from power generation in the next ten years will be critical to accelerating wider deployment through 2020 to 2050. In the near-term, projects are likely to mainly use post-combustion capture technologies from coal-fired power plants in OECD regions, albeit with an increasing share of the use of other capture technologies. Over the 2010 to 2050 time period, capture from power generation is estimated to result in cumulative capture of some 78 $GtCO_2$, of which coal-fired plants will account for around 80% (62 $GtCO_2$); capture from gas-fired plants will account for 12% (9.2 $GtCO_2$) and biomass plants will account for around 8% (7.1 $GtCO_2$), the latter mainly in industrial CHP (combined heat and power) plants (Figure 8). Total global installed CCS capacity will need to rise to over 1 100 GW by 2050, of which coal-fired CCS will account for around 65%. While this need presents major development and investment challenges, CCS-fitted plants will still only account for 17% of total electricity generation in 2050 (Figure 8).

8 Note that in 2008, the G8 leaders recommended that 20 large-scale demonstration projects be launched globally by 2010, with a view to beginning "broad deployment" by 2020. The roadmap's recommendation of 100 large-scale projects, which is based on achieving the BLUE Map scenario for emission reductions, is therefore in line with the G8 announcement.

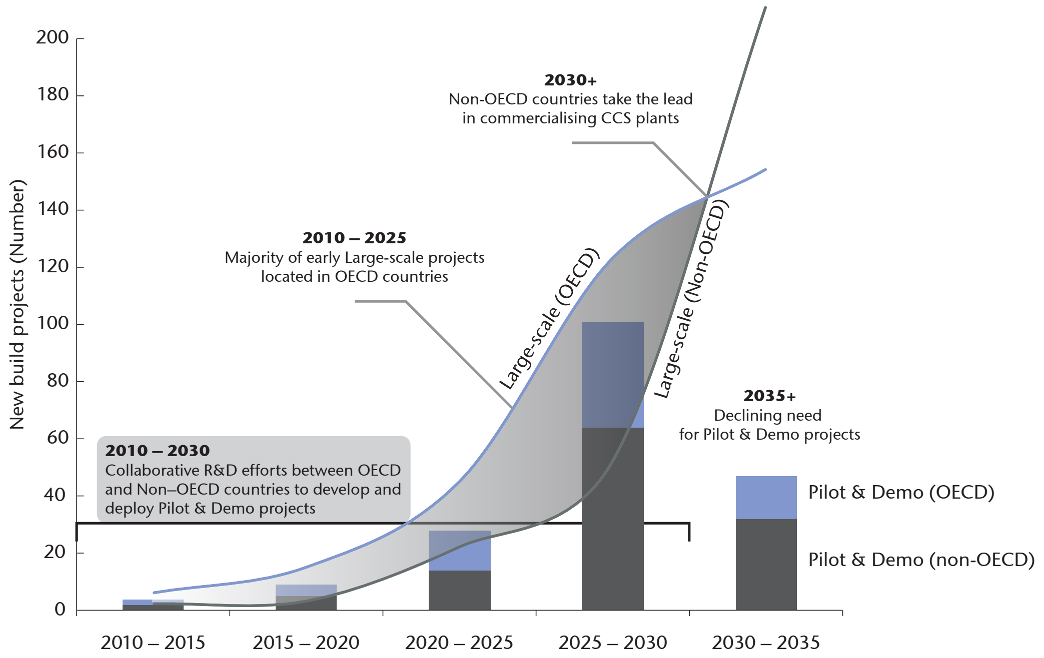
Figure 8: Global deployment of CCS in the power sector



KEY POINT: *Power plants must rapidly adopt CCS over the next three decades; by 2040, nearly all fossil-based power plants will use CCS.*

	Number of projects in 2020	CCS capacity in 2020 (GW)	Captured 2020 ($MtCo_2$/ year	Number of projects in 2050	CCS capacity in 2050 (GW)	Captured 2050 ($MtCo_2$/ year
OECD NA	17	11.1	77	250	150	810
OECD Europe	9	5.5	26	195	140	680
OECD Pacific	2	1.3	9	150	85	510
China & India	6	2.5	13	465	365	1 785
Non-OECD	4	1.6	6	610	400	1 725

Figure 9: Global transition from demonstration to commercial scale, 2010–35



Plant size assumptions (MW)

FUEL TYPE	PILOT	DEMONSTRATION	SMALL COMMERCIAL	LARGE COMMERCIAL
Biomass	75	100	175	250
Coal	200	300	500	1 000
Gas	150	250	400	800

***KEY POINT:** Expanded global collaboration on CCS research and development and technology transfer will be critical to achieve the BLUE Map emissions target.*

There are currently no large-scale, integrated CCS projects in the power generation sector. Over the next ten years, the majority of projects will be deployed within OECD countries, driven by emerging emission reduction policy frameworks and financial incentives. Early projects are likely to range from small-scale pilot and demonstration projects to a few large-scale plants able to capture over 3 $MtCO_2$ to4 $MtCO_2$/year. The share of CCS deployment within non-OECD regions will need to increase dramatically around 2025 to 2030 and beyond to effectively mitigate emissions from new coal-fired power plants built in emerging economies. To meet the emissions-reduction objectives of the BLUE Map scenario, capture of emissions from plants in China and India alone will need to account for over 30% of global CCS deployment in power generation over the 2010 to 2050 time period. Additionally, by 2050, non-OECD regions must account for around 64% of captured emissions with the remaining 36% from OECD regions.

At the global level, the BLUE Map scenario requires 38 CCS projects to be deployed globally in power generation by 2020, which translates to 130 $MtCO_2$/year captured by 22 GW of installed CCS capacity (Figure 8). To reach the BLUE Map target of 1 140 GW installed CCS capacity by 2050, a fifty-fold increase in CCS deployment is required – equivalent to an average rate of an additional 38 GW/year.

Successful demonstration of CCS capture technology within the next 10 to 20 years through large-scale demonstration plants is critical to establishing wider deployment by 2050. Early deployment of these types of projects will need to be shared between developed and developing economies. Given their existing investments and earlier start on the technology, OECD regions will need to move first. A progressive move toward the application of larger projects on a global basis by 2020 to 2030 will also be needed (see Figure 9). If non-OECD regions rapidly begin to invest in large-scale CCS applications, they will surpass the rate of OECD large-scale new build by 2035.

CCS retrofit and capture-ready plants: avoiding lock-in of non-CCS plants

As demand for electricity increases, there is a danger that if new fossil fuel power plants are built with no option for CCS retrofit, a large amount of CO_2 emission to the atmosphere will be "locked-in," since such plants may have an operational life of 40 years or more. Therefore, it is critical that fossil-fuelled plants built over the next 10 to 20 years utilise technologies and practices that enable CCS retrofit. Some governments have recognised this need; for example, the United Kingdom's April 2009 announcement requiring CCS on a proportion of all new coal plants greater than 400 MW and retrofit on the remainder when this becomes viable. While new build power generation is expected to account for the vast majority of worldwide CCS capacity installed by 2050, the share of retrofit CCS deployed in some regions, such as China, India and the US, is also likely to contribute (around 60 GW installed by 2050).

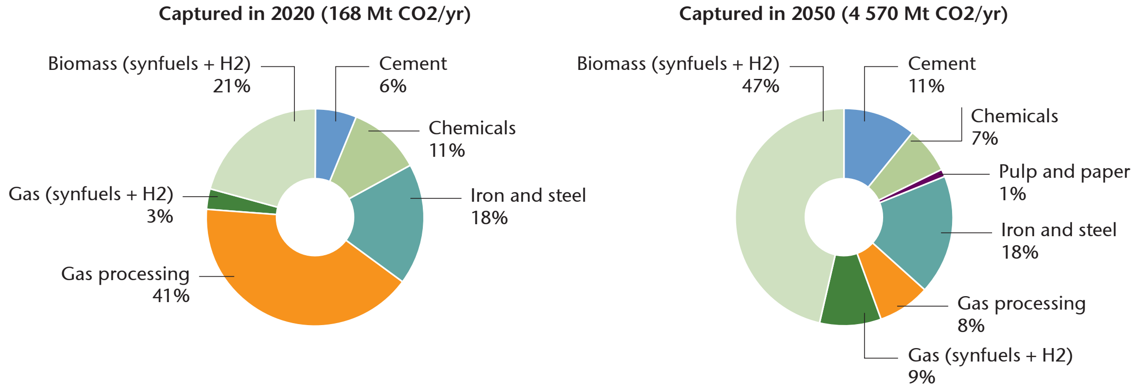
An IEA GHG study recently concluded that the key technical issues for developing capture-ready plants include ensuring the provision of sufficient space and access for the additional capture facilities that would be required, and identification of reasonable method(s) for storing CO_2. The study found that pre-investment in addressing these issues is relatively inexpensive and could result in significant reductions in the costs and downtime for retrofit. The study also identifies the need for permitting authorities to specify the information they require to judge plant capture-readiness, and suggests performing preliminayc consultation to determine whether a plant is capture ready. It is important to note, however, that while capture-ready plants will be important for preventing CO_2 lock-in, they do not provide any reductions in CO_2 without the retrofit of CCS. Accordingly, the aim for any capture-ready plant must be to retrofit with CCS as soon as possible.

Source: IEA GHG (2007), *CO_2 Capture Ready Plants*.

Industry and upstream

Capture from industrial and upstream sources will account for around 45% (4.6 $GtCO_2$/year) of worldwide CCS deployment in 2050. In the near-term, deployment in the upstream sector is likely to be dominated by low-cost opportunities in natural gas processing, notably from high-CO_2 gas fields in regions such as the South China Sea, Russia, North Africa and South America. The growing number of large gas-to-liquids (GTL) plants is also expected to represent a significant application where emissions can be captured from around 2020 to 2025. Post-combustion and oxy-fuel capture from cement plants and oxy-fuel capture from large iron and steel works is forecast to account for the majority of emissions captured within industry over the next 40 years. However, projects capturing CO_2 from sources such as ammonia and fertiliser production offer near-term, low-cost opportunities within the chemicals sector. The BLUE Map scenario depicts capture from upstream sources as accounting for around 59% (39 $GtCO_2$) of the combined cumulative capture emissions from 2010 to 2050, with industry representing the remaining 41% (27 $GtCO_2$) (see Figure 10).

Figure 10: Global deployment of CCS in industry and upstream



	Number of projects in 2020	Captured 2020 ($MtCO_2$/year)	Global deployment share 2020	Number of projects in 2050	Captured 2020 ($MtCO_2$/year)	Global deployment share 2050
OECD NA	12	44	26%	340	1 325	29%
OECD Europe	5	11	7%	120	310	7%
OECD Pacific	5	17	10%	125	390	9%
China & India	15	29	17%	485	890	19%
Other Non-OECD	25	68	40%	660	1 655	36%
World	**62**	**168**	**100%**	**1 730**	**4 570**	**100%**

KEY POINT: *In BLUE Map, the industry and upstream sectors start with low-cost gas processing, then transitions to synfuels and hydrogen production using CCS.*

CCS and bioenergy: Progress needed on climate change methodologies and demonstrations

To meet the BLUE Map scenario targets, major reductions in global emissions will need to be achieved through increases in bioenergy. Biofuels account for 26% of total transport fuel demand by 2050 in the BLUE Map scenario. This target will be met through growth in the production of first-generation biofuels, rapid breakthroughs in ”second-generation” technologies and potentially the use of ”third-generation” biofuels (e.g., from algae) over the next 30 years. Biofuel production leads to the formation of CO_2 from both combustion and process sources. Capture of CO_2 from these sources has the potential to create negative life-cycle emissions through the removal and permanent storage of carbon from the short-term biogenic cycle.

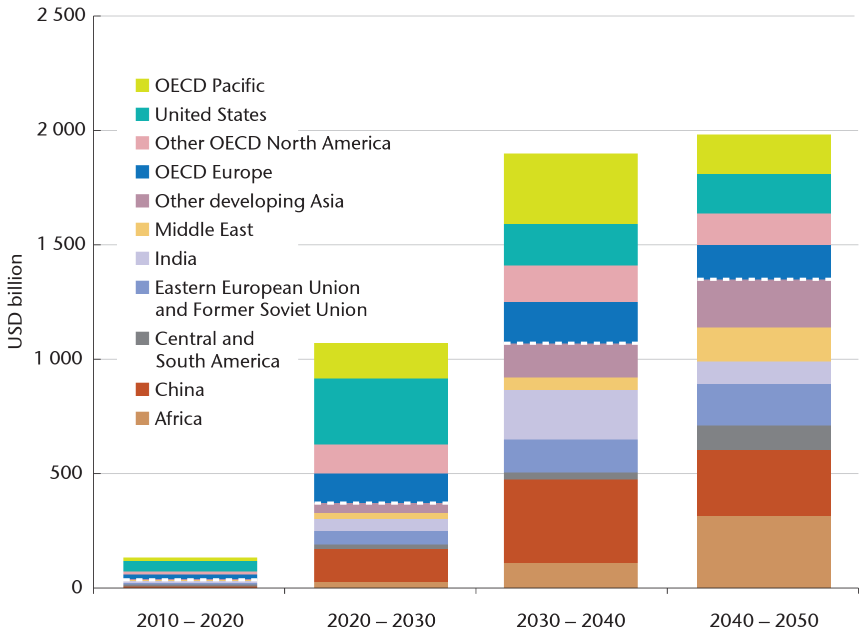
The implications for emissions accounting and policy design still need to be addressed. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories allow for such negative emissions to be allocated in national GHG inventories (IPCC, 2006). However, the realisation of these benefits has not yet been established by current policy frameworks. Incentives could be provided at the point of production – through appropriate emissions accounting, emissions “crediting” or other fiscal measures – or at the point of use, through policies, fiscal measures or biofuel obligations scaled according to the climate benefits delivered. The best approach needs careful consideration to ensure coherent policy-making that recognises the benefits of such technologies while avoiding “double-counting” emissions reductions.

CCS costs and investment needs

Roadmap deployment costs for CO_2 capture, CO_2 transport and CO_2 storage from 2010 to 2050 will be significant. The additional cost of CCS between now and 2050 will amount to USD 2.5 to USD 3 trillion for the deployment of some 3 400 projects. This is about 3% of the total low-carbon technology investment that is needed to achieve the BLUE Map scenario goal of halving CO_2 emissions in 2050. The additional cost of CCS is likely to amount to USD 350 bn to USD 400 bn per year by 2050, representing an additional cost of over 40%.

Costs vary considerably across regions and sectors. The total cumulative investment required for the base plant and the additional capture component from 2010 to 2050 is estimated to amount to around USD 5 trillion, representing an average rate of USD 125 bn invested per year from 2010 to 2050. Of this total, the additional investment associated with capture plant through 2050 will be almost USD 1.3 trillion – equal to around 25% of the total investment and 34% more than equivalent non-CCS plants (see Figure 11). The total investment requirements for CO_2 transport infrastructure is USD 0.5 trillion to USD 1 trillion and that for CO_2 storage represents an additional USD 88 bn to USD 650 bn through 2050.

Figure 11: Total CCS investment 2010–50 by region (USD billion)



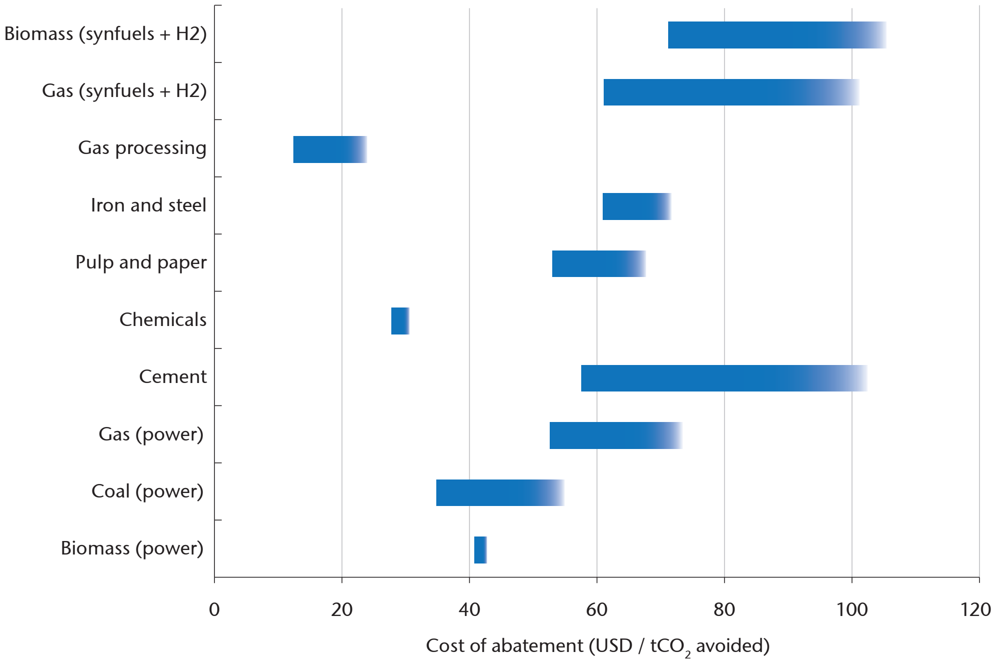
Notes: Does not include investment in transport and storage; the dashed line indicates separation of OECD/non-OECD groupings.

***KEY POINT:** Achieving BLUE Map levels of deployment will require over USD 1.3 trillion additional global investment and USD 5 trillion total investment from 2010 to 2050.*

The investment required will vary across regions as different patterns and rates of CCS deployment develop over time. In the near-term, accelerated deployment of CCS in OECD Europe and North America will require some USD 77 bn of total plant investment by 2020, more than half of all global CCS investment needs. Of this total, additional investment in capture plants will represent some USD 21 bn (of which around USD 12 bn will be required in the power generation sector). In the BLUE Map scenario, in 2050, these regions will account for just over 20% of global annual CCS investment – from 2010 to 2050, OECD regions are expected to account for around 42% of this total investment and non-OECD regions 58%.

The abatement costs associated with CCS (USD/ tCO_2 avoided) are different for different regions and sectors. The costs of capture technology are forecast to fall over time with increased demonstration of integrated projects and technology cost reductions, while transport costs will decrease with increasing optimisation of regional pipeline infrastructure. Figure 12 shows the range of abatement cost estimates for each sector over the period 2010 to 2050 that were used for the BLUE Map scenario analysis. Based on available data, CCS deployment in sectors such as chemicals and gas processing represent early, low-cost capture opportunities – capture costs are low (relative to other sectors) in the production of certain chemical products, such as ammonia, whereas transport costs are typically low for upstream projects where in-situ (or close proximity) injection is possible. Higher additional costs of capture technology and associated energy penalties typically occur in projects with higher abatement costs, such as those capturing emissions from fuel transformation plants and cement production facilities.

Figure 12: Ranges of CCS abatement costs used in the analysis for this roadmap (USD/tCO_2 avoided)



Source: IEA Analysis, based on IEA, 2008b.

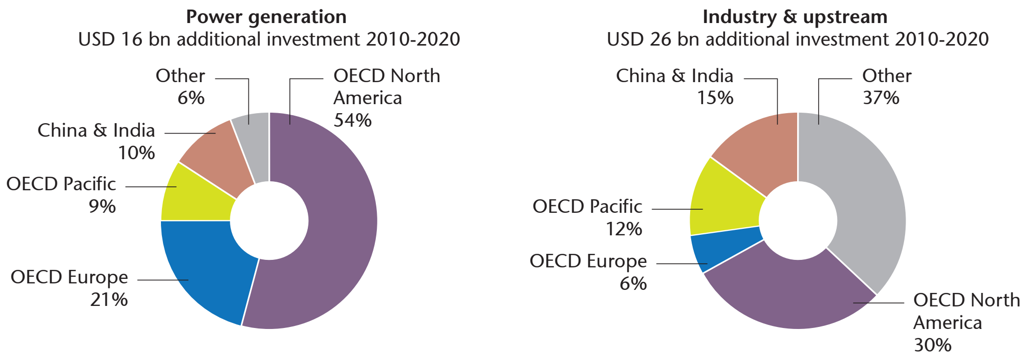
Note: The costs of CO_2 capture shown in Figure 12 represent the range of abatement costs resulting from the analysis compiled for this roadmap. These costs are therefore affected by the assumed level of CCS uptake in each sector within the scenario. For sectors with a low uptake (such as chemicals and biofuels), the ranges above relate only to early-opportunity, lower-cost applications; for sectors where uptake of CCS is high (such as gas and coal-fired power production), the ranges are more representative of total sector CCS application.

The GHG abatement costs also indicate the relatively low cost of CCS deployment within the power sector, which decrease over time with falling capture costs and optimisation of transport infrastructure. The BLUE Map scenario estimates that costs associated with large coal-fired power plants will represent the lowest cost opportunities within the power sector at around USD 35 to USD 50/tCO_2 avoided, with capture from gas-fired plants falling within the range of USD 53 to USD 66/tCO_2 avoided. This range of abatement costs is dependent upon a range of unknown factors, including future relative costs of gas and coal and the mix of different capture technologies employed across regions.

The next ten years

In the next ten years, the BLUE Map scenario analysis concludes that nearly 100 CCS projects will need to be deployed globally. Much of the focus for early pilot, demonstration and larger-scale projects is in the power sector; however, projects capturing CO_2 in the industrial and upstream sectors represent an important contribution as well, with over 60% of total CCS projects expected worldwide by 2020 (see Figure 13). The increase in project numbers from now to 2020 is likely to be driven by incentivising early, low-cost opportunities in sectors such as ammonia and fertiliser production, natural gas processing and LNG facilities. Although most current CCS projects are located within OECD regions, projects in non-OECD regions will account for an increasing share of the total over the next ten years, driven mostly by low-cost industrial and upstream opportunities in China and other Asian countries. Within the OECD, North America will account for over half of all projects deployed, driven by a range of industrial projects and capture from small- and large-scale coal-fired power generation plants.

Figure 13: Additional investment needs for CCS over the next ten years



	Total CCS projects in 2020	Captured 2020 ($MtCO_2$/year)	Additional CCS cost 2010-2020 (USD bn)**	Total CCS projects in 2020	Captured 2020 ($MtCO_2$/year)	Additional CCS cost 2010-2020 (USD bn)**
OECD NA	17	77	13.3	12	44	10.3
OECD Europe	9	26	4.8	5	11	2.0
OECD Pacific	2	9	2.4	5	17	3.5
China & India	6	13	3.5	15	29	4.1
Other Non-OECD	4	6	2.1	25	68	7.6
World	**38**	**130**	**26.1**	**62**	**168**	**27.5**

* Does not include investment in transport and storage.

** Includes cost of transport and storage.

KEY POINT: *The additional investment needs for CCS are about USD 42 bn over the next decade.*

Achieving these ambitious deployment rates over the next decade will require new, more vigorous policy developments and incentives. Cumulative total plant investment of around USD 150 bn will be required (USD 42 bn of which is additional investment capture-related), capturing some 300 $MtCO_2$/year by 2020. These estimates are equivalent to around USD 1.5 bn (and around USD 420 million of additional investment) per project, each of which will capture an average of 3 $MtCO_2$/year. In the power sector, the average project investment will be around USD 1.40 bn, capturing 3.4 $MtCO_2$/year per project. In the industry and upstream sector, around USD 1.25 bn will be required per project, capturing on average 2.7 $MtCO_2$/year. Approximately USD 15 bn to USD 20 bn/year in additional investment will also be required to finance transport infrastructure and storage sites through 2020. Taking operating costs into account, this translates into an additional per project cost of almost USD 70 million/year for the power sector and USD 45 million/year for the industry and upstream sectors through 2020 (the lower additional cost for industry and upstream arise from the low transportation costs for gas processing operations that are able to inject CO_2 at or near the production site). The OECD will account for around 85% (USD 44 bn) of the total investment required for CCS projects deployed in the power sector from 2010 to 2020 and around 60% (USD 47 bn) of the total investment required within industry and upstream sectors.

Early opportunities for CCS with enhanced oil and gas recovery: policies are needed to pave the way for technology development

"Early opportunity" CCS projects involve capture from high-purity, low-cost sources such as natural gas processing, ammonia production or synthetic fuel production; transportation of less than 50 km; and storage with a value-added application, such as enhanced oil recovery. The IPCC's 2005 Special Report concluded that up to 360 $MtCO_2$/year could be captured and stored from such projects under circumstances of low or no incentives. Another analysis by the IEA Greenhouse Gas R&D Programme concluded that 420 early opportunity projects and 500 Mt of annual CO_2 reductions could be achieved by transporting CO_2 less than 100 km with use in enhanced oil recovery (IEA GHG, 2002). These opportunities are particularly important for engaging developing countries, who have limited funds or incentive to invest in the higher cost of CCS.

Supporting economically attractive, early opportunity projects paves the way for large-scale CCS deployment, by providing early learning on CO_2 capture, creating parts of the infrastructure, building experience in storage site characterisation and selection, and enhancing public confidence. There is a large potential for early opportunities in developing countries; another IEA GHG study concluded that by 2020, 117 $MtCO_2$ to 312 $MtCO_2$ could be captured in developing countries through the Clean Development Mechanism. Therefore, a critical next step will be ensuring that the emissions benefits offered by early opportunity applications are recognized under global climate policies.

Technology Development: Actions and Milestones

To address this roadmap's ambitious growth pathway for CCS, there are a number of specific technology gaps that need to be addressed. This section summarises the list of specific action items that have been identified for each element of the CCS chain: CO_2 capture, CO_2 transport and CO_2 storage. The development and selection of the action items under each of these components was informed by the IEA CCS Roadmap meetings, as well as the recently published CSLF CCS Technology Roadmap and IEA Clean Coal Centre roadmaps (CSLF, 2009) (Henderson et al., 2009). Milestones for each element of the CCS chain are also included to measure and ensure progress. Improving the understanding and performance of CO_2 capture, transport, and storage is critical to the effective demonstration and large-scale deployment of CCS.

CO_2 capture

A number of different capture processes have been tested and deployed at various scales, but it is too early to tell if any particular technology will emerge as the preference for CO_2 capture. The main methods of CO_2 capture are post-combustion, oxy-coal combustion and pre-combustion capture. All capture options must address challenges that include: increased costs due to the capital equipment required by the CO_2 capture system; additional power generation capacity to overcome losses in output (known as the "energy penalty"); integration of auxiliary equipment; and air separation in oxyfuel plants. In addition, there are issues of scale, integration, combustion stream composition and other challenges that must be addressed.

Most of the RDD&D to date has focused on CO_2 capture from the power sector; additional resources must be dedicated to CO_2 capture technology demonstration in industrial sectors and with biomass. Variants of the available capture technologies are applicable to industrial facilities such as cement kilns and iron and steel furnaces; for example, oxy-fuel firing has been demonstrated in the iron and steel industry at commercial plants up to 250 MW capacity. One of the challenges for industrial applications is establishing a source of heat in post-combustion systems to regenerate the solvents, electrical power for oxygen production in oxy-fuel applications, and compression in all circumstances. This will likely require onsite CHP plants, raising costs. This section discusses the actions and milestones for the development of each of the capture technology options (see Figure 14 for a summary).

Post-combustion capture technology

Post-combustion capture, which separates CO_2 from gas mixtures, is a commercially available, mature technology used at hundreds of locations around the world. Typical projects involve the use of chemical amine-based solvents to selectively remove CO_2, which upon heating, releases a high-purity CO_2 offgas stream suitable for storage without any further treatment. Several smaller facilities using amine solvents to capture significant flows of CO_2 from flue gas streams are in operation today; however, the technology has yet to be fully demonstrated at commercial-scale power plants.

The evolution of alternative means of capturing CO_2, such as membrane separation, chemical looping and solid adsorption processes, are at the R&D stage and may be able to improve the overall efficiency of the process in the future. Further R&D is needed to identify solvents requiring less heating energy, lower solvent loss rates and corrosion risk, and alternative separation technologies.

Actions and milestones

- **Scale** – Develop an application at the scale required for flue gas streams for coal- and gas-fired plants, and reduce high capital costs (currently >USD 50 million for a 5 MMscm/d train or c.0.5 $MtCO_2$/yr in the case of a coal-fired plant).
- **Combustion stream composition** – Reduce the upstream concentration of nitrogen oxide (NO_X), sulphur dioxide (SO_2) and oxygen in the flue gas, which all react with solvents to form stable salts, leading to rapid solvent degradation and higher costs.

- **Energy penalty** – Improve boiler efficiency to reduce the gross energy penalty to <8% points by 2020 to 2025, with an associated reduction in capital and operating costs (currently the capture system requires a large amount of heat for amine solvent regeneration, as well as auxiliary power requirements for flue gas pre-treatments, blowers, pumps and compressors, which reduces the overall operating efficiencies of the plant in the range of 8% to10% points compared to standard plants).
- **Integration** – Optimise integration, particularly for retrofit applications, to achieve plant availabilities and capture rates above 85% by 2020.

Pre-combustion capture technology

IGCC plants involve the partial oxidation of solid fuel feedstock in a gasifier to produce a mixture of hydrogen and carbon monoxide. The gas mixture is then treated in a shift converter to produce CO_2 and H_2, and a physical adsorption unit is used to separate CO_2 from the mixture, while the H_2 is combusted in a turbine.

Actions and milestones

- **Scale** – Demonstrate IGCC for widespread use in baseload power generation with all types of fuels, especially equipped with CO_2 separation; improve the overall efficiency and reliability of the IGCC process; reduce the amount of steam required for the shift conversion; increase the efficiency of the gas turbine used to combust the hydrogen; improve availability to 85%.
- **Integration –** Achieve process control with the parallel processes in IGCC plants with CO_2 capture.
- **Energy penalty –** Reduce steam requirements in the shift converter on IGCC using gas separation membranes after 2030; develop novel methods for pre-combustion CO_2 capture, including pressure swing adsorption, electrical swing adsorption, gas separation membranes and cryogenics.
- **Hydrogen combustion –** Invest in further RD&D to develop high-efficiency and low-NO_x H_2 gas turbines (the combustion temperature of H_2 requires careful management to avoid damage to turbine blades, which can be achieved by recycling separated CO_2).

Oxyfuel capture technology

Oxyfuel systems offer a capture alternative by combusting fossil fuels in recycled flue gas enriched with oxygen. This leads to the production of CO_2 and steam. There are presently demonstration projects involving oxy-fuel firing in power generation.

Actions and milestones

- **Energy penalty –** Reduce the energy required for large-scale air separation (near-term) and further investigate how to optimise O_2 purity and post-combustion treatment needs to reduce the high energy requirements for pure oxygen production.
- **Combustion stream composition –** Develop advanced materials that can withstand the high temperatures associated with oxyfuel capture to help minimise air leakage into the firing chamber that can lead to nitrogen contamination of the exit gases.
- **Integration –** Better manage the emissions of air pollutants (NO_x and SO_2) through staged combustion design and clean-up where needed.
- **Use in cement sector** – Explore whether the flame temperature in oxy-fired cement kilns is suitable for clinker production (due to the cement sector's anticipated need for CCS).

All CO_2 capture processes result in a reduction in the efficiency of the power plant or industrial operation. Accordingly, in conjunction with the development and refinement of capture technology, work must continue to improve the host plant's efficiency to reduce the overall energy penalty as much as possible. Methods for improving the efficiency of different processes are discussed in detail in the IEA Clean Coal Centre's Technology Roadmap (Henderson et al., 2009). Other specific CO_2 capture technology milestones are included in Figure 14.

Figure 14: Technology status, actions and milestones for CO_2 capture

CO_2 capture	Technology status in 2010	Near-term RDD&D needs 2010–2020	Long-term goals 2020–2030 and beyond
All technologies	**Availability**: No commercial systems applicable for power plants and most industrial applications available today. Retrofit of CCS technologies unproven. **Efficacy**: Industrial facilities will require new sources of heat and power for CCS applications. Collection systems for disparate sources on, for example, petroleum refineries and LNG production trains. Complex integration and cost issues. **Costs**: Capital cost of plant prohibitive for new developments. Efficiency penalty increases cost of production.	**Efficiency**: Reduce energy penalty through process design and heat optimisation. Increase operating temperatures and pressures in all boiler and turbine combinations. By 2015: Prove technologies at large power plant scale. Identify most effective options for industrial applications: • Identify optimised design to maximise heat and power use in cement kilns and blast furnaces. • Prove centralised heat and power systems with CCS for fuel transformation facilities. • Identify appropriate CCS options for biofuel refineries. **Costs**: Reduce capital costs by 10% to 12%.	**Efficiency**: By 2025: • Commercially available systems with >85% capture rate available for all fuel types. • All capture systems, all coals, all firing configurations 45%+, LHV, including CO_2 capture after 2030. By 2030: Commercial pulverized fuel ultra supercritical (USC) boilers operating >700/720°C and >35 megapascals (MPa). **Costs**: Reduce capital costs by an additional 10%.

CO_2 capture	Technology status in 2010	Near-term RDD&D needs 2010–2020	Long-term goals 2020–2030 and beyond
Post-combustion technologies:	**Availability**: Existing technologies with hundreds of plants in operation around the world in gas processing and chemicals industry. Largely unproven for large-scale flue gas mixtures. No warranties from vendors for large-scale combustion application. Technical challenges: • Scale and integration of complete systems for combustion gases. • Combustion gas stream composition and solvent. **Costs**: By 2020: • Reduce capital and operating costs by 10% to15%. Provide warranty.	**Availability**: Large-scale plants commercially available for new build and retrofit applications. Warranties offered on proven technologies by 2017. PF-USC plants at ~25 MPa and 600/620°C are commercially available. **Efficacy**: By 2015: • Prove at commercial scale (>40 MMscm or c.4.0 $MtCO_2$/yr in the case of a coal-fired plant). • Prove sustainable solvent usage rates (e.g., hindered amines). Manage corrosion issues. • Develop solvents with lower reactivation temperatures to reduce heat requirements for regeneration. Reduce energy penalty to <8%. • Demonstrate integrated systems with flue gas pre-treatments and availability >85%. **Costs**: By 2020: • Reduce capital costs by 10% to 15% for large-scale systems. • Reduce operating costs by 2% to 3%.	**Availability**: Widespread availability of commercial plant (new and retrofit) with warranties by 2025 for all coal types and CCGTs gas plants. CCS plants with high-efficiency PF-USC boilers operating at ~35 MPa and 700/720°C are commercially available. **Efficacy**: By 2030: • Prove innovative capture options – chemical looping tested for coal and gas.

CO_2 capture	Technology status in 2010	Near-term RDD&D needs 2010–2020	Long-term goals 2020–2030 and beyond
Pre-combustion technologies:	**Availability**: Several coal IGCC plants in operation around the world. Several demo projects under development. No integrated system with warranty available from vendors. **Technical challenges**: • Scale and integration for large IGCC plants. Unproven for high availability baseload power generation. **Costs**: High capital and operating costs. Lack of warranty for large plants with CCS.	**Availability**: Integrated IGCC CCS plants with high availability and high-efficiency turbines for H_2 combustion. **Efficacy**: By 2015: • Reduce steam requirements for shift conversion. Reduce energy penalty to 7% . By 2020: • Prove hydrogen combustion with high-efficiency CCGTs.	**Availability**: By 2025: • Demonstrate biomass IGCC with physical solvents. **Efficacy**: Reduce energy penalty to ~6%. • Emergence of commercial systems with gas separation membranes to replace shift converter. • Demonstrate novel methods including pressure swing adsorption, electrical swing adsorption and possibly cryogenics. **Costs**: Reduce capital costs to be competitive with conventional PF power generation.
Oxyfuel technologies	**Availability**: Trials of small-scale plants in progress in the power sector (<30 MW) under development. 250 MW plants proven in blast furnaces. **Technical challenges**: High capital and operating costs. Lack of warranty.	Rotary kiln for oxy-fuel for cement.	Commercial USC combustion operating 30MPa and temperatures of 600°C/620°C by 2025.

CO_2 transport

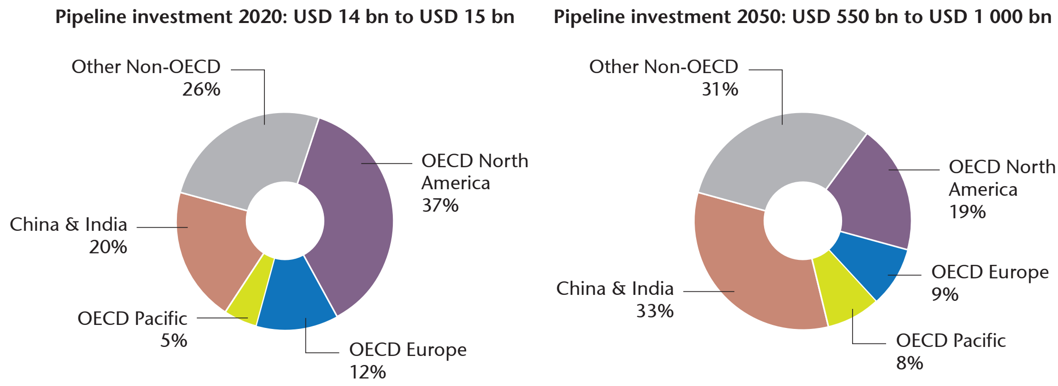
Achieving the BLUE Map scenario targets will necessitate transport of CO_2 from source to storage sites. The scale of CCS needed in the next 40 years means the main option for CO_2 transport is via pipelines.[9] However, a significant amount of additional work is needed to map out the way in which pipeline networks and common carriage systems will evolve over time, with a long-term view that takes into account expansion from demonstration to commercialisation. In many parts of the world, a storage exploration effort will be required before pipeline networks can be mapped beyond the concept stage. In addition, pipeline health and safety regulations are also needed to generate public confidence in the technology.

Given the uncertainties around where and how transport networks will evolve, it is difficult to make estimates regarding the overall levels of CO_2 pipeline development – and associated investment needs – with any degree of certainty. However, it is clear that particular focus will be required in those regions where the greatest capacity needs are located over the next 40 years; namely, the US, China and OECD Europe, which comprise nearly 50% of the global total CO_2 stored in 2050. In terms of transportation needs, the BLUE Map analysis shows that these three regions alone will, in 2050, require pipeline capacities able to handle daily mass flows of CO_2 of around 11.5 Mt to 14.5 Mt (Figure 15).

The roadmap makes a simple estimate for potential pipeline deployment, drawing on the average distance between CO_2 source and storage site and the level of optimisation achieved in developing a transport system. The results of the analysis in terms of pipeline construction requirements and total length are shown below (Figure 15). Between 70 000 km to 120 000 km and 200 000 km to 360 000 km of pipeline will be needed globally in 2030 and 2050, respectively. The US, China and OECD Europe regions comprise 33 000 km to 55 000 km and 80 000 km to 142 000 km for the same periods – 39% to 47% of total development. In the next ten years, around 10 000 km to 12 000 km of pipeline will be needed globally to transport 300 $MtCO_2$ from approximately 100 projects. Of this pipeline, about 6 000 km will be located in the US, China and OECD Europe. Total pipeline investment will be between approximately USD 0.55 trillion and USD 1 trillion through 2050, of which non-OECD regions will account for about 64%. In the near-term, this requirement will amount to around USD 15 bn in 2010 to 2020, of which OECD regions will account for over half.

9 As a short-term measure, ship and train transport present viable options, particularly for regions that have low prospective CO2 storage capabilities.

Figure 15: Global CO_2 pipeline development 2010-50



	Total CO_2 pipelines 2020	Total length in 2020 (km)	Total pipeline investment 2010-2020 (USD bn)	Total CO_2 pipelines 2050	Total length in 2050 (km)	Total pipeline investment 2010-2050 (USD bn)
OECD NA	25-30	2 800-3 500	5.5	250-450	38 000-65 000	160
OECD Europe	10-15	1 200-1 600	1.8	125-220	20 000-35 000	70
OECD Pacific	5-7	700-850	0.8	110-200	17 000-31 000	70
China & India	17-20	2 100-2 700	3.0	360-660	55 000-100 000	275
Other Non-OECD	20-25	3 900-3 700	3.8	460-840	70 000 -130 000	250
World	**77-97**	**10 700-12 350**	**14.9**	**1 305-2 370**	**200 00-361 000**	**825**

KEY POINT: *USD 15 billion may be required for CO_2 pipeline investment by 2020, half in OECD North America and Europe.*

To address the uncertainty around future pathways for CO_2 pipeline expansion, this roadmap has identified a list of specific action items. CO_2 transport costs need to be reduced through clustering sources and sinks; planning and developing pipeline networks similar to natural gas; and introducing new, lighter pipeline materials and advanced CO_2 compression technologies. Critical issues that must be addressed include managing different constituents in the CO_2 transport stream, leak remediation techniques, cross-border transport of CO_2 and ship transport of CO_2. Knowledge of potential leakage scenarios associated with CO_2 transport also needs to be improved and shared more effectively. Regulatory frameworks also need to be adapted based on early lessons learned in North America.

Actions and milestones

- Conduct analysis of source/sink distribution to identify clusters in OECD countries by 2012 and in non-OECD countries by 2015.
- Incentivise the linking of source and/or sinks through CO_2 transport hubs in OECD countries from 2012 to 2020 and in non-OECD countries from 2015 to 2025.
- Perform a country- or region-wide analysis of the optimal layout of a pipeline network connecting major sources with storage sites in OECD countries by 2012 and in non-OECD countries by 2015.
- Facilitate the phased roll-out of a pipeline network from 2012 to 2020 in OECD countries and 2015 to 2025 in non-OECD countries.
- Conduct studies on the design and cost of CO_2 transport via tankers between 2010 and 2015.
- Improve understanding and knowledge sharing of CO_2 transport leakage scenarios and the effects of impurities on CO_2 pipeline transport by 2015.

CO_2 storage

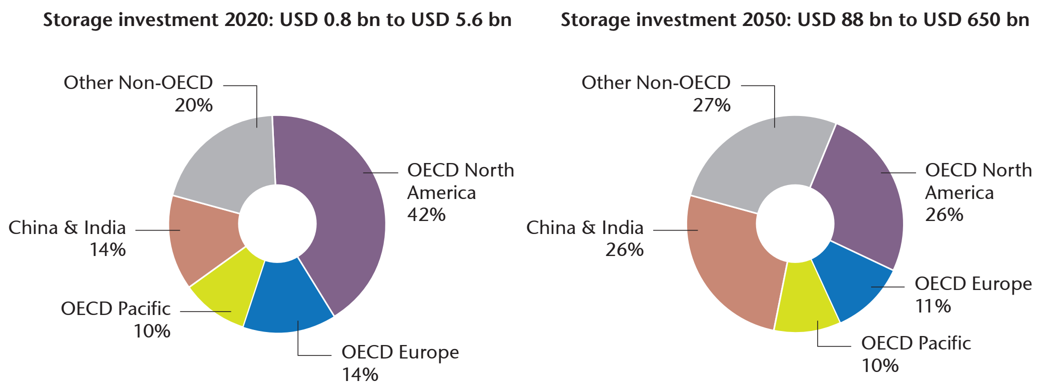
Deep saline formations are the most promising long-term CO_2 storage option (IPCC, 2005). However, the precise nature, scale, evolution and investment needs for CO_2 storage are not well understood. In particular, the capacity and injectivity of deep saline formations and the level of uptake for enhanced hydrocarbon recovery projects using CO_2 needs to be further studied, along with the capacity of different geological media to achieve long-term, secure storage.

There will need to be sufficient storage capacity to store over 1.2 $GtCO_2$ in 2020 and 145 $GtCO_2$ in 2050, as envisioned in the BLUE Map scenario. In theory, global storage capacity is more than sufficient to meet these requirements, with the latest basin-wide estimates running between 8 000 Gt and 15 000 Gt of storage (IEA, 2008b). However, there is significant uncertainty regarding estimates of viable capacity, particularly for deep saline formations. Further knowledge is needed from storage exploration, which will provide the data to locate and characterise prospective sites in order to assess security, injectivity, environmental and human health factors.

Similar uncertainty applies to the cost and investment needs for storage. Costs include site appraisal, well drilling and completion, facilities (e.g., compressors, platforms, etc.), site closure, and well plugging. In terms of operating costs, key factors include monitoring costs, costs for any insurance or indemnities and fuel cost. For a storage site receiving 5 $MtCO_2$ per year for 25 years, applying injectivity assumptions, the BLUE Map scenario analysis estimates that capital costs per tonne of CO_2 stored will range from USD 0.6 to USD 4.5. Global investment needs are found to range between USD 0.8 bn to USD 5.6 bn in 2020, and USD 88 bn to USD 650 bn in 2050 (Figure 16). These figures are highly uncertain and need to be refined based on data from a major expansion in storage exploration and from subsequent large-scale demonstration projects at a variety of storage sites in the next decade.

However, assuming that viable capacity were to represent just 10% of theoretical capacity, then less than 10% of world capacity would be utilised to meet the BLUE Map targets in 2050 (see Figure 16). Assuming capture and storage occurs predominantly within each region, some regions, such as the Middle East and Russia, will require a significantly smaller share of their total storage capacity than other regions, such as OECD Europe and India, from 2010 to 2050.

Figure 16: Global storage potential and investment by region



	Theoretical storage capacity ($GtCO_2$)	Total CO_2 stored 2020 (Mt)	Total storage investment 2010-2020 (USD bn)	Used storage where 10% of capacity is viable (%)	Total CO_2 stored 2050 (Mt)	Total storage investment 2010-2050 (USD bn)
OECD NA	2 170-4 650	520	0.3-2.3	8%	38 100	23-170
OECD Europe	120-940	170	0.1-0.8	17%	15 600	10-70
OECD Pacific	800-900	130	0.1-0.6	16%	14 300	8-65
China & India	1 520-3 020	170	0.1-0.8	12%	37 500	23-170
Other Non-OECD	3 480-5 990	250	0.2-1.1	7%	39 100	24-175
World	**8 090-15 500**	**1 240**	**0.8-5.6**	**9%**	**144 600**	**88-650**

***KEY POINT:** Less than 1% of theoretical storage capacity would be utilised to meet the BLUE Map scenario's storage requirements in 2050.*

In order to ensure the safety and security of large-scale CO_2 storage, this roadmap identifies a number of action items that need to be addressed. Storage-specific exploration is required to locate and characterise suitable, deep saline formations. To date there has been very little site-specific storage exploration undertaken, and there is clear need for both regional and site-specific exploration to establish viable storage resources. Additional needs include: improved CO_2 seismic modeling and monitoring techniques to enhance the ability to predict the fate of CO_2 in the subsurface and verify its location; greater knowledge about understanding of leakage, including detection, rectifying and accounting; a better understanding of the impacts of CO_2 storage on the subsurface, including on brine displacement; and more information about the effect of CO_2 impurities on the storage formation (CSLF, 2009; IEA, 2008c). In addition, best practice guidelines are also needed for well construction and completion, remediation, and risk assessment. These practices must be implemented via safety regulations for CO_2 storage.

Actions and milestones

- Agree on a common global methodology for CO_2 storage capacity estimation by 2010.
- Perform a comprehensive assessment of worldwide capacity for CO_2 storage by 2012.
- Review the key gaps in storage data coverage and knowledge in all of the emissions-intensive regions of the world to establish priorities for worldwide storage exploration and characterisation.
- Implement publicly funded, regional, pre-competitive exploration and evaluation programmes to fill the priority gaps identified in the worldwide review.
- Develop best practice guidelines for storage site selection, operation, risk assessment, monitoring, remediation and closure by 2012.
- Revise best practice guidelines, following testing by demonstration projects, by 2020.
- Develop safety regulations and criteria for CO_2 storage by 2012.
- Develop and improve tools for predicting spatial reservoir and cap rock characteristics between 2010 and 2020.

Additional Recommendations: Actions and Milestones

In addition to storage exploration and technology development, governments, industry and public stakeholders must address the additional challenges to achieving this roadmap's vision. These additional challenges include: financing near-term demonstration projects and incentivising longer-term commercialisation; establishing effective public regulatory schemes; engaging and educating the public adequately to incorporate their concerns into project designs; and using international collaboration to speed up the learning process and information sharing that needs to occur. This section establishes recommendations for each of these important areas and outlines and actions and milestones to achieve them.

Financing

This roadmap recommends the following:

1. OECD governments increase funding for CCS demonstration to achieve an average annual investment of USD 3.5 bn to USD 4 bn from 2010 to 2020.*
2. Establish incentives to accelerate commercial-scale CCS deployment beyond the demonstration phase.
3. Provide an average annual investment for CCS of USD 1.5 bn to USD 2.5 bn from 2010 to 2020 in non-OECD regions via the establishment of new financing strategies (e.g., approval of CCS in the Clean Development Mechanism or similar mechanism)

* The funding amounts in these recommendations refer to the additional investment required for CCS over the cost of a conventional non-CCS facility. See box, pp. 10-11.

Increase funding for CCS demonstration

Funding for near-term demonstration is required in order to continue to prove CCS at the commercial scale and to reduce costs. At current price levels, CO_2 markets and taxes will at most only provide up to half of the finances needed to cover the additional costs associated with CCS in OECD countries. Moreover, carbon markets do not provide a sufficiently stable mechanism to overcome the hurdles associated with large CCS investments. Governments will be required to address this gap, as without predictable market or regulatory drivers, it is unlikely the private sector will invest in CCS. Present CCS financing pledges from OECD governments are only about one-quarter to one-third of the additional investment needs envisaged for those regions over the next decade. Given the magnitude of investment needed and the global growth path for CCS, the private sector should be willing to take on additional risk for CCS. Governments can help facilitate private sector investments via public-private partnerships in CCS demonstration.

Actions and milestones

- Allocate between USD 3.5 bn to USD 4 bn investment per year between 2010 and 2020; funding should be provided to a portfolio of CCS projects across sectors, geologic media and capture technologies, and in all sectors.
- Form public-private partnerships that involve cost and risk-sharing between governments and the private sector for CCS demonstration.

Establish incentives to accelerate commercial-scale CCS deployment

A broad financing mechanism will be required for the commercial-scale deployment of CCS. Mechanisms will need to provide long-term certainty and/or a sufficiently high value for avoided CO_2 emissions. Without such a mechanism, CCS will not be deployed at the level required to meet the BLUE Map targets. There are a number of mechanisms that can be used to accelerate the commercialisation of CCS, including the provision of "bonus" allowances or contracts for additional carbon revenue related to CCS projects in cap-and-trade systems; mandating CCS via emissions performance standards or a similar mechanism; provision of tax credits or rebates for verified CO_2 storage; and the allowance of higher fuel or electricity costs to provide additional revenue for CCS investment.[10]

Actions and milestones

- Conduct national reviews of appropriate CCS financial incentive options by 2012; implement measures by 2015.
- Ensure that a CO_2 value commensurate with the additional costs imposed by operating CCS plants is in place for the period 2010 to 2020 and beyond.

Establish new financing strategies for non-OECD countries to invest in CCS

The BLUE Map scenario envisions a rapid growth of CCS in fossil-based non-OECD countries in the coming decades. Accordingly, governments need to consider ways in which they can work together to facilitate demonstration projects and technology transfer to these regions. In addition to demonstrating technology performance, these projects will help build local intellectual and technical capacity. The UK/EU-China Near-Zero Emissions Coal project is an example of the type of cooperation that is needed. Given their investment in developing country industrial and energy sectors, multilateral and bilateral financial and development institutions have an important role to play.

There are several examples of financial mechanisms that use public finance from developed countries to support climate change mitigation in developing countries, many of which are designed to leverage private investments. The newly created World Bank Climate Investment Funds, including the Clean Technology Fund[11] and the Global Environment Facility Trust Fund, rely on donor country pledges. Donor-supported funds may also become part of a post-2012 climate agreement that includes funding commitments from developed countries. These efforts will need to be supplemented by significant sources of bilateral funding.

In addition, there is a need to incentivise CCS in developing countries via carbon financing. The Clean Development Mechanism (CDM) under the Kyoto Protocol is currently the only mechanism that finances CO_2 reduction in developing countries. However, CCS does not currently qualify as a CDM project activity.[12] For the deployment of CCS in developing countries to achieve the levels envisioned in the BLUE Map scenario, CCS projects in these countries will need to be eligible for carbon market funding, either via inclusion in the CDM or through a new mechanism.

Actions and milestones

- Allocate between USD 1.5 bn to USD 2.5 bn additional CCS investment per year between 2010 and 2020 for developing country CCS demonstration (OECD and non-OECD governments).
- Assess existing multilateral and bilateral financial mechanisms, and identify and address gaps by 2010.
- Develop appropriate carbon finance mechanisms for developing country CCS projects by 2012.

10 These options and others are discussed in more detail in IEA, 2008b.

11 At present the CTF Trust Fund Committee does not provide for funding for CCS projects. However, the CTF eligibility criteria for greenfield fossil fuel power generation projects require the plants to be "CCS ready".

12 See IEA, 2008b for a full discussion of the status of CCS in the CDM.

Legal and regulatory

This roadmap recommends the following:

1. Review and adapt existing legal frameworks to regulate CCS demonstration projects by 2011 in OECD countries, 2013 in early-mover non-OECD countries, and 2015 in all non-OECD countries with CCS potential.
2. All countries with CCS activities review existing legal and regulatory frameworks for their ability to regulate CCS, identify barriers or gaps, and create a comprehensive CCS regulatory framework, if required, by 2020.
3. Address international legal issues, including development of an international monitoring and verification protocol for CO_2 storage and allowance of transboundary CO_2 transfer under the London Protocol by 2012.

Review and adapt existing legal frameworks to regulate CCS demonstration

Before CCS demonstration activity can commence in a region, an assessment of existing policy must be carried out. In most regions, there is existing legislation that covers part of the CCS chain; however, it is unlikely that all aspects of CCS regulation will be covered. Legislation that may govern CCS activities includes, but is not limited to: oil and gas legislation, mining legislation, waste legislation, health and safety legislation, property rights, transport legislation, groundwater legislation, and environmental impact assessment legislation.

The local community and other stakeholders will require the confidence that the demonstration projects are effectively regulated to ensure the safety and security of CO_2 transport and storage. Amending existing laws is likely to be the most effective way to facilitate demonstration projects. This may be done on a project-specific basis before broader amendments can be established. Amendments to existing laws may also provide a start for large-scale deployment of CCS in the future.

Actions and milestones

- Review and amend existing legal frameworks to regulate CCS demonstration projects by:
  - **2011 in OECD countries;**
  - **2015 in Non-OECD early mover countries;**
  - **2020 in non-OECD countries.**
- Consult appropriate stakeholders to gain a better understanding of how existing laws may be modified to accommodate CCS.

Develop comprehensive CCS regulatory frameworks

Following the amendment of existing laws to facilitate CCS demonstration, the effectiveness of the amendments should be reviewed. Reviews should assess whether the approach has effectively regulated public health and safety while ensuring that the time and effort required for approvals is non-restrictive. Governments should also assess whether any barriers or gaps in existing laws exist that should be addressed. If the amended policy is found to be inadequate, a more comprehensive CCS framework should be designed and implemented.

Actions and milestones

- Create comprehensive CCS regulatory frameworks for all countries by 2020.

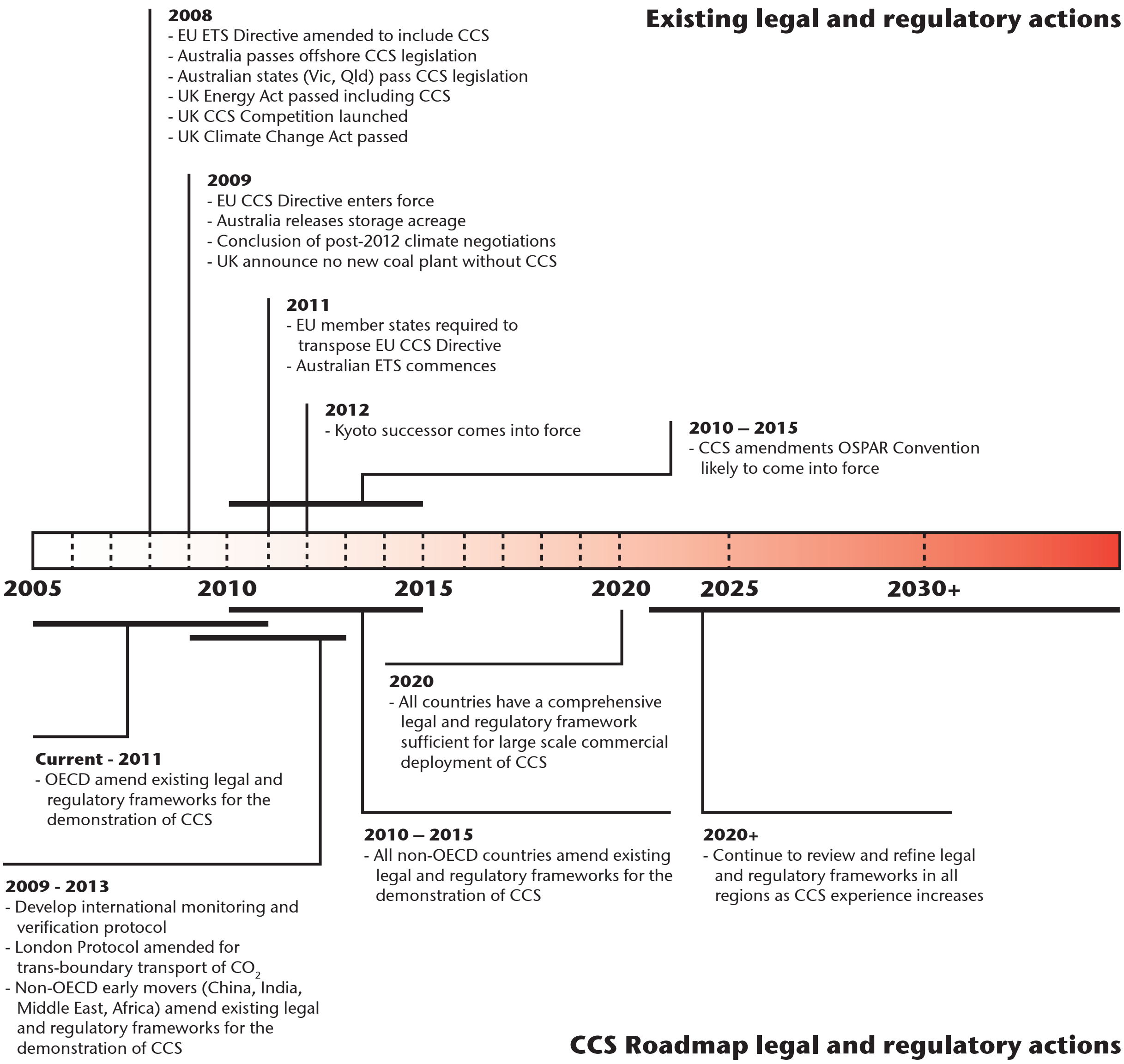
Address international legal issues

In parallel with the domestic actions outlined above, there is also a need to address outstanding international legal issues, such as the development of international protocols for monitoring and verification of CO_2 retention at storage sites, and the approval and enforcement of the 2006 IPCC *Inventory Guidelines*, which provide a methodology that could underpin international permitting and carbon financing or emissions trading for CCS projects. The London Protocol and related treaties should also address the transboundary transfer of CO_2 for the purpose of geological storage (and possible transboundary migration of CO_2).

Actions and milestones

- Develop a standard international approach for monitoring and verification (M&V) of CO_2 storage sites by 2012, using the IPCC *Inventory Guidelines* as a starting point
- Allow for transboundary transfer of CO_2 within international marine environment treaties by 2012.

Figure 17: CCS legal and regulatory timeline



Public education and engagement

This roadmap recommends the following:

1. Expand government education and engagement efforts; provide transparent information about planned CCS projects in a timely manner.
2. Formalise the existing international network of CCS public education and engagement professionals by 2010; use it to develop a CCS public engagement and communications toolkit by 2011.
3. Apply the toolkit to all large-scale CCS demonstration projects from 2010 to 2020 and revise as needed thereafter.

Expand government activities on CCS public outreach and engagement

Many governments have committed significant levels of funding for CCS demonstration in the next decade; more will be required to achieve this roadmap's vision. CCS involves a large, complex technology infrastructure, and injects CO_2 into geologic settings that may be located near communities. As a result, community residents have a legitimate concern about possible risks and impacts of CCS projects. To address these concerns and to support their CCS investments, governments need to prioritise public engagement and outreach efforts by providing adequate funding and by offering readily accessible information about planned projects to local communities. This information should convey the role of CCS within the larger set of GHG mitigation options, in order to build support for CCS at a national level. Regulations also need to require public consultation before planned project sites are chosen and as an ongoing activity. Regulators – including pipeline regulators, community safety officials and environmental impact assessment professionals – will require additional resources for training and to conduct public engagement activities that inform the public about the risks and mitigation plans for upcoming projects.

Actions and milestones

- Provide enhanced funding for governmental education and outreach programmes on CCS.
- Develop regulations that include requirements for public consultation at planned projects early in the project cycle and on an ongoing basis.
- Provide regular, transparent information to the public on planned CCS projects.
- Develop guidelines for regulators to conduct local public consultation and education activities regarding the risks and benefits of planned CCS projects.

Formalise international public engagement networks and create a public education and engagement toolkit

There is currently an informal international network of CCS public engagement, communication and outreach experts that meets on an ad-hoc basis. This network is in the process of becoming a formal Social Research Network of the IEA's GHG Implementing Agreement, which begins to address the need for more formal, widespread global interaction on CCS outreach. An increasing amount of information and lessons learned are being generated from CCS public engagement and education efforts; these emerging best practices should be collected together into a common platform that guides future CCS projects. This "toolkit" will need to be used as early as possible during the design stage, in order to avoid late-stage stakeholder protests and to inform the development of a risk communication strategy. Early large-scale demonstrations will be test-beds for the selection and configuration of the toolkit components. These demonstrations will help explore the adequacy of different communication methods and will aid in developing suitable guidelines for different contexts, since much of the difficulty lies in the site-specific nature of each CCS project's geologic and community setting. The toolkit also requires special sections for developing country engagement, as these regions hold a different set of challenges.

Following the demonstration phase, the most appropriate methods from the toolkit can be adopted for use with the later-stage development. The methods will need to be fine-tuned so that required public engagement resources can be used more efficiently. The toolkit should also include information that places CCS in the context of other GHG mitigation options, emphasizing the role that different options have to play, and should contrast the risks of using CCS to the climate change risks associated with not using it. Risk communications should be done at a level anyone can understand; for example, using graphics and comparisons to well-understood phenomena.

Actions and milestones

- Develop an international CCS public engagement toolkit defining common principles and strategies for public engagement; share the toolkit with CCS project proponents, governments, NGOs and community groups.
- Apply the toolkit to the first set of large-scale CCS projects and share the results widely; also, document the number of projects that have used the toolkit for public engagement and consultation.

International collaboration

This roadmap recommends the following:

1. Grow CCS collaborative efforts, particularly related to RD&D, and create common structures and links by 2010.
2. Create regional collaborative efforts to identify regional CO_2 storage and transport planning needs.
3. Expand capacity-building efforts in targeted developing economies with large fossil fuel use, such as the development of national CCS roadmaps for Brazil, China, India, South Africa and other key countries from 2010 to 2015.
4. Create new CCS collaborative efforts for the most important industrial sectors by 2012.

Grow existing international collaboration efforts

Technology collaboration enables the sharing of risks, rewards and progress of technology development and the coordination of priorities. In order to achieve this roadmap, it is clear that CCS will need to be rapidly developed in all major fossil-based economies. The analysis above indicates that while CCS will begin to be demonstrated in a handful of countries, by the end of the next decade, projects will become more equally distributed throughout the world. This scale of technology diffusion necessitates a major international collaboration effort to expand CCS RDD&D investment and to improve the effectiveness of technology transfer, including addressing intellectual property rights protection issues. These efforts will require the strengthening of existing institutions and activities, as well as the creation of new joint RDD&D initiatives. Developing countries must be particularly targeted for engagement due to the expected number of projects in these regions, as well as their reduced ability to pay for CCS; they will clearly require much higher levels of CCS funding and policy development assistance.

There is an urgent need to develop dozens of commercial-scale demonstration projects and share the results among project developers and government regulators. This effort includes monitoring data, regulatory approaches, financial mechanisms, public engagement experiences and other aspects of project development. The new Global CCS Institute has been created to address this need and will serve an important role as platform and forum for the sharing of early project results. The GCCSI, CSLF and IEA GHG will need to grow their memberships to address future CCS needs, ensuring representation from all major fossil-based economies and all major industry sectors. In addition, the IEA, CSLF and GCCSI will need to build on and strengthen their collaboration as they monitor the implementation of the actions and milestones included in this roadmap.

Actions and milestones

- Enhance international collaboration on CCS RDD&D.
- Expand membership in GCCSI, CSLF and IEA GHG.
- Monitor the implementation of the CCS Roadmap milestones and recommendations.

Create regional coordination groups to address CO_2 transport and storage planning

CCS projects will be large in terms of investment and geographical footprint, with pipelines and storage sites that are often transboundary in nature. As a result, there will be a need to develop common regulatory approaches for project permitting, pipeline safety standards and many other aspects. There is also much to be gained from taking a regional approach to CO_2 pipeline and storage network infrastructure planning and investment. The North Sea Basin Task Force was created in 2005 by the Norwegian and United Kingdom authorities with the mandate to develop broad, common principles that could form a basis for regulating the storage of CO_2 in the North Sea and to provide a consistent basis for managing this activity. This is one model that will need to be replicated in many other regions with high CO_2 storage prospectivity, as countries work together to develop common regulatory and infrastructure approaches. This network of regional entities can then share findings globally to accelerate learning.

Actions and milestones

- Identify regions in need of greater cooperation on CO_2 transport and storage infrastructure expansion and regulation by 2012.
- Create new institutions or mechanisms for regional cooperation by 2014.
- Link regional efforts to global efforts to ensure a harmonisation of approaches by 2020.

Expand capacity-building efforts in developing countries with large fossil fuel use

It is clear that CCS will need to be demonstrated and deployed in all major fossil-based economies. However, developing countries lack the resources and technology and regulatory capacity to adequately invest in CCS today. Some countries have already started to develop early CO_2 capture and CCS demonstration activities (see box) and some of these efforts include international collaboration. However, other countries need to be more actively engaged, through information-sharing efforts about the importance of CCS as well as the possible development of country-specific CCS roadmaps that are tailored to the country's unique needs. These roadmaps could identify the barriers to wider technology deployment and the means to overcome them, including regulation and policy, tariffs and non-tariff barriers, finance, and intellectual property. These efforts can use existing platforms, such as the GCCSI and the CSLF capacity building efforts, to share lessons learned and experiences.

Actions and milestones

- Identify priority countries for CCS implementation and assess current state of development by 2011.
- Develop national roadmaps for the priority countries by 2013.
- Build CCS technology development institutions at regional and national levels.
- Link developing country efforts via the CSLF and GCCSI to share lessons learned.

Create new CCS collaboration efforts for the most important industrial sectors

In the BLUE Map analysis, the industrial and fuel transformation sectors will capture nearly one-half of the CO_2 globally at CCS facilities worldwide by 2050 (IEA, 2009). Since these sectors are international in scope, they lend themselves well to sector collaboration on CCS. The World Business Council on Sustainable Development (WBCSD) has started the Cement Sustainability Initiative, and has begun to explore the role of CCS in the global cement industry. In fact, the WBCSD and the IEA are jointly publishing a cement industry roadmap that identifies CCS as one of four key strategies the industry will need to develop in order to mitigate its CO_2 emissions in the future. Similarly, the iron and steel sector in Europe has joined with European governments to form the Ultra Low-CO_2 Steel (ULCOS) cooperative research and development initiative, which has identified CCS as a key mitigation technology. These efforts should be expanded globally; other high-CO_2 emitting industry sectors are encouraged to follow these examples.

Actions and milestones

- By 2012, develop CCS workgroups in all sectors with CCS potential; these workgroups should develop research, development, demonstration and deployment goals.
- Identify regulatory and financial support for industrial sector CCS efforts.
- Monitor CCS RDD&D efforts in targeted sectors and address gaps.

CCS activities in key emerging economies

As part of the efforts to develop the CCS Roadmap, the IEA organised a series of CCS roundtables in key emerging economies, including China, Poland and Brazil. These roundtables explored country-specific CCS technology, regulatory, financing and public engagement efforts, with the aim of improving global understanding of the specific needs of emerging fossil-based economies. For more information, visit http://www.iea.org/Textbase/subjectqueries/ccs/ccs_roundtables.asp.

China – The Chinese government and industry are actively working with a variety of international agencies, bilateral partners and international companies to develop CCS demonstration projects. For example, the GreenGen project envisions an IGCC plant with CCS, and the Near-Zero Emission Coal (NZEC) partnership between China, the European Commission and the United Kingdom has a goal of developing a coal-fired power plant with CCS by 2020. Additionally, the China Huaneng Group has launched a post-combustion carbon capture project (without storage) at a commercial coal-fired power plant. Pilot CO_2 geologic storage projects are also underway. China is currently seeking collaboration in a variety of areas, including technology development, improving assessments of CO_2 storage capacity and developing regulatory approvals for early demonstration.

Poland – The Polish government is actively moving forward with CCS demonstration and the development of regulatory frameworks. The Belchatow and Kedzierzyn projects are large-scale integrated projects designed to become operational by 2015. The government is aiming to put a regulatory framework in place by 2011; this will be informed by the Polish Ministry of Environment's four-year assessment project on CO_2 storage prospectivity. Poland is seeking financing for these two projects via the European Union's Economic Recovery Package. It also seeks to expand public engagement and education about CCS, and seeks to learn from other countries' experiences.

Brazil – Brazil is taking an active role in CCS RDD&D with Petrobras, the national oil and gas company, by operating two CO_2 storage pilot projects. One of the projects injects 400 t CO_2/day into a saline formation – one of the largest CO_2 demonstration projects in the world. In 2006, Brazil also saw the creation of a new CO_2 storage consortium called CEPAC. However, CCS regulatory framework is not yet fully developed in Brazil, which could delay CCS deployment in the country.

Conclusion: Near-term actions for stakeholders

This roadmap has responded to the G8 and other government leaders' requests for more detailed analysis regarding the growth pathway for CCS, a key GHG mitigation strategy. It describes the current context regarding CCS RDD&D; financing; development of legal and regulatory frameworks; public engagement; and international collaboration. It provides regional and sector projections for CCS deployment from 2010 to 2050, in an effort to guide ongoing CCS development. Finally, this roadmap details actions and milestones to aid policy makers, industry and public stakeholders in their efforts to successfully use CCS as a GHG mitigation technology. Appendix I. identifies near-term priority actions for the full set of stakeholders that will need to take action to achieve the vision of this roadmap.

The CCS Roadmap is meant to be a process, one that evolves to take into account new developments from demonstration projects, policies and international collaborative efforts. The roadmap has been designed with milestones that the international community can use to ensure that CCS development efforts are on track to achieve the GHG emissions reductions that are required by 2050. As such, the IEA, together with government, industry and NGO stakeholders, as well as the CSLF and the GCCSI, will report regularly on the progress that has been achieved toward this roadmap's vision. For more information about the CCS Roadmap inputs and implementation, including additional analysis that informed the conclusions in this document, visit www.iea.org/roadmaps/index.asp.

Near-term actions for stakeholders

Stakeholder	Action Items
Finance ministries	• Provide funding for near-term demonstrations via fiscal incentives, financial rescue packages, other mechanisms. • Fund longer-term CCS R&D. • Finance CO_2 transport infrastructure.
Environmental Ministries	• Permit early demonstration projects while developing longer-term comprehensive frameworks. • Develop comprehensive CO_2 transport and storage permit frameworks, including environmental impact assessments, risk assessment and remediation processes, and public engagement and communication protocols. • Cooperate internationally to harmonise CO_2 storage monitoring and verification (M&V) methods. • Support CCS in UN FCCC framework; adopt 2006 IPCC Guidelines and recognise CCS in the CDM or alternative framework. • Incentivise CCS commercialisation via, e.g., bonus allowances in cap-and-trade schemes, emissions performance standards, carbon taxes, or a combination of these approaches. • Develop CCS educational/outreach programmes on environmental aspects of CCS.

Stakeholder	Action Items
Energy/Resource Ministries	• Establish CO_2 transport, storage property rights/access rights. • Establish pre-competitive regional storage exploration programmes, and policies to encourage competitive storage exploration. • Develop national CO_2 storage capacity estimates using approved methodologies and share this information widely. • Expand the number of geologists who are trained in CO_2 storage site assessment. • Fund RD&D programmes to target gaps in knowledge on different aspects of CCS technology development. • Ensure the provision of regular, transparent data from early projects. • Establish CCS outreach/education programmes for the general public.
Training/Science Ministries Universities	• Identify CCS educational development/training needs for important areas like geologic assessment; develop training plans/grants for universities. • Develop a national CCS technology RD&D roadmap that identifies pathways to achieve the longer-term technology breakthroughs that are needed.
International Development Ministries Multilateral Development Agencies	• Provide aid for CCS capacity building in fossil-based developing economies; including CO_2 storage prospectivity studies, CO_2 capture demonstrations, CO_2 pipeline planning models, etc. • Ensure maximum efficacy of international CCS aid in specific regions by coordinating with other donors (multilateral and bilateral).
CO_2 Pipeline Transport Regulators	• Establish health and safety regulations. • Develop long-term regional CO_2 pipeline infrastructure plans. • Develop educations/outreach programmes on CO_2 pipeline transport safety issues.
Industry	• Take more risk in funding near-term demonstration projects. • Develop international sector-specific CCS workgroups to address CO_2 capture and CCS generally. • Share demonstration project data more widely – transparent data will improve public confidence. • Ensure adequate public engagement is included in all CCS projects.
State, Provincial and Local Governments	• Take leading roles in CO_2 transport and storage planning, regional cooperation. • Local emergency resonse officials are key spokespeople; ensure that these figures have an adequate role in public engagement and communication processes.
Non-Governmental Organisations	• Use your role as a trusted public spokesperson to communicating the role of CCS in climate change mitigation. • Help monitor progress toward public engagement, CCS development milestones and publish results regularly to keep government and industry on track.

Appendix I. References

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Appendix II. Relevant Websites

International Energy Agency	www.iea.org
International Energy Agency – CCS page	www.iea.org/Textbase/subjectqueries/cdcs.asp
IEA Implementing Agreement – Greenhouse Gas R&D Programme (IEA GHG)	www.ieagreen.org.uk
IEA GHG CCS project website	www.co2captureandstorage.info
IEA Implementing Agreement – Clean Coal Centre	www.iea-coal.org.uk
IEA Coal Industry Advisory Board	www.iea.org/ciab
IEA Working Party on Fossil Fuels	www.iea.org/about/wpff.asp
Carbon Sequestration Leadership Forum	www.cslforum.org
CO_2CRC	www.co2crc.com.au
Global CCS Institute	www.globalccsinstitute.com
International Performance Assessment Centre for CCS	www.ipac-co2.com/
World Resources Institute	http://www.wri.org/project/carbon-capture-sequestration
Intergovernmental Panel on Climate Change (IPCC) – 2006 *Guidelines for GHG Inventories*	www.ipcc-nggip.iges.or.jp/public/2006gl/index.html
IPCC – CCS under the CDM	http://cdm.unfccc.int/about/ccs/index.html
London Protocol Webpage	www.imo.org/home.asp?topic_id=1488
Massachusetts Institute of Technology	http://sequestration.mit.edu/index.html
United Nations Framework Convention on Climate Change	http://unfccc.int
OSPAR Convention	www.ospar.org
Zero Emissions Platform	www.zeroemissionsplatform.eu
EU-China NZEC	www.nzec.info/en
FutureGen Alliance	www.futuregenalliance.org
North American CCS Association	http://naccsa.org
UK CCS Association	www.ccsassociation.org.uk
United States Department of Energy	https://carbonsequestration.us/
European Union CCS Directive	http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF

United States Department of Energy -National Energy Technology Laboratory	http://www.netl.doe.gov/technologies/carbon_seq/index.html
United States – CCS Regional Partnerships	http://fossil.energy.gov/sequestration/partnerships/index.html
United Kingdom – Department of Energy and Climate Change's CCS pages	www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/ccs/ccs.aspx
University College London – Carbon Capture Legal Programme	www.ucl.ac.uk/cclp
WBCSD Cement Sustainability Initiative	www.wbcsdcement.org
World Resources Institute	www.wri.org
North Sea Basin Task Force	http://www.nsbtf.org/
IZ Klima – Informationszentrum klimafreundliches Kohlekraftwerk e.V. (Information Centre for Climate-friendly Coal-Fired Power Plants)	www.iz-klima.de
Ultra-Low CO_2 Steel Cooperative	http://www.ulcos.org/en/index.php.
Australia – CCS roadmap (2004)	https://extra.co2crc.com.au/modules/pts2/download.php?file_id=593&rec_id=90
Canada – CCS roadmap (2006)	http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/fichier/78812/ccstrm_e_lowres.pdf
United States – CCS roadmap (2007)	http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2007/2007Roadmap.pdf
United Kingdom – CCS roadmap (2007)	http://www.geos.ed.ac.uk/research/subsurface/diagenesis/CCS_road_map_workshop_-_final_UKERC_4Sept07_copy.pdf
	http://www.berr.gov.uk/files/file50470.pdf
Bellona Foundation	http://www.bellona.org/ccs/index_html
Climate Action Network Europe	http://climnet.org/EUenergy/CCS/index.htm
Greenpeace	http://www.greenpeace.org/international/press/reports/CCS-briefing
Natural Resources Defense Council	http://www.nrdc.org/globalWarming/glo_07030601.asp
Pew Center on Global Climate Change	http://www.pewclimate.org/technology-solutions
CO2GeoNet	http://www.co2geonet.com/

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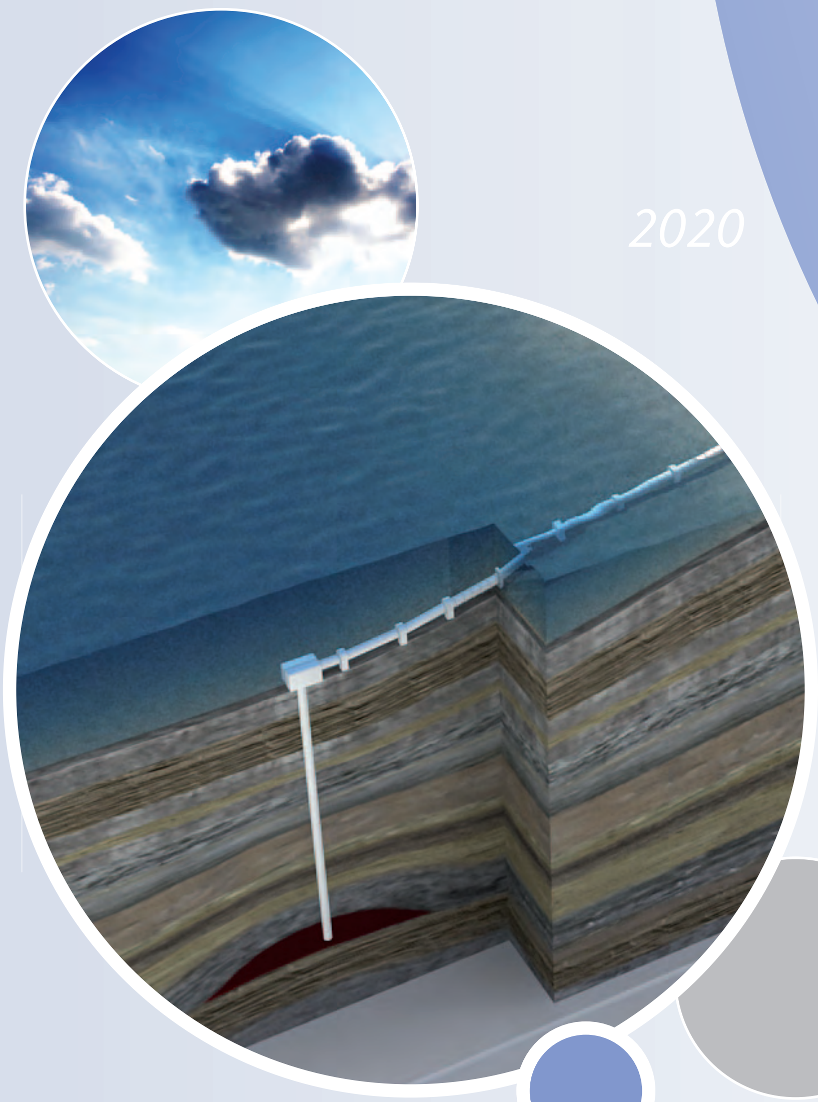

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