Technology Roadmap

Carbon capture and storage

2013 edition

International Energy Agency

Technology Roadmap Carbon capture and storage - 2013 edition

2013

2015

2020

2025

2030

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Foreword

As long as fossil fuels and carbon-intensive industries play dominant roles in our economies, carbon capture and storage (CCS) will remain a critical greenhouse gas reduction solution. With coal and other fossil fuels remaining dominant in the fuel mix, there is no climate friendly scenario in the long run without CCS. CCS has so far been developing at a slow pace despite some technological progress, and urgent action is now needed to accelerate its deployment.

It is clear that the world needs to dramatically reduce its energy-related CO_2 emissions in the coming decades. This will require massive deployment of various clean energy technologies, including renewable energy, nuclear energy, cleaner transport technologies, energy efficiency, and carbon capture and storage. Indeed, CCS must be firmly placed in this wider energy context. As we develop and deploy CCS, we should also strive to minimise the amounts of CO_2 resulting from fossil fuel use by building and operating most efficient power stations and industrial facilities. For the IEA, CCS is not a "silver bullet" by itself, but a necessary part of a coherent portfolio of energy solutions that can reinforce one another.

After many years of research, development, and valuable but rather limited practical experience, we now need to shift to a higher gear in developing CCS into a true energy option, to be deployed in large scale. It is not enough to only see CCS in long-term energy scenarios as a solution that happens some time in a distant future. Instead, we must get to its true development right here and now.

This Roadmap is an update of the 2009 IEA *CCS Technology Roadmap*. The energy landscape has shifted between 2009 and 2013 and new insights into the challenges and needs of CCS have been learned. This CCS roadmap aims at assisting governments and industry in integrating CCS in their emissions reduction strategies and in creating the conditions for scaled-up deployment of all three components of the CCS chain: CO_2 capture, transport and storage. To get us onto the right pathway, this roadmap highlights seven key actions needed in the next seven years to create a solid foundation for deployment of CCS starting by 2020. These near-term actions are directly relevant for government and industry decision-makers today. Perhaps the most critical task is to create business cases for the uptake of CCS. This will require decisive action from governments, but also continued engagement of the industry in a long term perspective.

It is critical that governments, industry, the research community and financiers work together to ensure the broad introduction of CCS by 2020, making it part of a sustainable future that takes economic development, energy security and environmental concerns into account. As we are all important stakeholders in this effort, we should join this journey and make it a success.

This publication is produced under my authority as Executive Director of the IEA.

Maria van der Hoeven
Executive Director
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Key findings and actions

What have we found?

- Carbon capture and storage (CCS) will be a critical component in a portfolio of low-carbon energy technologies if governments undertake ambitious measures to combat climate change. Given current trends of increasing global energy sector carbon dioxide (CO_2) emissions and the dominant role that fossil fuels continue to play in primary energy consumption, the urgency of CCS deployment is only increasing. Under the International Energy Agency (IEA) *Energy Technology Perspectives 2012 (ETP 2012)* 2 °C Scenario (2DS)[1], CCS contributes one-sixth of CO_2 emission reductions required in 2050, and 14% of the cumulative emissions reductions between 2015 and 2050 compared to a business-as-usual approach, which would correspond to a 6 °C rise in average global temperature.

- The individual component technologies required for capture, transport and storage are generally well understood and, in some cases, technologically mature. For example, capture of CO_2 from natural gas sweetening and hydrogen production is technically mature and commercially practiced, as is transport of CO_2 by pipelines. While safe and effective storage of CO_2 has been demonstrated, there are still many lessons to gain from large-scale projects, and more effort is needed to identify viable storage sites. However, the largest challenge for CCS deployment is the integration of component technologies into large-scale demonstration projects. Lack of understanding and acceptance of the technology by the public, as well as some energy and climate stakeholders, also contributes to delays and difficulties in deployment.

- Governments and industry must ensure that the incentive and regulatory frameworks are in place to deliver upwards of 30 operating CCS projects by 2020 across a range of processes and industrial sectors. This would be equivalent to all projects in advanced stages of planning today reaching operation by that time. Co-operation among governments should be encouraged to ensure that the global distribution of projects covers the full spectrum of CCS applications, and mechanisms should be established to facilitate knowledge sharing from early CCS projects.

- CCS is not only about electricity generation. Almost half (45%) of the CO_2 captured between 2015 and 2050 in the 2DS is from industrial applications. In this scenario, between 25% and 40% of the global production of steel, cement and chemicals must be equipped with CCS by 2050. Achieving this level of deployment in industrial applications will require capture technologies to be demonstrated by 2020, particularly for iron and steelmaking, as well as cement production.

- Given their rapid growth in energy demand, the largest deployment of CCS will need to occur in non-Organisation for Economic Co-operation and Development (OECD) countries. By 2050, non-OECD countries will need to account for 70% of the total cumulative mass of captured CO_2, with China alone accounting for one-third of the global total of captured CO_2 between 2015 and 2050. OECD governments and multilateral development banks must work together with non-OECD countries to ensure that support mechanisms are established to drive deployment of CCS in non-OECD countries in the coming decades.

- This decade is critical for moving deployment of CCS beyond the demonstration phase in accordance with the 2DS. Mobilising the large amounts of financial resources necessary will depend on the development of strong business models for CCS, which are so far lacking. Urgent action is required from industry and governments to develop such models and to implement incentive frameworks that can help them to drive cost-effective CCS deployment. Moreover, planning and actions which take future demand into account are needed to encourage development of CO_2 storage and transport infrastructure.

1. The 2DS describes how technologies across all energy sectors may be transformed by 2050 for an 80% chance of limiting average global temperature increase to 2 °C.

What we need to do: seven key actions for the next seven years

The next seven years are critical to the accelerated development of CCS, which is necessary to achieve low-carbon stabilisation goals (*i.e.* limiting long-term global average temperature increase to 2 °C). The seven key actions below are necessary up to 2020 to lay the foundation for scaled-up CCS deployment. They require serious dedication by governments and industry, but are realistic and cover all three elements of the CCS process.

- Introduce financial support mechanisms for demonstration and early deployment of CCS to drive private financing of projects.
- Implement policies that encourage storage exploration, characterisation and development for CCS projects.
- Develop national laws and regulations as well as provisions for multilateral finance that effectively require new-build, base-load, fossil-fuel power generation capacity to be CCS-ready.
- Prove capture systems at pilot scale in industrial applications where CO_2 capture has not yet been demonstrated.
- Significantly increase efforts to improve understanding among the public and stakeholders of CCS technology and the importance of its deployment.
- Reduce the cost of electricity from power plants equipped with capture through continued technology development and use of highest possible efficiency power generation cycles.
- Encourage efficient development of CO_2 transport infrastructure by anticipating locations of future demand centres and future volumes of CO_2.

Introduction

Between 2009 when the first IEA *Carbon Capture and Storage (CCS)* roadmap was published, and 2013, the need for CCS has not diminished: the urgency of its deployment has in fact grown. There have been many developments and significant gains in CCS technology and the enabling policy frameworks. However, given today's level of fossil fuel utilisation, and that a carbon price as a key driver for CCS remains missing, the deployment of CCS is running far below the trajectory required to limit long-term global average temperature increases to 2 °C.

Purpose for the roadmap

The goal of this updated CCS roadmap is to describe and analyse actions needed to accelerate CCS deployment to levels that would allow it to fulfil its CO_2 emissions reduction potential. The IEA is revising the 2009 roadmap to reflect developments in CCS that have occurred over the last four years and to develop a plan of action that fully reflects the current context.

This roadmap provides a brief status report on CCS technologies, outlines a vision for CCS deployment between 2013 and 2050 consistent with limiting the average global temperature increase to 2 °C, and suggests actions that need to be taken to facilitate this envisaged deployment, particularly between 2013 and 2020. We believe that the recommended near-term actions are of vital importance to the deployment of CCS not only to limit average global temperature increase to 2 °C, but for any scenario designed to achieve stabilisation of global temperature changes at 4 °C or below.

Rationale for CCS: CCS remains critically important

Global energy-related CO_2 emissions continue to rise. In 2011 they increased by 3.2% from 2010, reaching a record high of 31.2 gigatonnes (Gt) (IEA, 2012a). If this trend continues, it will put emissions on a trajectory corresponding to an average global temperature increase of around 6 °C in the long term (IEA, 2012a). The greater the emissions of greenhouse gases (GHGs), such as CO_2, the greater the warming and severity of the associated consequences. These consequences include a rise in sea levels, causing dislocation of human settlements, as well as extreme weather events, including a higher incidence of heat waves, destructive storms, and changes to rainfall patterns, resulting in droughts and floods affecting food production, human disease and mortality (IPCC, 2007).

Box 1: IEA technology roadmaps

The IEA technology roadmaps identify priority actions for governments, industry, financial partners and civil society that will advance technology development and uptake based on the *ETP* 2DS (the current one being *ETP 2012* [IEA, 2012c]). Roadmaps are important strategic planning tools for governments and industry to address future challenges, including energy security and climate change. The IEA low-carbon energy technology roadmaps seek to create an international consensus about priority actions and milestones that must be reached to achieve a technology's full potential. These IEA Technology Roadmaps cover a wide spectrum of technologies, including various renewable energy technologies; nuclear power; energy efficiency in buildings; the cement sector; high-efficiency, low-emissions (HELE) coal power; CCS and others.

Low-carbon energy technology roadmaps have a number of key commonalities. These include their elaboration of a vision for deployment of the technology and its CO_2, abatement potential relative to an identified baseline. Milestones for technology development are outlined, and the corresponding actions for areas such as policy, financing, research, public outreach and engagement, and international collaboration are described. Given the expected growth in energy use and related emissions outside of IEA member countries, the roadmaps also consider the role of technology development and diffusion in emerging economies. The roadmaps are designed to facilitate greater collaboration among governments, business and civil society in both industrialised and developing countries.

To significantly reduce energy-related CO_2 emissions, massive deployment of many different low-carbon energy technologies is required. This includes efforts to increase energy efficiency in power and industrial production, and on the demand side. A broad portfolio of renewable energy, nuclear power and new transport technologies are also critical in reducing the carbon footprints of our societies. While not a "silver bullet" in itself, CCS must be a key part of this portfolio of technologies.

Coal continues to be the largest incremental source of global primary energy consumption. Over the last decade, coal has been the fastest growing source of primary energy, with incremental consumption over 50% higher than the incremental demand for oil and gas combined. In 2011, coal demand grew by 4.3% from 7 080 megatonnes (Mt) in 2010 to 7 384 Mt in 2011, with most of this growth arising in non-OECD countries, particularly China and India (IEA, 2012b). This continued expansion of coal and other fossil fuels, despite strong advances in clean energy technologies worldwide, has meant that the CO_2 emissions intensity of the global energy supply has been stable but overall energy-related emissions have grown (IEA, 2013a). Thus, it is clear that in spite of rapidly increasing shares of non-fossil energy sources, coal and other fossil fuels will inevitably play a role for many decades to come. CCS offers a solution for dealing with emissions from fossil fuel use.

Governments and private entities around the world have proven reserves of coal, oil, and gas that, if combusted, would release approximately 2 860 gigatonnes of carbon dioxide ($GtCO_2$) (IEA, 2012a). If the world is to have a reasonable chance of limiting the global average temperature increase to 2 °C, a *cumulative* total of 884 $GtCO_2$ can be emitted from energy use between 2012 and 2050. This means that less than one-third of proven reserves of fossil fuels can be consumed prior to 2050, unless CCS technology is widely deployed (IEA, 2012a). Not only does CCS serve our climate objectives, but investing in development and deployment of CCS is an important risk management ("hedging") response for companies and governments who derive significant income from fossil fuels. CCS therefore promises to preserve the economic value of fossil fuel reserves and the associated infrastructure in a world undertaking the strong actions necessary to mitigate climate change (IEA, 2012a).

CCS also has strategic value because it can delay the retirement of valuable production and conversion assets in a CO_2 emissions-restricted world. CO_2 emissions from infrastructure in operation or under construction in 2011 (*e.g.* power plants, industrial facilities, even transportation fuel manufacturing) will total approximately 550 $GtCO_2$ through 2035, much of the emissions budget mentioned above. Retrofitting these applications with CCS will help prevent the "lock-in" of emissions from this infrastructure.

CCS is also a low-cost emissions reduction option for the electricity sector. If CCS is removed from the list of emissions reduction options in the electricity sector, the capital investment needed to meet the same emissions constraint is increased by 40% (IEA, 2012c). It is clear that CCS is the only technology available today that has the potential to protect the climate while preserving the value of fossil fuel reserves and existing infrastructure.

What is more, CCS is currently the only large-scale mitigation option available to make deep reductions in the emissions from industrial sectors such as cement, iron and steel, chemicals and refining. Today, these emissions represent one-fifth of total global CO_2 emissions, and the amount of CO_2 they produce is likely to grow over the coming decades. Further energy efficiency improvements in these sectors, while urgently needed, have limited potential to reduce CO_2 emissions, partly due to the non-energy-related emissions from many industrial processes. Failure to utilise CCS technology in industrial applications poses a significant threat to the world's capacity to tackle climate change (IEA, 2013b).

Some societies may have preferences for other low-carbon energy sources, such as prioritising renewable energy. However, this choice is not always cost effective, and in some cases, unavailable – notably – in industrial applications where fossil fuels are currently an intrinsic part of production processes. Improvements in energy efficiency will also affect CCS in one way or another. For example, the enhanced efficiency of power generation will reduce the impact of the energy penalty of CCS in the power sector (by lowering the levelised cost of energy) and improve its economics (IEA,2012f). Given the magnitude of required GHG emission reductions globally, it is important to understand that CCS is not wholly interchangeable with other climate mitigation options. All low carbon technologies – such as various forms of renewable energy, high efficiency coal power generation, improved efficiency at industrial facilities, demand side energy efficiency measures and new transport technologies – will play a role in required emission reductions. The role of each of these technologies will be defined by their characteristics and limitations. Their performance in addressing CO_2 emissions may influence the level of challenge for CCS in the long term.

CCS developments since the previous roadmap

Since the first IEA CCS roadmap, CCS technology and supporting policies have progressed, albeit at a slower pace than expected. Among developments in CCS between 2009 and 2013 are: increased experience and confidence with CO_2 capture technologies; increased understanding of the factors affecting the cost of storage; considerable progress in understanding the sizes and distribution of technically accessible storage resources; significant progress made by many OECD countries in developing laws that ensure that CCS is carried out safely and effectively; and the inclusion of CCS under the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM).

Much of the increased experience and confidence in CCS technology comes from the continued operation of four large-scale CCS projects that have stored millions of tonnes of carbon dioxide per year (CO_2/yr), and at least four other projects capturing similarly large volumes of CO_2 for use in enhanced oil recovery (EOR). Between 2009 and 2013, additional experience has come from at least two new projects that capture millions of tonnes of CO_2/yr for EOR and multiple relatively large – *i.e.* tens of megawatts of power generation capacity or hundreds of kilotonnes of carbon dioxide per year

Box 2: Rationale for CCS demonstration

The next step for many CO_2 capture technologies is to move to demonstration scale. This is also true for CO_2 storage, where the number of sites where CO_2 is injected and monitored at a rate and under commercial conditions representative of CCS on an industrial level remains limited. Without the experience that can only be gained through demonstration, CCS will not become a commercially investable proposition due to unresolved technical challenges and uncertain cost estimates.

New technologies do not jump directly from the pilot stage to full-scale operation. In the gas turbine industry, it can take over a decade to move a new design, such as a more efficient blade configuration, from pilot scale to an off-the-shelf product. During this period, large turbines are commercially operated, but under business arrangements that take into account the risks of first-of-a-kind plants. For example, equipment suppliers are often partners in these projects to gain experience and spread the risks.

Demonstration is therefore an essential intermediate technical step with reduced risk exposure that facilitates learning-by-doing and culminates in a technology that can be sold in the marketplace with performance guarantees bankable for investors. Individual demonstration projects need be only at a scale that is sufficiently large to be representative of commercial operation. This provides the marketplace and the engineering community with new information on equipment performance, the market for low-carbon production, the integration of the CCS value chain and the behaviour of stored CO_2. The scale is generally considered to be at least 0.8 megatonnes of carbon dioxide per year ($MtCO_2$/yr) for a coal-based power plant, or at least 0.4 $MtCO_2$/yr for other emission-intensive industrial facilities (Global CCS Institute, 2013).

– pilot projects[2] that have come online. In addition, positive investment decisions were made for seven projects that will demonstrate large-scale capture and storage and, as of 2013, are in construction.

Cumulative spending between 2007 and 2012 on projects that demonstrate CCS – or component technologies in the CCS chain – at large scale reached almost USD 10.2 billion (IEA, 2013a).[3] USD 7.7 billion of this total came from private financing, and while this figure reflects, in most cases, the costs related to the full industrial project and not just CCS components for controlling the facility's emissions, it is nonetheless a sign of growing confidence in CCS technology. In addition, research and development (R&D) funding from government and industry has driven a compound annual growth rate of 46% in CCS-related patent applications between 2006 and 2011 (IEA, 2013a).

Progress, although insufficient, has been made on a variety of fronts between 2009 and 2013 towards meeting some of the short-term milestones set in the IEA 2009 CCS roadmap, (Table 1).

2. Examples of large-scale pilot projects that began operation between 2009 (or thereabouts) and 2013 include: Schwarze Pumpe, (Germany), Mountaineer, (United States), Lacq, (France), Brindisi, (Italy), Plant Barry, (United States), Test Center Mongstad, (Norway), Compostilla, (Spain), Callide-A, (Australia), Decatur, (United States) and Citronelle (United States).

3. This total includes spending on CCS-equipped power generation with a capacity greater than 100 megawatts (MW) and at all scales for industrial applications of CCS under construction or operating between 2007 and the end of 2012. The private finance share includes significant spending on capture projects that supply CO_2 for EOR, some of which may not carry out monitoring sufficient to prove that injected CO_2 will be permanently retained.

Table 1: Progress in CCS

Area	Progress as of 2013
The 2009 CCS roadmap highlighted the need to develop 100 CCS projects between 2010 and 2020, storing around 300 $MtCO_2$/yr.	Four large-scale CCS projects have carried out sufficient monitoring to provide confidence that injected CO_2 will be permanently retained. Collectively, these projects have stored approximately 50 megatonnes of carbon dioxide ($MtCO_2$).* Nine further projects under construction together have the potential to capture and store 13 $MtCO_2$/yr. All nine projects should be operational by 2016. Numerous other large projects are in operation and demonstrate one or more technologies in the CCS chain.
The 2009 CCS roadmap suggested that OECD countries will need to invest USD 3.5 billion per year (b/yr) to USD 4 b/yr, and non-OECD countries USD 1.5 b/yr to USD 2 b/yr between 2010 and 2020 to meet the roadmap deployment milestones.	Actual cumulative spending between 2007 and 2012 on projects that demonstrate CCS reached almost USD 10.2 billion. Hence, while spending has been significant, the level targeted by the 2009 roadmap has largely not been met. Government grants contributed USD 2.4 billion of this total. Almost all of this funding is from governments in the United States and Canada (federal and state or provincial). In addition, over the same period a USD 12.1 billion of public funds was made available to CCS.**

Note: unless otherwise stated, all material in figures and tables derives from IEA data and analysis.

* Injection at the In Salah project was suspended in June 2011. The future injection strategy is under review; a comprehensive monitoring programme continues. The IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project ended in 2011, although Cenovus and Apache continue to operate the Weyburn and Midale fields, respectively, as CO_2-flood EOR projects. Snøhvit and Sleipner projects continue operation as integrated CCS projects.

** Some of these government grants are to CCS-equipped power generation with a capacity of less than 100 MW, while others may be to large projects in power or industry that have not yet reached construction or, in some cases, have been cancelled.

Table 1: Progress in CCS (continued)

Area	Progress as of 2013
The 2009 CCS roadmap highlighted the importance of CCS in industrial sectors and called for dedicated actions in specific industrial sectors.	Despite significant activity in some industrial areas, notably gas processing, CCS action in a number of key industrial sectors is almost totally absent (IEA/UNIDO, 2011). There is a dearth of projects in the iron and steel, cement, oil refining, biofuels and pulp and paper sectors. Only two possible demonstration projects at iron and steel plants, and one at coal-to-chemicals/liquids plants, are at advanced stages of planning (Global CCS Institute, 2013).
The 2009 CCS roadmap presented a vision for CO_2 transport and storage that started with analysis of CO_2 sources, sinks and storage resources, followed by the development of best-practice guidelines and safety regulations by 2020 and leading to a roll-out of pipeline networks to developed storage sites.	Considerable progress has been made in understanding the size and distribution of technically accessible storage resources, factors affecting the cost of storage, and in the development of best-practice recommendations and standards for geologic storage (CSA, 2012; DNV, 2009). The International Organization for Standardization (ISO) has also started a process to develop a series of international standards for CCS. However, much more needs to be done to develop these two elements of the CCS chain to support the scale of CCS deployment required in the near future.
Development of comprehensive CCS regulatory frameworks in all countries by 2020 and the resolution of legal issues for trans-boundary transfer of CO_2 by 2012 were identified as key regulatory milestones in the 2009 CCS roadmap.	Some OECD countries (*e.g.* in Europe; the United States; Canada; Australia) have made significant progress in developing laws ensuring that CO_2 storage is carried out safely and effectively, and are continuing to refine aspects of their frameworks through secondary legislation (IEA, 2012d). Other countries that plan to demonstrate CCS, such as South Africa, are undertaking processes that will lead to comprehensive regulations for CCS. In the area of international law, the 2007 amendment to the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR convention) entered into force in 2011; however, the 2009 amendment to the London Protocol has not yet been ratified by a sufficient number of signatory governments. As an important political development, CCS has also been accepted as a CDM activity under the UNFCCC with related modalities and procedures.

Note: unless otherwise stated, all material in figures and tables derives from IEA data and analysis.

In recent years, there has been increased interest in the possibilities for improving CCS economics through commercial use of captured CO_2 in place of direct geologic storage. It has been suggested that this could also boost public support. Save for use of CO_2 in EOR, efforts in this area have not achieved meaningful results (Box 3). In addition to the challenge of achieving sufficient scale of CO_2 use, quantifying any claimed reductions in net emissions – either through the long-term isolation of CO_2 from the atmosphere or the displacement of additional fossil fuel use – is not always straightforward. This creates a substantial challenge to the business case for such applications.

If it cannot be verified that the use of the captured CO_2 permanently isolates it from the atmosphere, it is unlikely that the party capturing the CO_2 would receive an economic benefit within a climate policy framework. The user of the CO_2 would thus have to pay a price that covered the cost of capturing the CO_2, and may furthermore need to agree to long-term contracts to provide sufficient certainty for the other party to invest in CO_2 capture[4]. If use of CO_2 displaces fossil fuel use, for example in the production of fuel from algae, and results in lifecycle emissions reduction, any resulting economic benefits would need to be distributed between the party capturing the CO_2 and the user in a manner that avoids double counting. These issues, including how the displacement of fossil fuels by using captured CO_2 in fuels production would be rewarded in carbon pricing systems, will need to be carefully considered by governments and businesses.

4. In this same case, but when a carbon price is present and it is higher than the cost of CO_2 capture and transport, the user of the CO_2 would have to pay a price for the CO_2 to cover the total penalty paid by the capturing facility, as the CO_2 would be considered to be emitted. In another possible case, if a captured CO_2 stream could be split between available geologic storage and utilisation, the user may need to pay above the carbon price in order to make the sale of CO_2 for utilisation more attractive than its permanent storage.

Box 3: CO_2 utilisation

Utilisation of CO_2 has been proposed as a possible alternative or complement to geologic storage of CO_2 that could enhance an economic value for captured CO_2. Many uses of CO_2 are known, although most of them remain at a small scale. Between 80 Mt and 120 Mt of CO_2 are sold commercially each year for a wide variety of applications (Global CCS Institute, 2011; IPCC, 2005). These include use as chemical solvents, for decaffeination of coffee, carbonation of soft drinks and manufacture of fertiliser. Some of these applications, such as refrigerants and solvents, demand small quantities of much less than 1 $MtCO_2$ per year ($MtCO_2$/yr) while the beverage industry utilises 8 Mt/yr. The largest single use is for enhanced oil recovery (EOR) which consumes upwards of 60 $MtCO_2$/yr, mostly from natural sources (Box 5). Other emerging uses, such as plastics production or enhanced algae cultivation for chemicals and fuels, are still small scale or require years of development ahead before they reach technical maturity.

Chemical uses of CO_2, which is a relatively abundant source of carbon, remain limited despite carbon being the basis for most of our goods and fuels. This is because CO_2 is unreactive and usually requires large amounts of energy to break its chemical bonds. This is the same property that makes it an inert and safe gas to trap underground. Research into catalysts that can reduce the energy required for CO_2 conversion is an active area (Cole and Bocarsley, 2010; Centi et al., 2013; Peters *et al.*).

The main challenge is scale. Given today's uses for CO_2, the future potential of CO_2 demand is immaterial when compared to the total potential of CO_2 supply from large point sources (Global CCS Institute, 2011). Mineral carbonation and CO_2 concrete curing have the potential to provide long-term storage in building materials. However, the mass of calcium carbonate that would result if the captured CO_2 in the 2DS were used for carbonation would equate to nearly double the total projected world demand for cement between today and 2050.

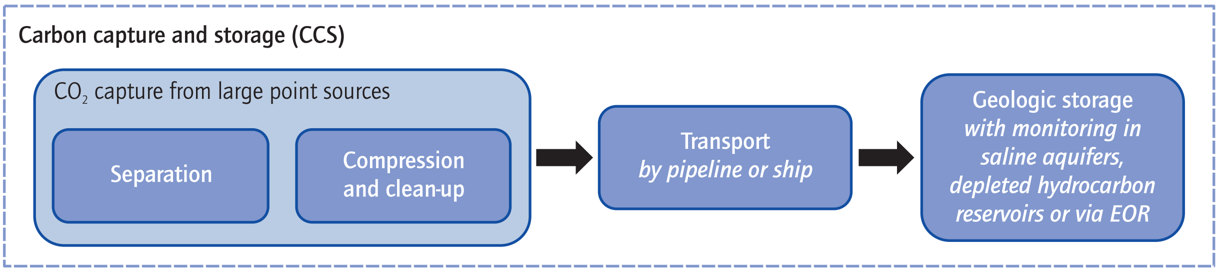
Another challenge is what happens to the CO_2 when it is used. In most existing commercial uses the CO_2 is not permanently isolated from the atmosphere and does not assist climate change mitigation. Carbon used in urea fertilisers returns to the atmosphere during a plant's lifecycle and fuels manufactured from CO_2 release the carbon when combusted. On the other hand, uses of CO_2 that can verify that the CO_2 is isolated from the atmosphere, such as bauxite residue carbonation in the aluminium industry and monitored EOR operations, can be classified as CCS.

Status of capture, transport, storage and integrated projects today: CCS is ready for scale-up

CCS involves the implementation of the following processes in an integrated manner: separation of CO_2 from mixtures of gases (*e.g.* the flue gases from a power station or a stream of CO_2-rich natural gas) and compression of this CO_2 to a liquid-like state; transport of the CO_2 to a suitable storage site; and injection of the CO_2 into a geologic formation where it is retained by a natural (or engineered) trapping mechanism and monitored as necessary (Figure 1).

This chapter provides a snapshot of where CCS technologies stand today and shows that many existing technologies are technically ready for deployment. It presents the status of the three components of the CCS process: CO_2 capture, transport and storage. It also outlines how the three components have been integrated in CCS projects to date, as well as the status of policy and institutional frameworks that are critical for assembling these parts together into integrated CCS projects.

Figure 1: CCS chain



Capture technologies: well understood but expensive

The way in which CO_2 can be captured depends fundamentally on the way that CO_2 is produced at an industrial facility. In power generation and some other industrial processes (*e.g.* cement manufacture and fluid catalytic cracking in refining), CO_2 is the product of combustion and is present in the mixture of flue gases leaving the plant. The separation of this CO_2 requires modification of the traditional processes, often by adding an extra process step. In some other industrial processes, CO_2 separation is an integral part of the process. In both cases, additional steps will almost always need to be taken to remove some unwanted components from the separated CO_2 (*e.g.* water) and to compress it for transport — all of which are commercially practiced today.

Approaches to the capture of CO_2 can be categorised according to whether and how the production process needs to be modified to enable CO_2 separation. In some cases, these approaches can be combined to create hybrid routes to capture.

- **Post-process capture**. CO_2 is separated from a mixture of gases at the end of the production process, for instance from combustion flue gases. This route is referred to as post-combustion capture in power generation applications.
- **Syngas/hydrogen capture**. Syngas, a mixture of hydrogen, carbon monoxide and CO_2, can be generated from fossil fuels or biomass. The CO_2 can be removed, leaving a combustible fuel, reducing agent or feedstock. In some cases, where either pure hydrogen or additional emission reductions are required, the syngas can be shifted to hydrogen while converting the carbon monoxide to separable CO_2. This route is referred to as pre-combustion capture in power generation applications.
- **Oxy-fuel combustion**. Pure (or nearly pure) oxygen is used in place of air in the combustion process to yield a flue gas of high-concentration CO_2. While in oxy-fuel combustion a specific CO_2 separation step is not necessary, there is an initial separation step for the extraction of oxygen from air, which largely determines the energy penalty.
- **Inherent separation**. Generation of concentrated CO_2 is an intrinsic part of the production process (*e.g.* gas processing and fermentation-based biofuels). Without CO_2 capture, the generated CO_2 is ordinarily vented to the atmosphere.

For all applications where CO_2 separation is an inherent part of production, CO_2 capture processes are commercially available and in common use. In other applications, such as coal-fired electricity generation, CO_2 separation processes are less advanced or require considerable redesign of traditional processes. This roadmap makes a distinction between industrial processes with mature CO_2 capture processes ("first-phase") and industrial processes that require further technical development and demonstration ("second-phase") (Table 2). In general, first-phase industrial applications are more mature than those in the power sector and are ready for deployment, while second-phase applications are lagging behind the power sector.

Table 2: Routes to CO_2 capture in power generation (by fuel) and industrial applications (by sector)

		Syngas-hydrogen capture	***Post-process capture***	***Oxy-fuel combustion***	***Inherent separation***
First-phase industrial applications	Gas processing	-	-	-	Sweetening
	Iron and steel	direct reduced iron (DRI)*, smelting (*e.g.* Corex)		-	DRI*
	Refining	-	-	-	Coal-to-liquids; synthetic natural gas from coal
					Hydrogen production
	Chemicals	-	-	-	Ammonia/methanol
	Biofuels	-	-	-	Ethanol fermentation
Power generation	Gas	Gas reforming and combined cycle	Natural gas combined cycle	Oxy-fuel combustion	Chemical looping combustion
	Coal	Integrated gasification combined cycle (IGCC)	Pulverised coal-fired boiler	Oxy-fuel combustion	Chemical looping combustion
	Biomass	IGCC	Biomass-fired boiler	Oxy-fuel combustion	Chemical looping combustion
Second-phase industrial applications	Iron and steel	Hydrogen reduction	Blast furnace capture	Oxy-fuel blast furnace	-
	Refining	Hydrogen fuel steam generation	Process heater and combined heat and power (CHP) capture	Process heater and CHP oxy-fuel	-
	Chemicals	-	Process heater, CHP, steam cracker capture	Process heater and CHP oxy-fuel	-
	Biofuels	Biomass-to-liquids	-	-	Advanced biofuels
	Cement	-	Rotary kiln	Oxy-fuel kiln	Calcium looping
	Pulp and paper	Black liquor gasification	Process heater and CHP capture	Process heater and CHP oxy-fuel	-

Legend: technical maturity of operational CO_2 capture plants to date.

Commercial Demonstration Pilot Lab or concept

* Capture approach is dependent on DRI technology used.

Studies of the costs of CCS have estimated that for new coal-fired plants built in the 2020s, after large-scale demonstration has been achieved, the three different routes to CO_2 capture on coal-fired generation all have comparable costs using today's technologies (IEA, 2011a). Costs of coal-fired power generation could be increased 40% to 63% by the addition of CO_2 capture, to around USD 100 per megawatt hour (MWh) for commercial (*i.e.* first-of-a-kind) plants using current technology. However, this is still at a level comparable to or lower than solar photovoltaic and offshore wind costs (IEA, 2012), and has the advantage that the electricity can be supplied on demand. The relative costs of gas-fired power generation with CCS, in comparison to coal-fired power with CCS or other low-carbon options, would be highly dependent on natural gas prices, which tend to be more variable than coal prices. Under a relatively high gas price scenario[5] an increase of 33%, to around USD 100 per MWh could be anticipated with CCS. The comparatively low capital cost of combined cycle gas plants with CCS could make them attractive to power markets for the provision of low-carbon base-load power (Box 4).

5. USD 7.40 per gigajoule in the United States.

Box 4. CCS and gas-fired power generation

Fuel switching from coal- to gas-fired power generation is presently attractive due to current low prices in some regions. Gas produces less CO_2 (less than 400 kilograms per megawatt hour [kg/MWh] compared to around 800 kg/MWh for coal) and provides insurance against potentially rising CO_2 prices. Today, investments in gas-fired capacity can also be more attractive than coal because gas plants are better able to follow the residual load in systems with high capacities of variable renewables. They are also less capital-intensive, which is especially appealing given uncertainties over future gas prices and climate policies.

However, natural gas is not a carbon-free fuel. Switching from coal to gas can assist with meeting near-term GHG emissions reduction goals, but from 2025 in the *ETP 2012* 2DS scenario, the goal for average emissions intensity of global electricity generation is below that of a gas-fired plant. The only way to enable gas-fired plants to conform to a lower emissions trajectory will be to fit many of them with CCS.

Using CCS to avoid 85% or more of the emissions from gas-fired power plants has been proven technically possible in pilot-scale projects such as the one at Mongstad in Norway. The most mature method is post-combustion capture. It is estimated that capturing the CO_2 would reduce the net efficiency of power generation from around 57% to 48%, but that the price of electricity generated would still be competitive (IEA, 2011a). At a cost of around USD 80 to 100 per MWh, a combined cycle gas turbine (CCGT) plant[6] with CCS is competitive on a levelised cost of electricity (LCOE) basis with solar, wind and coal plants with CCS (IEA, 2011a).

Cost estimates are, naturally, highly sensitive to gas price and load factor assumptions. The higher the number of hours the plant operates in a year, the lower the electricity price necessary to recuperate the investment in the power plant, including CCS components. Conversely, if gas plants are used to follow the variable load of renewable power and thus run for less than half of their available hours, the payback period may be longer and less attractive to investors. In the 2DS, 20% of gas-fired capacity is equipped with CCS in 2050. In general, capacity that operates at low load factors does not have CCS installed.

A gas plant with CCS could therefore be an attractive investment prospect in the 2030s if the world (or a particular region) endeavours toward a maximum 2 °C temperature rise. By 2050 all gas plants providing more than just occasional peaking power would likely need to be equipped with CCS.

6. Gas plants today are generally CCGT.

It is important to note, however, that the capital costs and efficiencies of power plants equipped with capture are expected to improve both as a result of R&D to improve technology, and due to learning effects as capacity increases (McDonald and Schrattenholzer, 2001; Rubin *et al*., 2007; Jones, McVey and Friedman, 2012).

Transporting CO_2 is the most technically mature step in CCS

Transport of CO_2 in pipelines is a known and mature technology, with significant experience from more than 6 000 km of CO_2 pipes in the United States. There is also experience, albeit limited, with transport of CO_2 using offshore pipelines in the Snøhvit project in Norway. Guidance for the design and operation of CO_2 pipelines that supplements existing technical standards for pipeline transport of fluids (*e.g*. ISO 13623 and ASME B31.4) was released in 2010 (DNV, 2010). CO_2 is also transported by ship, but in small quantities; understanding of the technical requirements and conditions for CO_2 transport by ship has improved recently (*e.g*. Decarre *et al*., 2010; Chiyoda Corporation, 2011).

To achieve CCS deployment at the scales envisioned in the *ETP 2012* 2DS, it will be necessary to link CO_2 pipeline networks across national borders and to shipping transportation infrastructure (*i.e*. temporary storage and liquefaction facilities) to allow access to lowest-cost storage capacity. The main challenge is to develop long-term strategies for CO_2 source clusters and pipeline networks that optimise source-to-sink transport. Government-led national or regional planning exercises are required in this regard.

CO_2 storage has been demonstrated but further experience is needed at scale

Geological storage of CO_2 involves the injection of CO_2 into appropriate geologic formations that are typically located between one and three kilometres under the ground; it also involves the subsequent monitoring of injected CO_2. Suitable geologic formations include saline aquifers, depleted oil and gas fields, oil fields with the potential for CO_2-flood EOR, and coal seams that cannot be mined with potential for enhanced coal-bed methane (ECBM) recovery (Figure 2). Storage in other types of geologic formations (*e.g*. basalts) and for other purposes, such as enhanced gas recovery or geothermal heat recovery, are active topics of investigation.

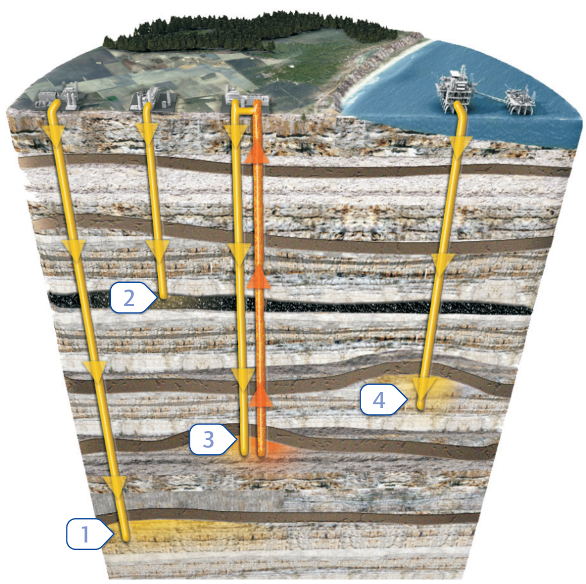
Figure 2: Storage overview

1 Saline formations/aquifers

2 Injection into deep unminable coal seams or ECBM

3 Use of CO_2 in enhanced oil recovery

4 Depleted oil and gas reservoirs



Source: Global CCS Institute, 2013.

The fundamental physical processes and engineering aspects of geological storage are well understood, based on decades of laboratory research and modelling; operation of analogous processes (*e.g.* acid gas injection, natural gas storage, EOR);[7] studies of natural CO_2 accumulations; pilot projects; and currently operating large-scale storage projects. These experiences have shown not only that CO_2 storage can be undertaken safely – provided proper site selection, planning and operations – but that all storage reservoirs are different and need extensive dedicated characterisation.

Progress has been made in understanding the size and distribution of technically accessible storage resources on a country or regional level (*e.g.* NETL, 2010; Ogawa *et al.*, 2011; Council for Geoscience, 2010; Vangkilde-Pedersen *et al.*, 2009; Carbon Storage Taskforce, 2009; Norwegian Petroleum Directorate, 2012). However, such estimates are not easily comparable, as countries or organisations typically use their own methods to estimate CO_2 storage resources. It is therefore important to ensure that jurisdictional or national-scale CO_2 storage resource assessments are comparable with each other and can be aggregated to provide meaningful assessment of the global CO_2 storage resource (IEA, 2013c).

Beyond these general but very useful assessments, the current level of efforts around the world to identify specific storage sites will be insufficient for the rapid deployment of CCS (IEAGHG, 2011a). Exploring for suitable CO_2 storage resources is an activity with an associated risk that a site will be found to be unsuitable (*i.e.* the risk of "drilling dry wells" in oil industry jargon). Today, the rewards for finding suitable pore space to store CO_2 are small. There are no incentives for industry to carry out comprehensive and costly exploration works, and governments have generally not been proactive in commissioning such investigations. Yet the availability of specific storage sites that can accept CO_2 injection at rates comparable to those of capture from large emission sources could limit CCS deployment.

A suitable geologic formation for CO_2 storage must have sufficient capacity and injectivity to allow the desired quantity of CO_2 to be injected at acceptable rates through a reasonable number of wells. It must also be able to prevent this CO_2 (and any brine originally present in the formation) from reaching the atmosphere, sources of potable groundwater, or other sensitive regions in the subsurface (Bachu, 2008). In addition, the potential for interaction with other uses of the subsurface must be considered, such as other CO_2 storage sites, oil and gas operations, or geothermal heat mining. One of the major technical challenges for CO_2 storage is to ensure that geological formations can accept the injection of CO_2 at a rate comparable to that of oil and gas extraction from the subsurface today.

The availability and characteristics of storage will have a strong influence on the cost and spatial patterns of deployment of capture and transport infrastructure (Middleton *et al.*, 2012). It is expected that storage will be the part of the CCS value chain that will determine the pace of CCS deployment in some regions. Experience indicates that it typically takes five to ten years from the initial site identification to qualify a new saline formation for CO_2 storage, and in some cases even longer. For projects using depleted oil and gas reservoirs or storing through EOR, this lead time may become shorter, but the storage capacities are usually more limited (CSLF, 2013). While the cost of storage is considered to be much lower than the capture cost, lessons from existing projects show that many years and often several hundred million dollars of at-risk funds must be made available for the development of a storage site (Chevron, 2012).

It is difficult to make general statements about the cost, performance and, to some extent, risk associated with geological storage, due to geological variability and site-specific characteristics. However, based on experience from operating projects, storage analogues and studies, the risks associated with geological storage can be addressed through careful storage site selection, thorough monitoring of CO_2 behaviour during and after storage operations, as well as a clear plan for remedial actions. Since selection of an appropriate storage site is the first step in addressing storage risks it is particularly important that it is done properly and with careful analysis.

Legal and regulatory frameworks[8] are critical to ensuring that geological storage of CO_2 is both safe and effective, that natural resources are effectively used, and that storage sites and the accompanying risks are appropriately managed after sites are closed. In addition, they may also be required to

7. Numerous comprehensive studies of analogues have been made: for example, Benson *et al.* (2002), Benson and Cook (2005) and Bachu (2008).

8. While all parts of the chain may have their distinct legal issues, the most significant and novel areas for regulation are in CO_2 storage.

make certain aspects of geological storage legal (*e.g.* where use of the subsurface for geologic storage is currently prohibited). The first step in developing legal and regulatory frameworks for CO_2 storage is to understand the playing field. For example, most jurisdictions that have a history of oil and gas exploration will have a multitude of regulations that can be adapted to meet the needs of geologic CO_2 storage. Many OECD member countries have already taken the steps in reviewing and adjusting their legal frameworks to incorporate CCS (Table 3). In addition, governments are considering whether they would like to develop comprehensive regulatory frameworks (*e.g.* as Alberta has done), or project-specific frameworks to facilitate limited demonstration while advancing development of general comprehensive frameworks (*e.g.* as in Western Australia) (IEA, 2011b). However, regardless of the approach taken, governments should ensure that their framework is kept up to date with the rapidly advancing knowledge base on geological storage (Morgan *et al.*, 2012).

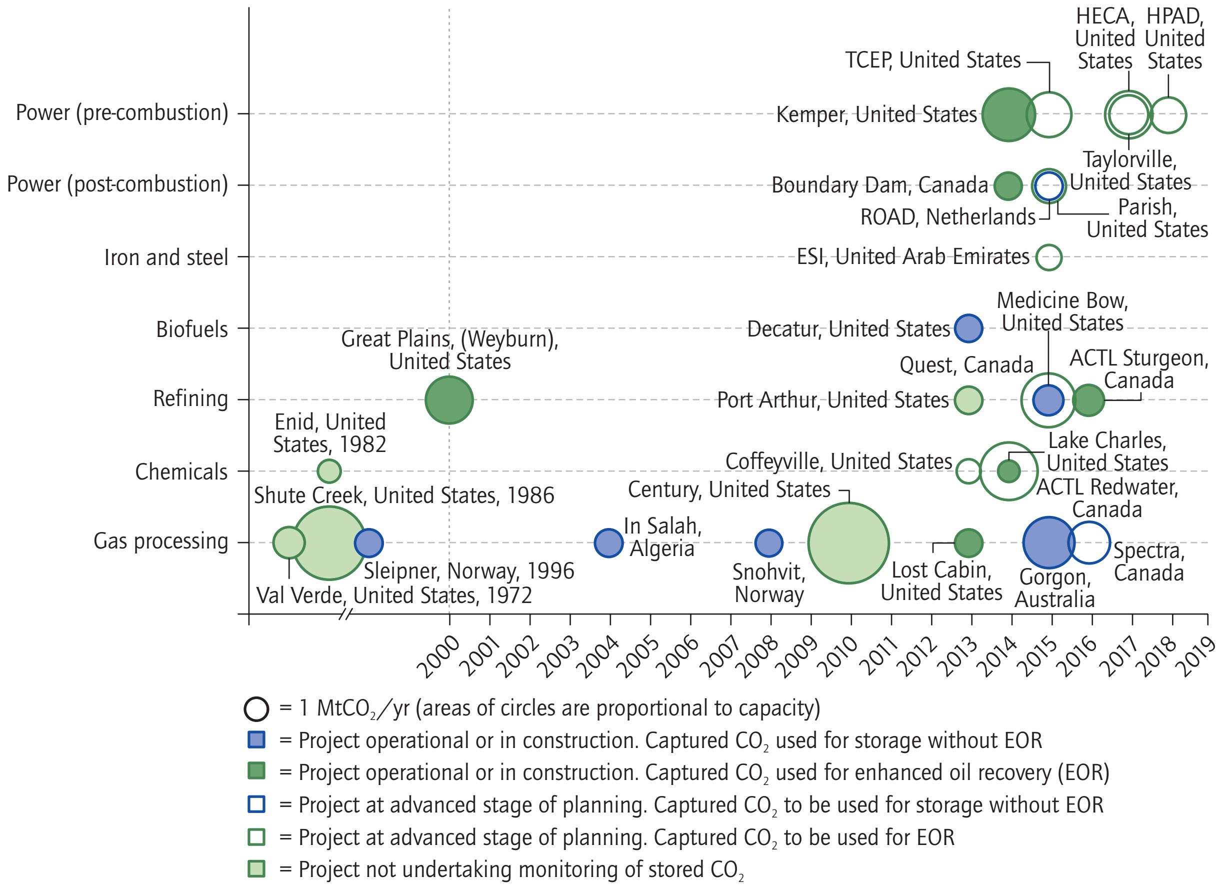
Table 3: Selected national or regional CO_2 storage regulatory frameworks

Australia	Australia completed in 2011 all elements of its CO_2 injection and storage framework at the federal level for offshore storage. Three of its states have state-level legislation in place to regulate onshore storage (Victoria, South Australia and Queensland), and one state (Victoria) also has a legislative framework for offshore CO_2 storage in its jurisdiction. In addition, The Barrow Island Act 2003 is project-specific legislation that was enacted solely to regulate the CCS activities associated with the Gorgon project in Western Australia. The Western Australian government is now in the process of developing broader CCS regulation through amendments to the existing Petroleum and Geothermal Energy Resources Act 1967, building on knowledge gained from the application of the Barrow Island Act.
Canada	The Province of Alberta established the key aspects of its regulatory framework in 2010 and 2011. During 2011 and 2012 the province conducted an expert review of its regulatory framework to ensure it had addressed all gaps and barriers and developed recommendations for amendments to regulation (*i.e.* secondary legislation) and other framework enhancements. The neighbouring provinces of British Columbia and Saskatchewan have been working towards the establishment of comprehensive regulatory frameworks. Saskatchewan amended its Oil and Gas Conservation Act in 2011 to expand and clarify its regulatory authority for carbon storage and British Columbia's CCS regulatory framework will also build on existing petroleum legislation.
United States	In late 2010, a new rule creating requirements for geologic storage wells came into effect as part of the Underground Injection Control (UIC) program, which regulates the construction, operation, permitting, and closure of injection wells that place fluids underground for storage or disposal. This new rule created a well class, referred to as Class VI under the UIC, which is intended to protect underground sources of drinking water from the potential impacts of geologic storage. Around the same time, a new, complementary rule came into effect that created reporting requirements under the Greenhouse Gas Reporting Program for geologic storage operations (Subpart RR) and CO_2-EOR projects (Subpart UU). More recently, due to the nature of CO_2 storage, the Environmental Protection Agency (EPA) has proposed excluding CO_2 streams from hazardous waste regulations under the Resource Conservation and Recovery Act (RCRA). There are also seven states that have developed state regulations for geologic storage.
European Union	In 2009 the European Commission introduced Directive 2009/31/EC on the Geological Storage of Carbon Dioxide which includes provisions for the management of environmental and health risks related to CO_2 storage, requirements on permitting, composition of the CO_2 stream, monitoring, reporting, inspections, corrective measures, closure and post-closure obligations, transfer of responsibility to the state, and financial security. The Directive was transposed by most European Union (EU) member states, but in many cases it was not done in full compliance with the EU requirements. The process of a complete transposition of this Directive is continuing.

Source: based on IEA, 2012d.

Three key regulatory challenges, amongst others, are worth highlighting: first, in almost all jurisdictions, aspects of the way that post-closure stewardship will be addressed and liabilities managed have yet to be settled; second, the relationship between carbon dioxide-enhanced oil recovery (CO_2-EOR) and geologic storage under regulation is an important and contentious question that needs to be resolved; and finally, the means by which the public can provide input into the development of regulatory frameworks and the siting of individual projects (IEA, 2012d). These legal developments must start today if the milestones in this roadmap are to be met by countries that have significant potential CO_2 storage resources.

Figure 3: Large-scale CO_2 capture projects in operation, under construction or at an advanced stage of planning as of end-2012, by sector, storage type, capture potential and actual or estimated start date



Note: "Large-scale integrated projects" are defined as projects involving capture, transport and storage of CO_2 at a scale of at least 800 000 tonnes (t) annually for a coal-fired power station and 400 000 t annually for other emissions-intensive industrial facilities. All projects using CO_2 for EOR that are not yet operational are presumed to undertake monitoring in a way that is sufficient to provide confidence that injected CO_2 is permanently retained. Other noteworthy projects that are scheduled to enter operation in 2017 or after include FutureGen 2.0 in the United States, and the White Rose and Peterhead projects in the United Kingdom. These have not yet reached the Define lifecycle stage in accordance with the Global CCS Institute Asset Lifecycle Model.

Source: based on data from the Global CCS Institute (2013).

KEY POINT: while only four large CCS projects had become operational by 2012, government funding programmes have stimulated a series of projects that are progressing towards operation in the next five years.

Progress with integrated projects

Despite the absence of coherent incentive policies linking near-term demonstration and early deployment of CCS with the long-term need for emissions reductions, over 20 CCS projects are today in operation or advanced stages of planning (Figure 3). There is thus tangible progress with starting demonstration and early deployment, but this progress is significantly below the trajectory required.

The majority of these projects – about two-thirds – have been driven in some measure by mature markets for CO_2 that is used in CO_2-EOR. Most of these projects have also received some level of government support from CCS demonstration programmes. Box 5 below details further aspects of CO_2-EOR, noting that experience with CO_2-EOR merits cautious treatment as an indicator of progress in CCS deployment.

Assembling the parts still presents significant challenges

While many of the component technologies work at scale and are ready for deployment, there is limited experience in integrating the components into full-chain projects, as shown above. While technical challenges obviously remain in integrating the parts of the chain, the major impediment is the lack of policy and economic drivers. Lack of public support and poor understanding of the technology exacerbate the situation.

Box 5: CO_2 storage and EOR

Injection of CO_2 to improve recovery of oil has been practiced commercially since the early 1970s in the United States. In 2010, there were nearly 140 projects under development or in operation globally. The majority of the projects operate in the United States, where they produce nearly 280 000 barrels of oil per day (Moritis, 2010). Projects in the Unites States inject over 60 $MtCO_2$/yr, the majority of which should remain stored at the end of the project life. However, most of these projects use CO_2 from natural geologic accumulations, and of those using anthropogenic CO_2, few engage in sufficient monitoring, measurement and verification (MMV) to qualify as CCS. The notable exception is the Weyburn CO_2-EOR project in Canada, which has monitored and verified the storage of around 2 $MtCO_2$/yr generated by a coal gasification project in the United States.

Historically, CO_2 is the largest expense associated with EOR projects, so most projects in operation today are designed to minimise the amount of CO_2 used to recover a barrel of oil and, hence, the amount stored. While some CO_2 storage projects can afford to purchase anthropogenic CO_2, particularly from high-purity sources (IEA/UNIDO, 2011), there are numerous commercial challenges and open questions surrounding storage in CO_2-EOR projects (Dooley *et al.*, 2010; MIT, 2010; IEA and OPEC, 2012). For example, as noted above, conventional CO_2-EOR projects do not undertake MMV activities sufficient to assess whether storage is likely to be permanent; they also do not select and operate sites with the intent of permanent CO_2 storage. Furthermore, because CO_2-EOR consumes additional energy in the recycling of produced CO_2 and results in production of additional oil that, when combusted, generates additional CO_2 emissions, a CCS project involving CO_2-EOR (known as CCS-EOR) will deliver a smaller net emissions reduction than a comparable project storing CO_2 in a saline aquifer (Jaramillo *et al.*, 2009).

Climate and energy policies as well as storage regulations may be able to mitigate these issues. At present, however, the extent to which CO_2-EOR can contribute to emission reduction goals is unclear. Despite this uncertainty, in the short term CO_2-EOR can offer a valuable means to offset the costs of demonstrating CO_2 capture, drive development of CO_2 transportation infrastructure, and present opportunities for learning about aspects of CO_2 storage in some regions.

Today, there are no clear-cut business cases for CCS and more effort must be put into creating them. Otherwise, progress in CCS deployment will continue to depend entirely on direct financial support by governments. In the long run, it is expected that technology-neutral emission reductions mechanisms (*e.g.* a high cost of emitting CO_2) will drive uptake of CCS as a competitive low-carbon technology to reach emissions reductions. Today, however, CO_2 emission constraints – represented by caps, prices or otherwise – are relatively loose and there is considerable uncertainty over their future stringency. Apart from a few exceptional cases, current carbon prices do not drive CCS.

Moreover, because markets do not value the public benefits of CCS demonstration (*e.g.* knowledge spill-over, long-term co-ordination and planning) and the benefits cannot be captured in full by early adopters, there is currently little commercial incentive for private entities to invest in CCS. Thus, governments can drive private investment in CCS-equipped facilities today by creating incentive frameworks that, in the near term, provide funding to demonstrate CCS in integrated projects, share knowledge, and drive long-term planning, and over the longer term provide appropriate incentives for deployment beyond demonstration. Of course, CCS incentive frameworks must be complemented by strong and credible emissions reduction policies.

The lack of CO_2 emissions constraints and financial incentives that could make CCS a competitive emissions reduction option is not the only barrier to private sector investment. As the previous chapter noted, the technical risks associated with installing or scaling up CO_2 capture in some applications must be adeptly managed (Esposito, Monroe and Friedman, 2011).

There are also significant commercial risks introduced by the storage component of the system, as not all storage reservoirs examined will be found to be suitable for storage. Some may be found to be unsuitable only after considerable sums have been spent on characterisation, and some may perform more poorly than anticipated during operations (the case in the Snøhvit project in Norway). Furthermore, the involvement of many different parties in constructing and operating each part of the CCS chain will require that all these risks be managed through complex commercial arrangements.

The technical risks associated with capture and storage can be progressively reduced through learning-by-doing (*i.e.* implementing more projects), developing transport networks that can link multiple sources and sinks, and developing (or adopting) management systems to manage risks inherent in resource development. However, the political risks presented by indecisive policy making and market uncertainties remain. This situation is compounded by a lack of understanding and experience with CCS in the finance sector, and a focus on the additional costs of CCS rather than the overall competitiveness of low-carbon energy production in the long term. Governments, industry and the finance community need to work together to identify and develop the key features of a model incentive framework (as part of a broader emissions reduction framework where one exists) that would encourage adequate CCS investment.

Public attitudes towards CCS also play an important role. Some projects that envisaged onshore storage have faced prohibitive public opposition. Current research also indicates a varying degree of understanding and acceptance of CCS by the public in different countries and low awareness in general everywhere. Most research in the area calls for more efforts in this regard (*e.g.* P. Ashworth *et al.*, 2012; C. Oltra *et al.*; 2010, M. Prangnell, 2013).

Important public engagement efforts are needed prior to making final decisions regarding storage. While it is critically important to resolve issues and challenges at the project level, it is also clear that broader communication on CCS as an important part of a national/regional climate change mitigation strategy is needed. Significant efforts are also needed to explain the potential health and environmental risks (associated with leakage of stored CO_2) and the ways to mitigate them. Governments must enhance their role in such communication.

Vision for CCS: where does CCS need to be by the middle of the century?

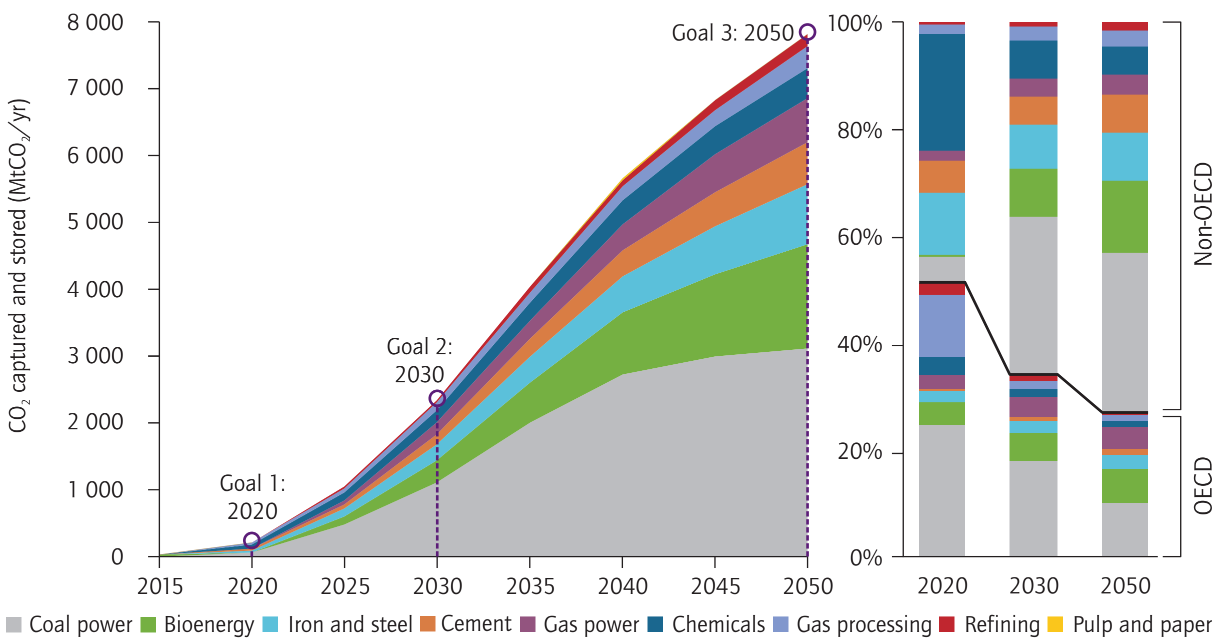
IEA analysis shows that CCS is an integral part of any lowest-cost mitigation scenario where long-term global average temperature increases are limited to significantly less than 4 °C, particularly for 2 °C scenarios (including in *ETP 2012*). Other studies have reached similar conclusions (Edenhofer *et al.*, 2010; Edmonds *et al.*, 2007; IPCC 2007).

The *ETP 2012* 2DS provides insights into an ambitious change in the energy sector (Box 5). In the 2DS, CCS is widely deployed in both power generation and industrial applications (Figure 4). The total CO_2 capture and storage rate must grow from the tens of megatonnes of CO_2 captured in 2013 to thousands of megatonnes of CO_2 in 2050 in order to address the emissions reduction challenge. The potentials and relative competitiveness of different emissions reduction options, coupled with the distribution of production for cement, iron and steel, and similar products, mean that the applications of CCS vary widely by region and through time.

By 2020, CCS could be deployed at relatively low cost on processes such as coal-to-liquids and chemicals in non-OECD countries (*e.g.* China, and in Africa and the Middle East) and on gas processing in OECD countries (*e.g.* Canada, the United States and OECD Europe). Higher-cost applications of CCS in power generation in Canada, the United States, and OECD Europe, and in iron and steel production in non-OECD countries also need to be undertaken as early as 2020. In 2050, 70% of all CCS projects would need to be implemented in non-OECD countries where the largest share of global industrial growth takes place. For CCS to play such a large, global role requires the creation of a significant CCS industry.

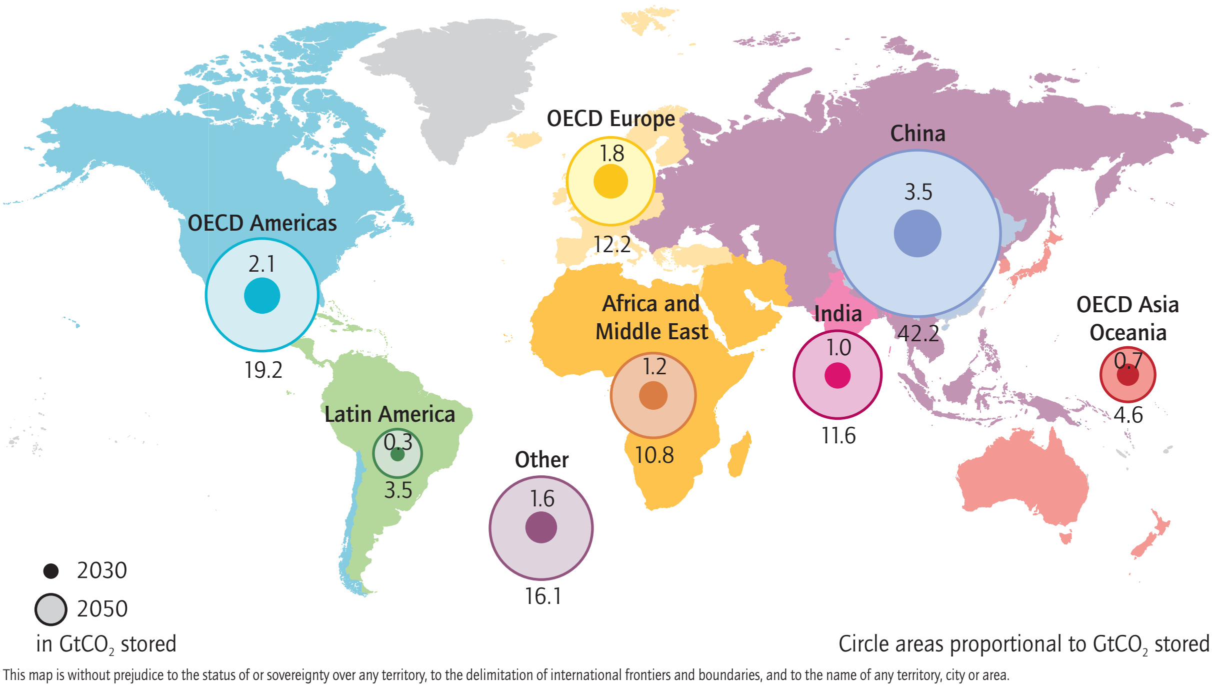
While the 2DS sees fossil fuel generation considerably reduced by 2050 compared to current levels, the largest single application of CCS in the 2DS is in coal- and gas-fired power generation. By 2050, a total of over 950 gigawatts (GW) of power generation capacity would be equipped with capture, or 8% of all power generation capacity globally. This includes about two-thirds of all coal capacity and one-fifth of gas. Nonetheless, industrial applications of CCS are just as important in the 2DS, particularly in iron and steel manufacture and biofuel production, as they would account for 45% of the total volume captured and stored between 2013 and 2050. In fact, in some regions, such as the non-OECD Americas, and some

Figure 4. CCS in the power and industrial sectors in the 2DS



KEY POINT: the 2DS suggests a steep deployment path for CCS technologies applied to power generation and a number of industries. Over 70% of all CCS projects take place in non-OECD countries by 2050.

Figure 5: Cumulative CO_2 captured 2015-30 and to 2050, by region in the 2DS



Note: geographic distribution of cumulative captured CO_2 is aligned with locations of large point sources of CO_2 emissions.
Source: IEA, 2012c.

KEY POINT: between 2015 and 2050, 120 $GtCO_2$ are captured globally under the 2DS and will need to be transported to suitable sites and stored.

other non-OECD countries (*e.g.* India), industrial applications of CCS are far more important than applications in power generation.

A total cumulative mass of approximately 120 $GtCO_2$ would need to be captured and stored between 2015 and 2050, across all regions of the globe (Figure 5). As a comparison, current natural gas production is around 2.5 Gt per year. Thus, in the 2DS in 2050, storage capacity will be a valuable asset for governments and private companies. Large-scale networks that transport billions of tonnes of CO_2 annually between capture facilities and storage sites, within the same region and further afield, will need to be available to facilitate this rate of storage.

The total undiscounted investment in CCS technology from now until 2050 in the 2DS would amount to USD 3.6 trillion. Although this requires a step-change in financing priorities, investment in CCS can pay off. Our analysis shows that if CCS is removed from the list of options to reduce emissions in the electricity sector, the capital investment required to meet the same emissions constraint increases by 40%.

For CCS to help fulfil the ambitions of the IEA 2DS, this roadmap identifies three time-specific goals for its deployment:

- By 2020, the capture of CO_2 is successfully demonstrated in at least 30 projects across many sectors, including coal- and gas-fired power generation, gas processing, bioethanol, hydrogen production for chemicals and refining, and DRI. This implies that all of the projects that are currently at an advanced stage of planning are realised and several additional projects are rapidly advanced, leading to over 50 $MtCO_2$ safely and effectively stored per year.[9]

9. Projects that will be in operation in 2020 are in all likelihood already at an advanced stage of planning; the 2020 goal has therefore been set in this context. The 2030 and 2050 goals are in line with the 2DS deployment vision, and will require accelerated action from 2020 to be met.

- By 2030, CCS is routinely used to reduce emissions in power generation and industry, having been successfully demonstrated in industrial applications including cement manufacture, iron and steel blast furnaces, pulp and paper production, second-generation biofuels and heaters and crackers at refining and chemical sites. This level of activity will lead to the storage of over 2 000 $MtCO_2$/yr.
- By 2050, CCS is routinely used to reduce emissions from all applicable processes in power generation and industrial applications at sites around the world, with over 7 000 $MtCO_2$ annually stored in the process.

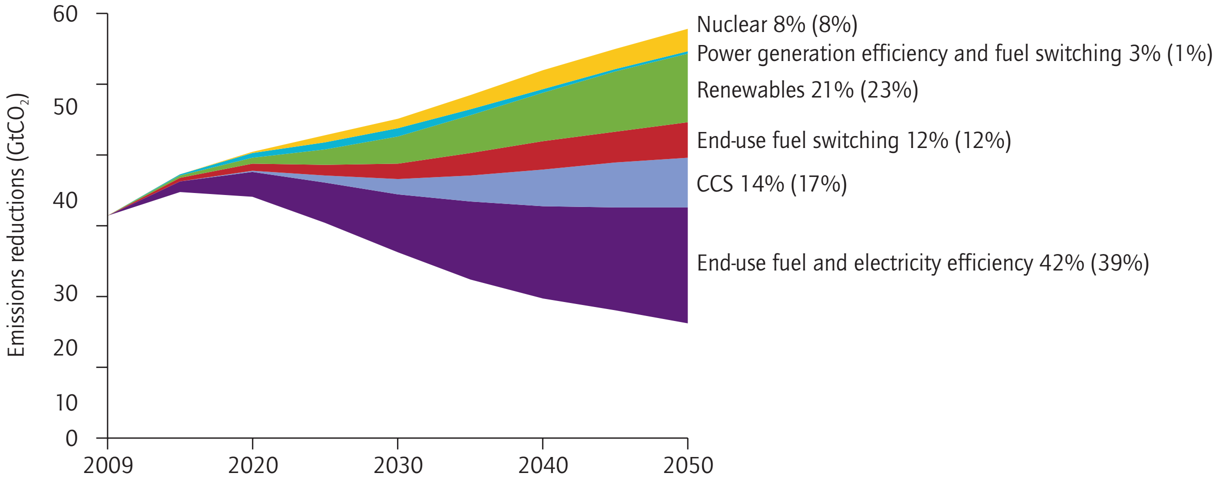
Box 6: *ETP 2012* 2DS and 6DS

The 2DS describes how technologies across all energy sectors may be transformed by 2050 for an 80% chance of limiting average global temperature increase to 2 °C. It targets cutting energy-related CO_2 emissions by more than half by 2050 (compared with 2009 emissions levels) and ensuring that they continue to fall thereafter.

The 2DS acknowledges that transforming the energy sector is vital but not the sole solution: the goal can only be achieved if CO_2 and GHG emissions in non-energy sectors are also reduced. The 2DS is broadly consistent with the *World Energy Outlook (WEO)* 450 Scenario through 2035.

ETP 2012 also considers 6 °C and 4 °C scenarios. The 6 °C Scenario (6DS) – which is also a baseline for roadmaps – is largely an extension of current trends. By 2050, energy use almost doubles (compared to 2009). In the absence of efforts to stabilise atmospheric concentrations of GHGs, the average global temperature is projected to rise by at least 6 °C in the long term. The 6DS is broadly consistent with the *WEO* Current Policy Scenario through 2035 (IEA, 2012c). Figure 6 below shows how different technologies contribute to meeting the energy sector target of cutting CO_2 emissions by more than half by 2050. The IEA develops roadmaps for most of these technologies, CCS being one of them.

Figure 6: CCS contributes 14% of total emission reductions through 2050 in 2DS compared to 6DS



Note: numbers in brackets are shares in 2050. For example, 14% is the share of CCS in cumulative emission reductions through 2050, and 17% is the share of CCS in emission reductions in 2050, compared with the 6DS.

Source: IEA, 2012c.

Actions and milestones for the next seven years: creating conditions for deployment

Our vision to 2020: over 30 large projects in operation, providing experience and enabling cost reduction; incentive policies are in place to drive early deployment.

To an objective observer in 2020, CCS is a visible and tangible technology, operating at large scale in multiple locations worldwide. A global commitment to reducing GHG emissions and the explicit recognition of CCS in governments' CO_2 emissions reductions strategies will have led to the implementation of consistent policies. These policies in turn would have generated the private sector confidence to invest in CCS projects that was lacking in 2013. Principally, these policies would have created sector-specific, stable CCS support mechanisms for deployment, backed by a credible expectation of increasing carbon prices (or otherwise tightening emissions constraints).

By 2020, over 30 projects that capture, transport and store CO_2 are up and running, in addition to the four that have been operational as of 2013. The experience and lessons from these four projects complement the continued R&D into novel technologies that are expected to reduce the capital and operational costs of plants coming online in the 2020s. In parallel, policy frameworks are widely in place to ensure that companies take adequate measures preparing CCS technologies to be added at a later stage. Furthermore, in recognition of the current imbalance between private sector risks and rewards in the exploration of geological CO_2 storage capacity, governments will have taken measures that speed up pre-competitive storage site screening, reducing the project development timelines for the growing number of projects in each region. Comprehensive and transparent regulatory frameworks for the storage of CO_2 will have been developed in parallel with the operation of the first major projects, incorporating lessons from these projects and ensuring that the concerns of local populations have been recognised and addressed. Crucially, the monitoring of CO_2 under these frameworks, along with the widespread recognition of the urgency of climate change action, would have contributed to public confidence in the safety and effectiveness of CCS.

The actions described in this section are achievable and must be taken in the near term in order to enable subsequent wider CCS deployment. They are organised in four sections:

- policy and regulation conducive to integrated CCS projects;
- storage;
- capture;
- transport.

In combination, they are the necessary building blocks that will carry CCS from being a proven but non-commercial technology today, to being a commercially demonstrated and supported component of low-carbon energy production. From 2020 onwards, it is conceivable that society should to be able to rely increasingly on CCS to enable sustainable use of fossil fuels, revitalise industrial production processes and help avoid dangerous climate change. Greater details of each action are laid out in Annex 1.

Policy and regulatory frameworks are critical to CCS deployment

This roadmap recommends the following actions	Time frame
Action 1: introduce financial support mechanisms for demonstration and early deployment of CCS to drive private financing of projects.	2013-20
Action 2: develop national laws and regulations as well as provisions for multilateral finance that effectively require new-build, base-load, fossil-fuel power generation capacity to be CCS-ready.	2013-20
Action 3: significantly increase efforts to improve understanding among the public and stakeholders of CCS technology and the importance of its deployment.	2013-20
Action 4: governments and international development banks should ensure that funding mechanisms are in place to support demonstration of CCS in non-OECD countries.	2013-20
Action 5: governments should determine the role they will play in the design and operation of CO_2 transport and storage infrastructure.	2013-20

These five actions concern the entire CCS chain. They relate to policy measures that establish a pathway for CCS deployment, through important gateways that distinguish between technology demonstration, early deployment in selected applications, and widespread deployment. The most pressing requirement for the next seven years is creating and consolidating business cases for the initial large-scale CCS projects. This cannot be achieved without immediate strong policy measures and incentives. The actions in this section recognise that demonstration programmes cannot afford to focus on CO_2 capture without equal attention to CO_2 storage. Likewise, incentives for companies to adopt CCS may be unsuccessful if the commercial model for CO_2 transport and storage remains uncertain. CCS deployment can only move as quickly as the slowest developing part of the CCS process.

Action 1: introduce financial support mechanisms for demonstration and early deployment of CCS to drive private financing of projects.

Current carbon pricing mechanisms have mostly proven unsuccessful at driving the initial uptake of CCS. Other mechanisms are therefore needed in the immediate to medium term to supplement economy-wide carbon prices, even where they exist. The role of government is to set out the policies that will support the three distinct phases – demonstration, early deployment and wide deployment when CCS-equipped facilities compete against other low-carbon production routes without specific support – and manage the transitions between them. The immediate emphasis must be placed on demonstration and early deployment, the latter providing essential experience and knowledge to help wide-scale deployment.

The first large-scale CCS demonstration projects around the world have shown the importance of public support, mainly through capital grants, and also the value of CO_2 utilisation as a near-term market incentive. Individual countries may not be able to commit resources to a large variety of CCS demonstration projects. Governments have the opportunity to co-ordinate activities to ensure that a global portfolio of demonstration projects covers the range of possible CO_2 sources and storage geologies. In addition, it is important that governments create mechanisms by which the learning from early CO_2 demonstration projects is shared and contributes to improved design of subsequent projects. Co-operation among countries should be established to ensure that a global portfolio of early deployment projects covers post- and pre-combustion and oxy-fuel technologies in the power sector, DRI-produced steel, hydrogen produced at refineries and chemical sites, bioethanol, coal-to-liquids and gas processing, as well as technologies that reduce water consumption (*e.g.* dry cooling systems).

In the short to medium term, governments must put more emphasis in stimulating CCS deployment through adequate specific incentive mechanisms. Such policies can include:

- direct financial support by governments (grants, investment tax credits, preferential loans, public-private partnerships, etc.) to share the burden of the learning cost – the cost of developing the first-of-its-kind project that uses pre-commercial technologies and as a result has high capital costs;
- direct support for operation (feed-in tariffs, production tax credits, portfolio standards, *e.g.*, similar to renewable obligation schemes that require purchase of certificates, etc.) to cover, partly or totally, the increased operating costs for a limited period of time, when a cost pass-through in electricity prices may not be possible due to market arrangements, or political and social reasons;
- supportive tools to address the issue of carbon leakage and international competitiveness that industrial facilities with CCS in sectors such as cement and steel may face in relation to competitors that are not required to invest in comparable levels of GHG abatement (or are not currently required to undertake any GHG abatement);
- support for the development and access to infrastructure to facilitate early project developers' access to CO_2 transportation pipelines and injection facilities;
- leverage of existing markets for CO_2 utilisation options where possible to facilitate deployment.

Several national and sub-national governments have already been putting in place policies to stimulate investments in CCS. There are examples of policies that are intended to "pull" such investments by providing capital grants and support for research, development and demonstration (RD&D) (*e.g.* the

United Kingdom, Japan, China, the United States, the European Union, Canada), and examples of policies that intend to "push" investments in CCS through performance requirements, direct regulation and high carbon prices (*e.g.* Norway, the United Kingdom, Canada). A more extended discussion and various examples are provided in Annex 3.

Successful policies to support CCS will have to evolve over time, for example by adopting a "gateway" approach (Box 7). This approach assumes a stable policy framework with clearly defined break points or gateways that denote changes in policy, such that policy is suited to the state of technology and market maturity. These frameworks would include a combination of policies, and would create certainty for individual CCS projects.

Box 7: Possible gateways within a CCS policy framework

To combine flexibility and certainty, a potential solution is to set policy within a stable framework, so that the broad architecture and rules of policy evolution are certain. Within a stable framework, breakpoints or "policy gateways" can provide the flexibility required. They comprise three components: 1) the criteria defining when or if policy moves to the next stage; 2) the policies within each stage; and 3) an outline of how government will react if gateways are missed.

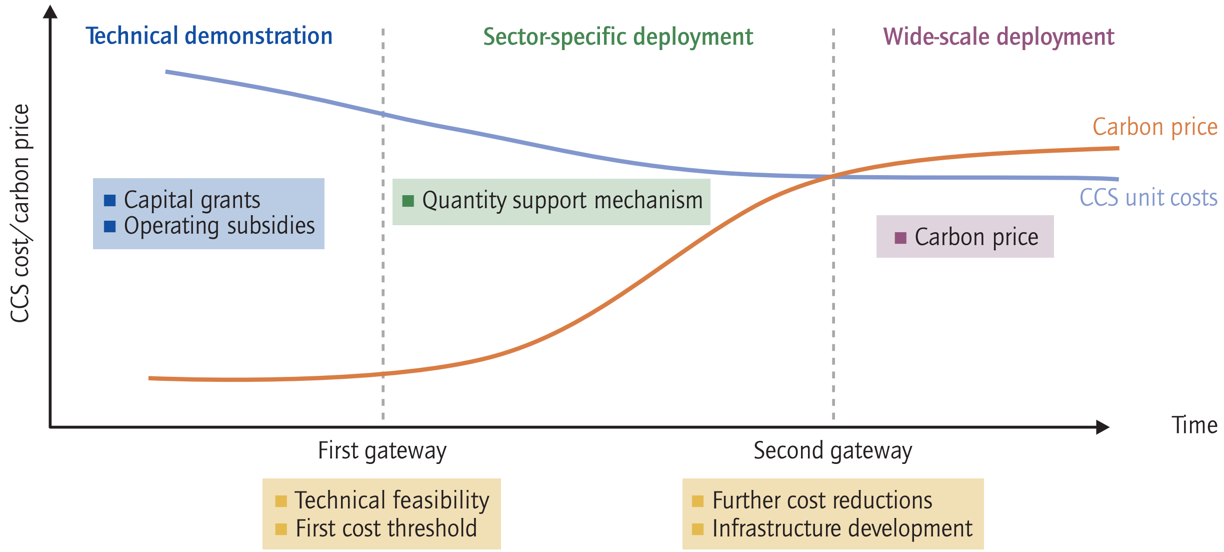
Gateways can be used to link commitment of government and private resources to achieving certain targets (such as performance thresholds). This allows government to commit funds without the risk of overstretching its resources or imposing poor value-for-money obligations on others. For firms, this greater policy commitment may reduce policy risk and ease financing costs by reducing the risk of asset stranding. Many different types of gateways could be put in place within a CCS policy framework.

In a first policy phase, for example, public capital grants and operating subsidies deliver a sufficient number of projects to test efficacy of the technology. After an initial operating period of some years, policy might switch to the next phase, provided that certain criteria have been met, probably relating to technological efficacy or the development of commercially competitive uses for CO_2 in the local market.

A second phase could be a period of larger-scale deployment. Widespread deployment, even in one sector, is unlikely to be feasible through public grants, so the emphasis would switch to private financing with implicit subsidies.

If CCS technology becomes fully proven at commercial scale, and the supply chain matures, then a third phase could follow in which CCS is stimulated by a price instrument wherever it is a cost-effective solution. This might be achieved through a stable economy-wide carbon price, but narrower, sectoral approaches, including the use of mandates, might also be used.

Figure 7: Policy gateways within a CCS policy framework



Source: IEA, 2012f.

Action 2: develop national laws and regulations as well as provisions for multilateral finance that effectively require new-build, base-load, fossil-fuel power generation capacity to be CCS-ready.

Given that the cost of electricity from fossil-fuel power plants equipped with CCS – particularly those that are coal-fired – is not competitive with unabated power generation capacity, and expectations of CO_2 prices (or equivalent constraints) are low, power plants continue to be built at an astounding rate (in some markets) without considering CCS. By and large, these power plants are built today in a way that makes the later addition of capture more difficult and expensive than need be, or in locations where transport of captured CO_2 may be challenging. To avoid this potential lock-in, governments should require through laws and regulations that new-built base-load fossil-fuel power plants be constructed in a way that allows for the addition of CO_2 capture at a later date (Box 8). This requirement should not necessarily extend to "peaking" capacity (*e.g.* open cycle gas turbines) where the capital costs of retrofitting with CCS would be difficult to recoup, nor to CHP plants. International finance institutions should also include such requirements in their lending policies.

Box 8. CCS-ready power generation and retrofitting power plants with CCS

With more than 1 600 GW of installed generation capacity in 2010, global coal power-plant installations account for almost 9 $GtCO_2$ of emissions each year. Moreover, the number of coal-fired power-plant installations has been expanding rapidly in the past decade and is expected to continue to grow in the near future due to relatively low international coal prices driven by coal-to-gas switching in the United States (IEA, 2012e). The emissions from these installations pose a serious threat to the climate. To avoid retiring existing, but not fully depreciated, power plants early, while staying within a 2DS carbon trajectory, they can in some cases be retrofitted with capture (IEA, 2012c). In some circumstances, retrofitting plants is a lower-cost option to reduce CO_2 emissions than replacing the plant with an alternative form of low-carbon electricity generation (IEAGHG, 2011b).

Retrofitting CCS to existing plants is a complex process, encompassing many site-specific aspects, and largely depends on market- and technology-specific operational conditions. A combination of technical factors will determine the technical attractiveness of retrofitting capture to the installation, and the access to transport and storage is also critical (IEAGHG, 2011b; IEAGHG, 2007).

To ensure that retrofits are technically feasible and improve the economic attractiveness of future retrofits, it is possible to take actions at the time of design and construction that will reduce the cost of a retrofit, thus making the facility "CCS-ready". A CCS-ready facility is a large industrial or power source of CO_2 which is intended to be retrofitted with CCS technology when the necessary regulatory and economic drivers are in place, and which has designed and taken steps to ensure that the retrofitted plant will be as competitive as possible with other newly built CCS-equipped plants. These steps include: ensuring that sufficient space is available on site for the installation of additional capture-related equipment; installing high-performance flue-gas desulphurisation; allowance for extra cooling (*i.e.* water) and heating (*i.e.* steam) needs; and ensuring that appropriate rights-of-way are available to allow for CO_2 transport to identified potential storage sites (IEA, 2010). The assessment of CO_2 transport and storage solutions moves this definition beyond that for 'capture ready'.

CCS readiness does not stop with the construction of the plant but has to be maintained until the plant is operating with CCS. For example, for a power plant to hold a temporary exemption under the recent Canadian emissions performance standard for coal-fired electricity generation it must regularly demonstrate that its CCS-ready status is preserved (Reduction of Carbon Dioxide Emissions from Coal-Fired Generation of Electricity Regulations, 2012).

Action 3: significantly increase efforts to improve understanding among the public and stakeholders of CCS technology and the importance of its deployment.

In some parts of the world, CCS is not well understood and perceived as risky by the public and some climate and energy stakeholders. To address these concerns and win support for CCS, concerted effort by all relevant players is needed. Governments need to take responsibility for explaining the role of CCS in national energy and climate strategies, also discussing its risks and the ways of addressing them.

National, regional and local government, where political, social and cultural traditions allow, should also work with important stakeholders at both national and CCS project levels to facilitate information exchange and fair dialogue. Industry must take responsibility for explaining the benefits and risks of particular CCS projects to the local population. Working actively to gain public acceptance is an integral part of any single CCS project and subsequently of wider deployment.

Other key stakeholders such as NGOs and academia can also play an important role in national and international policy development, as well as in shaping up public opinion.

Action 4: governments and international development banks should ensure that funding mechanisms are in place to support demonstration of CCS in non-OECD countries.

Some of the lowest-cost opportunities for demonstration projects, and some of the largest potential for deployment sites exist in non-OECD countries. Several international financing mechanisms like the CDM, Nationally Appropriate Mitigation Actions (NAMAs) and the Green Climate Fund have been established by the UNFCCC to facilitate climate change mitigation actions in developing countries and assist developing countries in implementing those measures that they select as appropriate for their national circumstances and priorities. These mechanisms have to be made suitable for financing CCS projects, technical studies and CCS-related policy development.

Action 5: governments should determine the role they will play in the design and operation of CO_2 transport and storage infrastructure.

Scaling up CCS deployment is not possible without transport and storage infrastructure. As policies move CCS towards commercial viability in the coming years, these components of the CCS chain will need to develop into industrial activities with established revenue streams. However, at this early stage of CCS development, there may be a need for governments to step in and initiate activities that are normally performed by the private sector. Governments should consult with stakeholders on the options for future ownership and operation of CO_2 transport and storage infrastructure, and the extent to which government co-ordination might be required.

Box 9: Example of UK government actions in determining its role in developing CCS infrastructure

As part of the United Kingdom (UK) CCS roadmap, the government identified the types and timing of actions that it will undertake in support of CCS infrastructure development. The government stated that it was willing to consider supporting the development of infrastructure through the CCS Commercialisation Programme that anticipates future demand as well as the development of local networks, provided there is clear value for money justification. Beyond the CCS Commercialisation Programme, the government's long-term strategy is that CCS infrastructure be funded through private investment and develop over time in line with demand. The UK government has also established regulatory powers to ensure that third parties can access infrastructure on a fair and equitable basis, and that new pipelines can interconnect with existing capacity in order for a network to develop.

The government sought views on how to most effectively develop the pipeline and storage capacity needed for CCS deployment as part of a consultation on developing CCS infrastructure in 2010. It was particularly interested in whether setting up a single body, whose role was to construct a pipeline and storage network (either nationally or regionally), would make it easier for the United Kingdom to make more effective decisions about the timing, scale and location of investment in CCS infrastructure. The results were inconclusive, and the government remains open to the possibility of different structural arrangements in the future.

Source: UK DECC, 2012.

It will be valuable for governments to examine patterns of current industrial production and its development in order to determine whether opportunities exist to significantly lower the public and private costs of CCS through joint development of infrastructure. Innovative approaches should also be considered to encourage the emergence of multi-user CO_2 transport and storage infrastructure in industrial clusters (*e.g.* public investment in pipeline capacity).

Timely identification of suitable CO_2 storage is paramount

This roadmap recommends the following actions	***Time frame***
Action 6: implement policies that encourage storage exploration, characterisation, and development for CCS projects.	2013-20
Action 7: implement governance frameworks that ensure safe and effective storage, encourage sound management of natural resources – including pore space – and ensure that the public is appropriately consulted in the development of storage projects.	2013-20
Action 8: continue to develop and employ co-ordinated international approaches and methodologies to improve understanding of storage resources and to enhance best practices.	2013-20
Action 9: where CO_2-EOR is being undertaken as part of geological storage operations, ensure that it is conducted under a storage-specific regulatory regime.	2013-20
Action 10: support R&D into novel technologies that could utilise significant quantities of CO_2 in a manner that leads to their permanent retention from the atmosphere.	2013-20

Identifying suitable storage capacity that can safely accept CO_2 at desired injection rates and retain this injected CO_2 is perhaps the largest challenge associated with CCS. This challenge is also exacerbated by the large amount of CO_2 to be stored unless solutions are found to significantly reduce the amount of fossil fuels used globally in power generation and industrial processes. Actions are needed to assess, identify and characterise suitable storage formations. While high-level assessments of storage resources have been carried out at national and global levels, the focus should shift now to the identification and siting of specific storage locations. Governments need to initiate or incentivise the identification of storage sites for capture projects that are under development and in planning. Some legal issues, especially those related to long-term liability and stewardship, need to be resolved to render CO_2 storage less risky for investors. Given that CO_2-EOR creates an early opportunity for CCS and makes it economical in the absence of strong climate regulations, this type of CCS should be carefully examined and regulated as CO_2 storage in addition to being subjected to regulations that are usually applied to oil fields. This will create incentives for CO_2 storage and secure the environmental integrity of CCS-EOR projects.

Action 6: implement policies that encourage storage exploration, characterisation, and development for CCS projects.

Given the length of lead times and the commercial risks associated with delivering proven storage capacity, there is a need for publicly funded regional or national pre-competitive exploration and evaluation programmes. The IEA estimates suggest that the cost of pre-competitive storage investigation work necessary to meet the 2020 roadmap goal will be in the order of the magnitude of USD 1 billion globally.

While some countries and regions have undertaken thorough assessments of potential storage capacity, others may still require specific actions in this regard. Governments (together with appropriate industrial players) should review the key gaps in storage data coverage and knowledge in all of the emissions-intensive regions/countries to establish priorities for storage exploration and characterisation. In jurisdictions where there is public ownership of subsurface resources, governments must develop processes by which the CO_2 storage resources will be allocated (*e.g.* licensing rounds for exploration blocks). Governments may consider amending (or, if appropriate, developing) subsurface resource management plans to include CO_2 storage resources.

Action 7: implement governance frameworks that ensure safe and effective storage, encourage sound management of natural resources – including pore space – and ensure that the public is appropriately consulted in the development of storage projects.

Governments should undertake a comprehensive review of their existing laws and regulations to identify barriers to storage of CO_2, and determine whether an existing regulatory framework is suited to the regulation of geologic storage. Governments should engage with industry, academia, and civil society to develop suitable laws and regulations, including permitting procedures, to enable safe and effective storage.

Governments should also ensure that the public participation requirements of environmental impact assessment processes (or other applicable storage-specific regulations) are tailored for consistency with commonly accepted best-practice principles.

Unresolved long-term liability issues have been causing concerns to the industry and contributing to the financial risks of investing in CCS. Governments should develop a clear framework for the management of long-term liability and storage site stewardship, including appropriate risk-sharing between the private and public sectors.

Action 8: continue to develop and employ co-ordinated international approaches and methodologies to improve understanding of storage resources and to enhance best practices.

To improve comparability of national/regional storage information, governments and relevant authorities and stakeholders should agree on a shared global method to estimate and classify CO_2 storage capacity. As a first step, stakeholders should share their respective methodologies and understand their differences so that these differences can be considered when data are compared across jurisdictions. They should also encourage participation of relevant industry, non-governmental organisations and intergovernmental bodies in relevant standard-making processes (*e.g.* ISO TC265 and International Maritime Organization [IMO] processes) and ensure that the knowledge gained from first-mover CCS projects is reflected in emerging technical standards. The 2006 Intergovernmental Panel on Climate Change (IPCC) Inventory Guidelines for national GHG reporting include provisions for CO_2 accounting from CCS projects. These Guidelines should be made mandatory under the UNFCCC to facilitate global consistency in treating CCS projects in terms of CO_2 emissions accounting.

Industry and the research community should also demonstrate the monitoring and verification procedures specific to the post-injection phase of CO_2 storage projects. As well, they should demonstrate techniques to manage unintended migration of CO_2 or formation fluids outside the storage complex, and develop and improve tools for predicting special reservoir and cap rock characteristics. In addition, it is important to continue advancing the state-of-the-art techniques for managing injection pressure build-up, including the production and treatment of formation fluids where necessary.

Action 9: where CO_2-EOR is being undertaken as part of long-term geologic storage operations, ensure that it is conducted under appropriate, storage-specific regulatory regimes.

It is important for governments to decide what role they consider EOR should play in long-term CO_2 storage. If EOR is to be considered a strategy for long-term storage, the relevant regulatory requirements must be put in place. In consultation with industry, governments must develop MMV frameworks suited to CO_2-EOR.

Action 10: support R&D into novel technologies that could utilise significant quantities of CO_2 in a manner that leads to their permanent retention from the atmosphere.

There are several potential uses of CO_2 that could effectively store CO_2 in material products and provide alternative business cases for CO_2 capture (see Box 3). These include mineral carbonation and CO_2 concrete curing. Today, these technologies are at a very early stage of development and further research is required to prove concepts, increase scale and demonstrate the effectiveness and cost-benefit of resulting building materials. Other uses of CO_2 for chemicals and fuels, which do not lead to permanent CO_2 storage, could play a role in providing individual early projects with an additional revenue stream. In addition to the conversion of CO_2 by algae, these applications include the production of synthetic natural gas, methanol, fertilisers, plastics and speciality chemicals. A key focus for research will be the catalytic, photocatalytic and electrocatalytic reduction of CO_2. Another critical R&D topic will be the clean production of hydrogen, which is likely to be essential for the conversion of CO_2 to products.

Improvements and cost reductions of capture technology through RD&D need to be pursued

This roadmap recommends the following actions	*Time frame*
Action 11: reduce the cost of electricity from power plants equipped with capture through continued technology development and use of highest possible efficiency power generation cycles.	2013-20
Action 12: prove capture systems at pilot scale in industrial applications where CO_2 capture has not yet been demonstrated.	2013-20
Action 13: support research into novel capture technologies and power generation cycles that will dramatically lower the cost of capture and resource consumption.	2013-20

While the current capture technologies are mature in some applications, there is much learning that is still required for others – namely certain processes in iron and steel, cement, refining, chemicals, and pulp and paper sectors. In addition, there is significant room for improvement in current, reasonably mature capture technologies, as they are relatively inefficient from the standpoint of energy requirements (*e.g.* McGlashan and Marquis, 2007; Bhown and Freeman, 2011) and water use (Zhai, Rubin and Versteeg, 2011). A forthcoming CCS technology roadmap developed by the Carbon Sequestration Leadership Forum (CSLF) provides more details on the status and needs of technological development of CCS (CSLF, 2013).

By taking the following actions, decision-makers in government and industry – including equipment manufacturers – can help drive cost reductions and the development of improved and novel capture technologies.

Action 11: reduce the cost of electricity from power plants equipped with capture through continued technology development and use of highest possible efficiency power generation cycles.

Many technical improvements are possible on capture technologies. R&D efforts have identified actions that would improve the efficiency of CO_2 capture and reduce costs. The improvements include: reduced regeneration energy requirements for solvents used in pre- and post-combustion capture; improved heat integration of the capture plant with the base plant while considering operability requirements; better management of corrosion issues for post-combustion technologies at high solvent concentrations; optimised absorber feed gas composition when using amine-based solvents to reduce solvent degradation; and reduced concentration of nitrogen oxide (NO_x), SO_2 and possibly oxygen in flue gas to minimise degradation and operational costs. These improvements can be made with dedicated R&D efforts supported by governments and industry, sharing of experiential learning, and shared research efforts that could reduce costs for all parties. Training of qualified experts would also contribute to the development and updating of new techniques and technologies. Standardised training should be developed for flue-gas scrubbing-system operators in sectors where these processes are unfamiliar.

The cost of electricity from a power plant equipped with CCS is lower when the base power plant has higher efficiency parameters. In 2012, the IEA developed a roadmap on HELE power plants, and actions in the HELE roadmap should be followed (IEA, 2012f). The HELE roadmap particularly calls for, at minimum, installation of supercritical technology on all new combustion power plants of over 300 MW.

Action 12: prove capture systems at pilot scale in industrial applications where CO_2 capture has not yet been demonstrated.

Pilot-scale tests are needed of gas scrubbing at cement kilns; gas scrubbing at steel blast furnaces; and gas scrubbing at steam and catalytic crackers.

Further research is needed into cost-effective capture techniques for gas recycling blast furnaces. Optimised solutions for aggregating CO_2 sources at refinery and petrochemical complexes for flue-gas scrubbing are also needed.

Additional improvements are required in hot gas clean-up technology, and designs for cement production based on oxy-firing must be improved to minimise air leakage into cement kilns being retrofitted with CO_2 capture. Further research enabling refractories to withstand higher operating temperatures needs to be undertaken, and the commercial viability of cement clinker produced via oxy-firing techniques has to be proved.

Options could be explored for fluidised catalytic cracking and heat and power production at refinery and petrochemical sites using oxy-firing.

Pilot-scale CCS projects on industrial installations are most beneficial if done through open-access capture pilots (similar to the pilot facility at Mongstad in Norway). Open-access approaches to projects developed with public funding could accelerate the learning curve through distributed peer review, knowledge-sharing and process transparency.

Action 13: support R&D into novel capture technologies and power generation cycles that will dramatically lower the cost of capture and resource consumption.

Novel approaches and techniques to alleviate the high energy penalty and related additional costs of CO_2 capture technologies have already been identified, but need to be pursued and tested. For example, innovative flue-gas scrubbing processes using sorbents (*i.e.* ultra-high surface area porous materials), hybrid capture systems and novel regeneration methods (*e.g.* electrolysis and electrodialysis) should be tested at pilot scale. Novel processes for oxy-fired power generation, such as oxy-fired gas turbines, should also be tested at pilot scale.

Likewise, new CO_2 separation processes for hydrogen or syngas production (*e.g.* for IGCC) such as high-temperature solvents, solid sorbents, membranes, and enhanced water-gas shift reactors should be tested. In cement production, the suitability of membranes and solid absorption processes for CO_2 capture should be tested at pilot scale, along with new production processes for industrial products that integrate low-cost CO_2 capture.

Development of CO_2 transport infrastructure should anticipate future needs

This roadmap recommends the following actions	Time frame
Action 14: encourage efficient development of CO_2 transport infrastructure anticipating locations of future demand centres and future volumes of CO_2.	2013-20
Action 15: resolve outstanding legal issues pertaining to the trans-boundary movement of CO_2 for geologic storage under the London Protocol.	2013-20
Action 16: ensure that laws and regulations are suitable for pipelines and shipping.	2013-20
Action 17: reduce the cost and risk of pipeline transport by sharing knowledge gained from experience and developing common methodologies.	2013-20

It is clear that large-scale networks will be required to transport millions of tonnes of CO_2 annually to selected storage sites at various distances from capture sites. Planning and development of transportation networks and clusters is needed now. In addition, countries will need regulations to address siting of pipelines, their safe operation and rights for third-party access.

Action 14: encourage efficient development of CO_2 transport infrastructure by anticipating locations of future demand centres and future volumes of CO_2.

Various future demands and conditions must be considered when developing transport infrastructure that will support CO_2 transportation for years to come. Among many considerations are offshore storage and the capital cost of shipping infrastructure, and oversizing and routing to minimise cost in the future. Development of integrated pipeline networks should also be considered. Governments will need to decide on what role they intend to play in at least the first steps of CO_2 transport infrastructure development.

Action 15: resolve outstanding legal issues pertaining to the trans-boundary movement of CO_2 for geological storage.

Annex 1 of the 1996 London Protocol was amended in 2006, with the intent of allowing trans-boundary movement of CO_2 for offshore geological storage. However, the ratification of the amendment by contracting parties has proven difficult; contracting parties must therefore continue to pursue this ratification to enable trans-boundary movement of CO_2. In the absence of ratification of this amendment of the London Protocol, they could consider alternative approaches to enable such movements of CO_2 (*e.g.* provisional application, separate agreement between contracting parties).

Action 16: ensure that laws and regulations are suitable for pipelines and shipping.

Laws and regulations that facilitate infrastructure siting must be adapted to include CO_2 pipelines. It must be ensured that health and safety laws and regulations pertaining to pipelines are adequate for CO_2 transport, including requirements for monitoring, and public participation provisions should be included in CO_2 transportation regulations. Governments should establish market rules for transport providers by 2020.

Action 17: reduce the cost and risk of pipeline transport through knowledge sharing and use of common methodologies.

While transport of CO_2 is the most mature technology of the CCS chain, improvements are still possible and desirable. CO_2 behaviour during leakage events could be better understood so that appropriate and cost-effective mitigation plants could be developed. International standards would provide guidance and confidence to the transport industry and governments hosting CO_2 transportation routes; relevant industry should be encouraged to participate in pertinent standard-making processes (*e.g.* ISO TC265 and IMO processes). Governments and industry should ensure that the lessons from first-mover CCS demonstration projects are reflected in emerging technical standards.

Actions and milestones for 2020 to 2030: large-scale deployment picks up speed

Our vision to 2030: CCS grows into an industry, with large-scale deployment picking up speed; continued R&D and economies of scale reduce costs significantly; business cases are consolidated and drive private investment.

*An objective observer who, in 2030, looks at the progress in CCS deployment since 2020 will see a technology that has grown explosively and matured greatly over the past decade. Over the decade 2020 to 2030, CCS will have been deployed on two out of every three new coal-fired power plants, and one out of eight gas- or biomass-fired power plants – hundreds of gigawatts of CCS-equipped generation capacity, primarily in OECD member countries and China. Bioenergy with CCS and biofuel plants equipped with CCS will have begun to play an important role in removing CO_2 from the atmosphere (Box 10). In addition, almost one-third of global gas processing capacity will be CCS-equipped, along with large amounts of biofuel, chemicals, and hydrogen production capacity (in refining). While most capture processes employ improved versions of tried-and-true solutions (*e.g.* amine-based absorption), new processes are under testing at pilot scales, and a portfolio of novel technologies – including production processes with inherent CO_2 separation – are under development.*

*Such growth will have been driven by the creation of sound business models for private companies involved in developing capture, transport and storage projects. Positive results from CCS projects will have yielded the confidence and wide acceptance of the public. In the first half of the decade, incentives for CCS in most applications will have been transitioned from demonstration-phase mechanisms to early deployment (e.g. quantity commitments or portfolio standards). At the same time, a CCS-focused service industry has emerged, engaged in developing storage solutions for individual projects and the financial valuation of pore space as a resource. This service industry also explores and develops tens of billions of tonnes of CO_2 storage capacity. During the decade, storage regulations have been revised in many regions to ensure that they reflect the emerging body of knowledge. By the latter half of the decade, a networked pipeline infrastructure that moves billions of tonnes of CO_2 annually has emerged in many places, reducing the commercial risks from failure of any single piece of infrastructure (*e.g.* storage sites).*

Box 10: Combining CCS with biomass energy sources

Bioenergy with carbon capture and storage (BECCS) is an emissions reduction technology offering permanent net removal of CO_2 from the atmosphere. BECCS works by using biomass that has removed atmospheric carbon during its growth cycle, and then permanently storing underground the CO_2 emissions that result from its combustion or fermentation. A decrease in the amount of CO_2 in the atmosphere results from the combination of the benefits of biomass use with the benefits of CCS, with the ultimate aim of storing more CO_2 from biomass use than that emitted from fossil fuel use.

While BECCS has significant potential, it is important to ensure that the biomass is produced sustainably, as this will significantly impact the level of emissions reduction that can be achieved, and will hence define "how negative" the resulting emissions can be (IEAGHG, 2011c). BECCS can be applied to a wide range of biomass conversion processes and may also be attractive from a relative cost perspective. Applications range from capturing CO_2 from biomass co-firing and biomass-fired power plants, to biofuel production processes. To date, however, BECCS has not been fully recognised or realised. Incentive policies to support it need to be based on an assessment of the net impact on emissions that the technology can achieve. The IEA (2011c) recommends that, to the greatest extent possible, all carbon impacts of BECCS be fully reflected in carbon reporting and accounting systems under the UNFCCC and Kyoto Protocol. A solid understanding of the life-cycle emissions savings that BECCS could achieve will be an essential prerequisite for well-calibrated BECCS support. BECCS merits a specific set of incentives that reflects the negative life-cycle emissions that BECCS can achieve compared to emissions reductions of other CCS applications.

Source: IEA, 2012c.

Our vision foresees a significant industrial-scale ramp-up of CCS deployment during the 2020s, as compared with this decade (*i.e.* through 2020). Achieving this vision will require many actions to be taken. While many of the actions below may be applicable only as of 2020, it is important to consider them now as part of a co-ordinated policy framework for CCS, as they will influence the decisions to be taken before 2020. The underlying assets to which CCS will be applied (*e.g.* coal-fired power plants, steel mills) have a lifespan of multiple decades and require many years of advance planning. We also stress that, in addition to the specific actions listed below, the success of the period 2020 to 2030 will depend on the success of the actions from 2013 to 2020 which are necessary to create the conditions for rapid deployment of CCS between 2020 and 2030.

This roadmap recommends the following actions	***Time frame***
Action 18: governments should manage the transition from demonstration phase support to wider deployment mechanisms.	2020-30
Action 19: governments in non-OECD member countries should build on global CCS demonstration project experiences and develop appropriate support mechanisms to encourage deployment.	2020-30
Action 20: increase RD&D collaboration among nations to further decrease the electricity cost and resource footprint of fossil-fuel plants equipped with capture.	2020-30
Action 21: encourage R&D into innovative and novel processes that will reduce the cost of production equipped with CCS.	2020-30
Action 22: encourage the development of integrated transport and storage networks to reduce risk to network users from failures or bottlenecks in the system. Enable long-distance, cross-border, multi-modal transport of CO_2.	2020-30
Action 23: continue learning and improvement in developing best practices for storage and its regulation.	2020-30
Action 24: foster a commercial environment for geological storage.	2020-30

Action 18: governments should manage the transition from demonstration-phase support to wider deployment mechanisms.

An evolving policy framework needs to be in place that allows graduation from targeted support for early CCS demonstration projects to wider sector-specific quantity mechanisms, such as feed-in tariffs or portfolio standards. These policies will complement carbon pricing and drive private financing of CO_2 capture. The emphasis of support mechanisms should start to shift from technology learning to achieving significant emissions reductions through CCS early in this period.

By this period, the roadmap anticipates that a global emissions reduction framework will be in operation, through which long-term and ambitious GHG emissions reduction goals are established, along with mechanisms and tools to facilitate their attainment. This framework should create certainty for national policy makers as well as private sector players that any investments in low-carbon technologies and measures will have increasing value over time. In this context, costly investments in all steps of the CCS process will be more easily justified. However, given that carbon prices – or the equivalent policies – may not quickly reach levels to make CCS-equipped facilities competitive in the marketplace, and also recognising that other market and non-market barriers will exist, sector-specific support mechanisms are likely to be needed for early projects. Support will also be needed to facilitate storage and transport infrastructure development at scale.

Action 19: governments in non-OECD member countries should build on global CCS demonstration project experiences and develop appropriate support mechanisms to encourage deployment.

It is expected that there will be significant gains in CCS technology experience and confidence in the period to 2020 in OECD, and some non-OECD countries. These achievements should motivate an increasing number of non-OECD governments to develop strategies for CCS deployment that build on international support mechanisms. International mechanisms should be available to support these efforts, such as those that were developed under the UNFCCC. Non-OECD governments should ensure that CCS-specific mechanisms proven to be effective in other countries that had an earlier start are integrated into their broader domestic frameworks for CO_2 emissions reduction. In addition, innovative approaches to technology licensing and knowledge transfer will be helpful.

Action 20: increase RD&D collaboration among nations to further decrease the electricity cost and resource footprint of fossil-fuel plants equipped with capture.

Reductions in the cost of capture will be achieved through the deployment of diverse capture technologies in different plant applications, and harnessing the lessons learnt from each new project. The costs and resource footprint of fossil-fuel power generation with CCS could further be reduced by: employing standardised and modular designs for CO_2 capture systems; further developing and employing membranes (*e.g.* ion-transport membranes) for air separation and commercial gas turbines that are suitable for near-100% hydrogen firing; considering intermediate syngas or hydrogen storage options that allow optimisation of the gasifier island and more flexible operation; optimising energy requirements for CO_2 separation using solvents, solid sorbents, membranes or low temperatures; and developing capture technologies and power cycles that dramatically reduce water consumption. These technical improvements require testing and piloting that industry will most likely find reasonable to support if the demand for CCS technologies continues to grow.

Action 21: encourage R&D into innovative capture processes that will reduce the costs of producing goods and electricity at CCS-equipped plants.

Novel and innovative approaches to CO_2 capture could significantly reduce the energy penalty and cost of capture given the relative inefficiency of current systems. Research at laboratory and bench-scales into novel capture approaches should continue to receive significant funding. Promising approaches to gas scrubbing include: novel sorbents (*e.g.* ultra-high surface area porous materials), hybrid capture systems and novel regeneration methods (*e.g.*, electrolysis and electrodialysis). Novel CO_2 separation approaches to hydrogen or syngas production (*e.g.* for IGCC) include: high-temperature solvents, solid sorbents, membranes and enhanced water-gas shift reactors. In particular, novel approaches for capture from cement production (*e.g.* membranes and solid absorption processes) should be an area of focus, along with new production processes for industrial products that integrate low-cost CO_2 capture.

Action 22: encourage the development of integrated transport and storage networks that will reduce the impacts of any failures or bottlenecks in the CO_2 transport and storage system.

During the period 2020 to 2030, the volume of CO_2 captured and stored per year should increase up to forty-fold. This necessitates the building and operation of a significant pipeline infrastructure. CO_2 transport systems to accommodate the long-distance movement of CO_2 using combinations of ship and pipeline infrastructure will need to be expanded rapidly if a significant proportion of the CCS deployment envisaged comes into operation between 2020 and 2030. Opportunities for the integration of CO_2 transport networks across national borders, particularly in member states of OECD Europe, will need to be explored thoroughly and as early as possible. Early adoption of the

London Protocol amendment to enable trans-boundary movement of CO_2 for offshore geological storage will be greatly beneficial.

Action 23: continue learning and improvement in developing best practices for storage and its regulation.

International processes that seek to harmonise national law and regulation pertaining to CO_2 monitoring and verification in line with development of international markets for CO_2 storage will be important if lowest-cost storage is to be accessed. In addition, governments should, in consultation with industry and civil society, review and, where necessary, revise laws and regulations pertaining to the safe and effective storage of CO_2 based on global experience and emerging best practices.

Action 24: foster a commercial environment for geological storage.

Encourage development of a supply chain, consisting of a variety of independent service companies, for geological storage of CO_2 that converts pore-space resources into commercially available storage capacity, in compliance with appropriate safety and environmental regulation. Modify financial accounting standards to allow valuation of discovered pore space by capital markets.

Actions and milestones after 2030: CCS goes mainstream

Our vision beyond 2030: in 2050 CCS is routinely used to reduce CO_2 emissions from fossil fuel power plants and all suitable industrial applications.

All new coal-fired power plants, one out of two gas-fired power plants, and one out of five biomass-fired power plants are equipped with CCS; by 2050, a total of over 950 GW of power generation capacity is equipped with capture. Between 25% and 40% of all production of steel, cement and chemicals are equipped with CCS globally.

The total global storage rate exceeds 7 gigatonnes of carbon dioxide per year ($GtCO_2$/yr); CO_2 storage is a well-developed industry exceeding the size of gas and oil industry in 2013; by 2050, around 120 $GtCO_2$ have been stored in geological storage sites around the world, and the exploration and storage industry has projects in development to meet a market demand of 10 $GtCO_2$/yr.

Policy conditions are such that CCS projects are commercial under technology-neutral climate change policies worldwide in all sectors.

The period after 2030 involves the continuation and consolidation of actions in progress in 2030, leading to a significant ramp-up of the CCS industry. It is assumed that governments and industry will conduct regular evaluation of the status and deployment of CCS technologies and design follow-up policies, R&D, financing and other actions accordingly.

Near-term actions for stakeholders

The next seven years are critically important for putting CCS onto a sound path toward full deployment in line with international climate goals. It is strongly recommended that governments and key stakeholders implement all the actions outlined in the main section of this roadmap. However, the following seven key actions represent the backbone of activities absolutely necessary during the seven years up to 2020. They are challenging but realistic and spread across all three elements of the CCS chain; they will require serious dedication by governments and industry. A strong commitment by governments to significantly reduce GHG emissions will create an environment conducive to the actions required for CCS deployment. While international discussions on a global, long-term climate regime are not finalised, governments need to create business cases for CCS through supportive policies and regulations.

Lead stakeholder	*Actions*
Government	Introduce financial support mechanisms for demonstration and early deployment of CCS to drive private financing of projects.
Government	Implement policies that encourage storage exploration, characterisation, and development for CCS projects.
Government	Develop national laws and regulations as well as provisions for multilateral finance that effectively require new-build, base-load, fossil-fuel power generation capacity to be CCS-ready.
Industry	Prove capture systems at pilot scale in industrial pilot applications where CO_2 capture has not yet been demonstrated.
Government	Significantly increase efforts to improve understanding among the public and stakeholders of CCS technology and the importance of its deployment.
Industry/R&D	Reduce the cost of electricity from power plants equipped with capture through continued technology development and use of highest possible efficiency power generation cycles.
Government	Encourage efficient development of CO_2 transport infrastructure by anticipating locations of future demand centres and future volumes of CO_2.

Annex 1. Detailed actions

Actions 2013 to 2020

2020 actions	Integrated CCS

Action 1. Introduce financial support mechanisms for demonstration and early deployment of CCS to drive private financing of projects:

a. introduce specific financial mechanisms that stimulate CCS deployment, including direct financial support by governments, direct operational support, tools to address competitiveness issues, and support for the development of infrastructure; leverage existing markets for CO_2 utilisation where possible;
b. create mechanisms by which the knowledge gained from early CO_2 demonstration projects is shared and contributes to improved design of subsequent projects;
c. establish co-operation between countries to ensure that a global portfolio of demonstration projects covers the range of possible CO_2 sources and storage geologies;
d. as CCS technology passes through the gateway from the demonstration to the early deployment phase, governments should manage the transition from demonstration to early deployment support policies.

Action 2. Develop national laws and regulations as well as provisions for multilateral finance that effectively require new-build, base-load, fossil-fuel power generation capacity to be CCS-ready:

a. include and enforce a requirement on CCS readiness on all new power stations as above;
b. ensure that the provisions mandate the CCS-ready status to be maintained.

Action 3. Significantly increase efforts to improve understanding among the public and stakeholders of CCS technology and the importance of its deployment.

Action 4. Governments and international development banks should ensure that funding mechanisms are in place to support demonstration of CCS in non-OECD countries:

a. operationalise international financing mechanisms like CDM, NAMAs and Green Climate Fund to be relevant for CCS.

Action 5. Governments should determine the role they will play in the design and operation of CO_2 transport and storage infrastructure:

a. consult with stakeholders on the options for future ownership and operation of CO_2 transport and storage infrastructure, and the extent to which government co-ordination – and perhaps regulation – might be required;
b. examine patterns of current industrial production and its future development in order to determine whether opportunities exist to significantly lower the public and private costs of CCS through joint development of infrastructure;
c. consider innovative approaches to encourage the emergence of multi-user CO_2 transport and storage infrastructure in industrial clusters.

2020 actions	CO_2 storage

Action 6. Implement policies that encourage storage exploration, characterisation and development for CCS projects:

a. implement publicly funded regional or national pre-competitive exploration and evaluation programmes;
b. make public funds available for pre-commercial storage work at the scale of USD 1 billion to USD 6 billion globally by 2020;
c. review the key gaps in storage data coverage and knowledge in all of the emissions-intensive regions/countries to establish priorities for storage exploration and characterisation;
d. in jurisdictions where there is public ownership of subsurface resources, governments to develop processes by which the CO_2 storage resources will be allocated (*e.g.* licensing rounds for exploration blocks);
e. amend (or, if appropriate, develop) subsurface resource management plans to include CO_2 storage resources.

Action 7. Implement governance frameworks that ensure safe and effective storage, encourage sound management of natural resources – including pore space – and ensure that the public is appropriately consulted in the development of storage projects:

a. governments to undertake a comprehensive review of existing laws and regulations to identify barriers to storage of CO_2, and determine whether existing frameworks are suited for the regulation of geologic storage;
b. where necessary, governments to engage with industry, academia, and civil society to develop suitable laws and regulations, including permitting procedures, to enable safe and effective storage;
c. governments to ensure that the public participation requirements of environmental impact assessment processes (or other applicable storage-specific regulations) are tailored to be consistent with best-practice principles;
d. develop a clear framework for the management of long-term liability and storage site stewardship.

Action 8. Continue to develop and employ co-ordinated international approaches and methodologies to improve understanding of storage resources and to enhance best practices:

a. agree on a shared global method to estimate and classify CO_2 storage capacity;
b. encourage participation of relevant industry in relevant standard-making processes (*e.g.* ISO TC265 and IMO processes);
c. ensure that the learnings from first-mover CCS demonstration projects are reflected in emerging technical standards;
d. ensure that technical standards reflect best available technology and encourage further technology development;
e. adopt 2006 IPCC Inventory Guidelines as mandatory for GHG reporting under the UNFCCC;
f. demonstrate the performance of monitoring and verification procedures specific to the post-injection phase of CO_2 storage projects;
g. develop algorithms for the optimal design of integrated monitoring networks;
h. demonstrate techniques to manage unintended migration of CO_2 or formation fluids outside the storage complex;
i. develop and improve tools for predicting special reservoir and cap rock characteristics;
j. advance the state-of-the-art technologies and processes for managing injection pressure build-up, including the production and treatment of formation water.

Action 9. Where CO_2-EOR is being undertaken as part of long-term geological storage operations, ensure that it is conducted under appropriate, storage-specific regulatory regimes:

a. governments to decide and give guidance on what role CO_2-EOR is to play in conjunction with long-term CO_2 storage;
b. governments to develop relevant regulatory requirements;
c. government, the research community and industry to develop MMV techniques and frameworks suited to CO_2-EOR.

Action 10. Support R&D into novel technologies that could utilise significant quantities of CO_2 in a manner that leads to their permanent retention from the atmosphere:

a. a key focus for research will be the catalytic, photocatalytic and electrocatalytic reduction of CO_2;
b. another critical R&D topic will be the clean production of hydrogen, which is likely to be essential for the conversion of CO_2 to products.

2020 actions	***CO_2 capture***

Action 11. Reduce the cost of electricity from power plants equipped with capture through continued technology development and use of highest possible efficiency power generation cycles:

a. implement recommendations of the IEA HELE roadmap on efficient fossil-fuel power generation;
b. reduce overall electricity output penalties for solvents used in pre- and post-combustion capture;

c. improve heat integration of the capture plant with the base plant while considering operability requirements;
d. co-optimise construction materials and solvent formulations for specific power plants and other applications;
e. better manage corrosion issues for post-combustion technologies at high solvent concentrations;
f. optimise absorber feed gas composition when using amine-based solvents to reduce solvent degradation;
g. reduce the upstream concentration of NO_x, SO_2 and oxygen in flue gas to levels that minimise formation of heat-stable salts and other degradation products that affect solvent CO_2 absorption characteristics and increase solvent make-up costs;
h. consider using staged combustion design as a means of reducing upstream concentration of NO_x;
i. develop operator training and strategies for improved operation under arranged operating conditions.

Action 12. Prove capture systems at pilot scale in industrial applications where CO_2 capture has not yet been demonstrated, for example:
a. create open-access capture pilots (Mongstad sets an example);
b. conduct pilot-scale tests of flue-gas scrubbing at cement kilns;
c. conduct pilot-scale tests of flue-gas scrubbing at steel blast furnaces;
d. conduct pilot-scale tests of flue-gas scrubbing at steam crackers;
e. stimulate further research into the most cost-effective capture techniques to use on gas recycling blast furnaces;
f. develop optimised solutions for aggregating CO_2 sources at refinery and petrochemical complexes for flue-gas scrubbing;
g. use pilot-scale tests to optimise designs for cement production based on oxy-firing;
h. develop techniques to minimise air leakage into cement kilns for retrofitting with CO_2 capture;
i. explore options for fluidised catalytic cracking and heat and power production at refinery and petrochemical sites using oxy-firing;
j. prove the commercial viability of cement clinker produced via oxy-firing techniques;
k. undertake further research on refractories to enable them to withstand higher operating temperatures;
l. examine options for reducing the LCOE and/or reducing CCS costs from gasification-based systems by other co-benefits such as hydrogen production.

Action 13. Support R&D into novel capture technologies and power generation cycles that will dramatically lower the costs of capture and resource consumption:
a. novel gas scrubbing processes such as innovative sorbents;
b. hybrid capture systems;
c. novel regeneration methods such as electrolysis;
d. oxy-fired gas turbines;
e. novel CO_2 separation processes for hydrogen or syngas production such as high-temperature solvents, solid sorbents, membranes and enhanced water-gas shift reactors;
f. membranes and solid absorption processes for CO_2 capture from cement production.

2020 actions	***CO_2 transport***

Action 14. Encourage efficient development of CO_2 transport infrastructure by anticipating locations of future demand centres and future volumes of CO_2:
a. consideration of offshore storage and capital cost of shipping infrastructure;
b. oversizing or "right-sizing" and routing to minimise cost in the future;
c. move towards development of integrated pipeline networks.

Action 15. Resolve outstanding legal issues pertaining to the trans-boundary movement of CO_2 for geologic storage under the London Protocol :

a. continue to pursue ratification of the London Protocol amendment to enable trans-boundary movement of CO_2 for offshore geological storage;
b. in the absence of ratification of the amendment of the London Protocol, consider alternative approaches to enable such movements of CO_2 (*e.g.* provisional application, separate agreement between contracting parties).

Action 16. Ensure that laws and regulations and market structures are suitable for pipelines and shipping:
a. ensure that laws and regulations that facilitate infrastructure siting are adapted to include CO_2 pipelines;
b. ensure that health and safety laws and regulations pertaining to pipelines are adequate for CO_2 transport, including requirements for monitoring;
c. governments should create market rules and incentives for transport providers.

Action 17. Reduce the cost and risk of pipeline transport by sharing knowledge gained from experience and developing common methodologies:
a. improve understanding of CO_2 behaviour during leakage events;
b. encourage participation of relevant industry in relevant standard-making processes (*e.g.* ISO TC265 and IMO processes);
c. ensure that the learnings from first-mover CCS demonstration projects are reflected in emerging technical standards.

Actions 2020 to 2030

2030 actions	Integrated CCS

Action 18. Governments should manage the transition from demonstration-phase support to wider deployment mechanisms (*e.g.* quantity commitments or portfolio standards) that complement carbon pricing and drive private financing of CO_2 capture in power generation in OECD member countries.

Action 19. Governments in non-OECD member countries should build on global CCS demonstration project experiences and develop appropriate support mechanisms to encourage deployment (*e.g.* international consortium and innovative licensing, knowledge transfer, use of available international financing tools).

2030 actions	CO_2 capture

Action 20. Increase RD&D collaboration among nations to further decrease the electricity cost and resource footprint of fossil-fired plants equipped with capture. For example:
a. use standardised and modular designs for CO_2 capture systems wherever possible;
b. develop capture technologies and power cycles that dramatically reduce water consumption;
c. demonstrate use of membranes for air separation;
d. provide commercial turbines that are suitable for near-100% hydrogen firing;
e. consider syngas or hydrogen storage options that allow optimisation of the gasifier island sizing and more flexible operation;
f. optimise the overall electricity output penalty for CO_2 separation using solvents, solid sorbents, membranes or low temperatures and subsequent compression.

Action 21. Encourage R&D into innovative and novel processes that will reduce the cost of production equipped with CCS:
a. test novel flue-gas scrubbing processes such as novel sorbents (*e.g.* ultra-high surface area porous materials), hybrid capture systems, and novel regeneration methods (*e.g.* electrolysis and electrodialysis) at pilot scale;
b. test novel processes for oxy-fired power generation, such as oxy-fired gas turbines, at pilot scale;

c. test novel CO_2 separation processes for hydrogen or syngas production (*e.g.* for IGCC) such as high-temperature solvents, solid sorbents, membranes, and enhanced water-gas shift reactors at pilot scale;
d. test the suitability of membranes and solid absorption processes for CO_2 capture from cement production at pilot scale;
e. develop new production processes for industrial products that integrate low-cost CO_2 capture.

2030 actions	***CO_2 transport***

Action 22. Encourage the development of integrated transport and storage networks that will reduce the impacts of any failures or bottlenecks in the CO_2 transport and storage system:
a. expand CO_2 transport systems to accommodate the long-distance movement of CO_2 using combinations of ship and pipeline infrastructure;
b. examine opportunities for integration of CO_2 transport networks across national borders, in particular in OECD Europe member states;
c. adopt the London Protocol amendment to enable trans-boundary movement of CO_2 for offshore geological storage.

2030 actions	***CO_2 storage***

Action 23. Continue learning and improvement in developing best practices for storage and its regulation:
a. engage in international processes to harmonise national laws and regulations pertaining to CO_2 monitoring and verification, in line with development of international markets for CO_2 storage;
b. governments should, in consultation with industry, review and, where necessary, revise laws and regulations pertaining to the safe and effective storage of CO_2 based on global experience and emerging best practices.

Action 24. Foster a commercial environment for geological storage:
a. encourage development of a supply chain, consisting of a variety of independent service companies, for geological storage of CO_2 that converts pore-space resources into commercially available storage capacity, in compliance with relevant safety and environment regulations;
b. modify financial accounting standards to allow valuation of discovered pore space by capital markets.

Milestones 2030 to 2050

Capture	Around 964 GW of power generation capacity equipped with capture worldwide. All new coal-fired power plants, one out of two gas-fired power plants, and one out of five biomass-fired power plants equipped with CCS. Annual CO_2 capture rate in second-phase industry is around 2.8 $GtCO_2$/yr. Annual CO_2 capture rate in first-phase industry is about 0.9 $GtCO_2$/yr.
Transport	Transportation infrastructure capable of moving over 7 $GtCO_2$/yr.
Storage	Over 120 $GtCO_2$ stored in geological storage sites around the world. An established exploration and storage industry has projects in development to meet a market demand of 10 $GtCO_2$/yr.
Integrative	CCS projects commercial under technology-neutral climate change policies worldwide in all sectors in accordance with pre-defined policy gateways.

Annex 2. CCS deployment in IEA scenarios: regional and sectoral specificities

This annex details CCS deployment under the IEA *ETP 2012* 2DS. Supplementary to the "Vision for CCS" chapter in this roadmap, this annex provides information regarding the deployment of CCS geographically and in different sectors. This annex also details certain aspects of CCS cost.

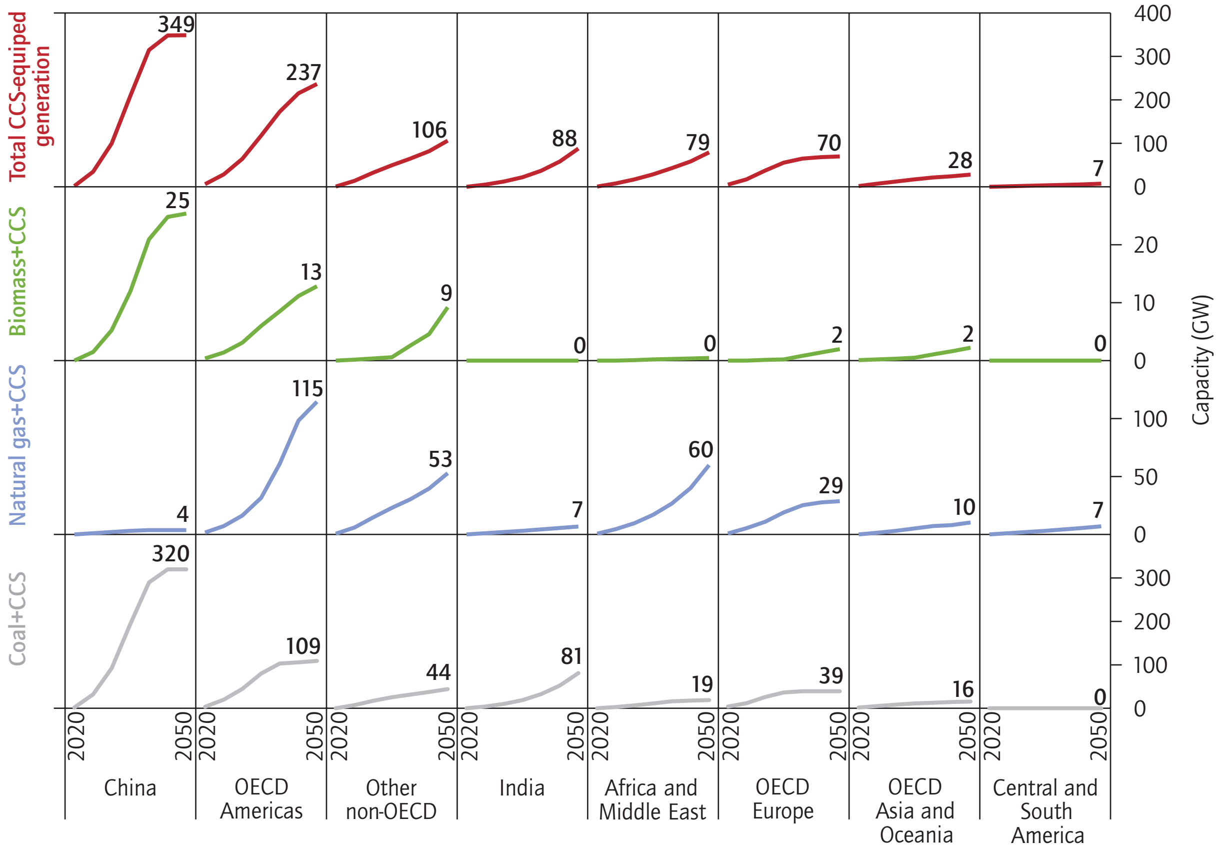
CCS in the electricity sector

In the 2DS, capture-equipped power generation is installed in almost all regions of the world. By 2050, 15% of net power generation could come from CCS-equipped plants. However, the types of power generation equipped with CCS (*i.e.* coal, gas and biomass), the amount of generation capacity, and rates at which this capacity is built vary widely from region to region. Of the total 964 GW of power generation capacity equipped with capture in the 2DS in 2050, over 60% (586 GW) are located in China and the OECD Americas (principally the United States). However, as Figure 8 shows, in China more than 90% of this capacity is coal-fired, while in the United States only about half of capture-equipped capacity is coal-fired, the remainder being mainly gas-fired capacity.

Other regions of the world where a substantial amount of gas-fired capacity is capture-equipped include the Middle East, OECD Europe and Southeast Asia. In the Middle East, it is particularly noteworthy that over 90% of capture-equipped capacity is gas-fired.

The rate of CCS deployment and the year in which deployment starts differ widely around the world in the 2DS. India, Southeast Asia, Russia, and Africa do not have any capture-equipped capacity in 2020 while OECD member countries have nearly 13 GW, with smaller amounts in China and the Middle East.

Figure 8: Coal, gas, and biomass-fired power generation capacity equipped with capture (as well as sum of capacity) for ten regions of the world 2020-50 in the 2DS



KEY POINT: regions of the world vary significantly in the way CCS is deployed in power generation.

By 2050, the growth in capture-equipped capacity has flattened in China, OECD Europe, and Africa; however, the amount of CCS-equipped capacity continues to grow rapidly in India, the Middle East, and Southeast Asia. In most countries, the absolute growth rate in capture-equipped capacity of all types occurs between 2030 and 2040 in the 2DS, with the growth rate in biomass generally peaking later than for coal or gas-fired capacity.

The impact of the addition of capture in power generation applications is reflected in the LCOE. In the absence of a CO_2 price, the LCOE produced by a power plant with CCS is higher than that of a similar plant without CCS due to the increased capital cost of the power plant, additional fuel consumption due to the capture process, and increased consumption of other resources. In the 2DS, the increase in LCOE ranges from 33% for natural gas combined cycle (NGCC) with post-combustion capture to 64% for pulverised coal (PC) plants with post-combustion or oxy-combustion capture (Table 4).

It is important to note, however, that the capital costs and efficiencies of power plants equipped with capture are expected to improve as capacity increases due to learning effects (McDonald and Schrattenholzer, 2001; Rubin *et al.*, 2007). There is

Table 4: Average cost and performance impact of adding CO_2 capture in OECD countries

	Coal			*Natural gas*
Capture route	**Post-combustion**	**Pre-combustion**	**Oxy-combustion**	**Post-combustion**
Reference plant without capture	PC	IGCC (PC)	PC	NGCC
Net efficiency with capture (LHV, %)	30.9	33.1	31.9	48.4
Net efficiency penalty (LHV, percentage points)	10.5	7.5	9.6	8.3
Relative net efficiency penalty	25%	20%	23%	15%
Overnight cost with capture (USD/kW)	3 808	3 714	3 959	1 715
Overnight cost increase (USD/kW)	1 647	1 128 (0)	1 696	754
Relative overnight cost increase	75%	44% (0%)	74%	82%
LCOE with capture (USD/MWh)	107	104	102	102
LCOE increase (USD/MWh)	41	29 (0)	40	25
Relative LCOE increase	63%	39% (0%)	64%	33%
Cost of CO_2 avoided (USD/tCO_2)	58	43 (55)	52	80

Notes: average figures for OECD member countries do not include cost of CO_2 transportation and storage.

LHV = low heating value; kW = kilowatt; MWh = megawatt hour; tCO_2 = tonne of carbon dioxide.

The accuracy of capital cost estimates from conceptual design studies is on average ± 30%; hence, for coal the variation in average overnight costs, LCOE and cost of CO_2 avoided between capture routes is within the uncertainty of the study.

Underlying oxy-combustion data include some cases with CO_2 purities < 97%. Overnight costs include owners', engineering procurement construction (EPC) and contingency costs, but not interest during construction (IDC).

A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared with a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations.

Source: IEA, 2011b.

KEY POINT: applying CCS to a power plant is expected to increase the LCOE by between one-third and two-thirds depending on the type of plant; however, the LCOE and cost of CO_2 avoided is competitive with alternative low-carbon electricity generation options.

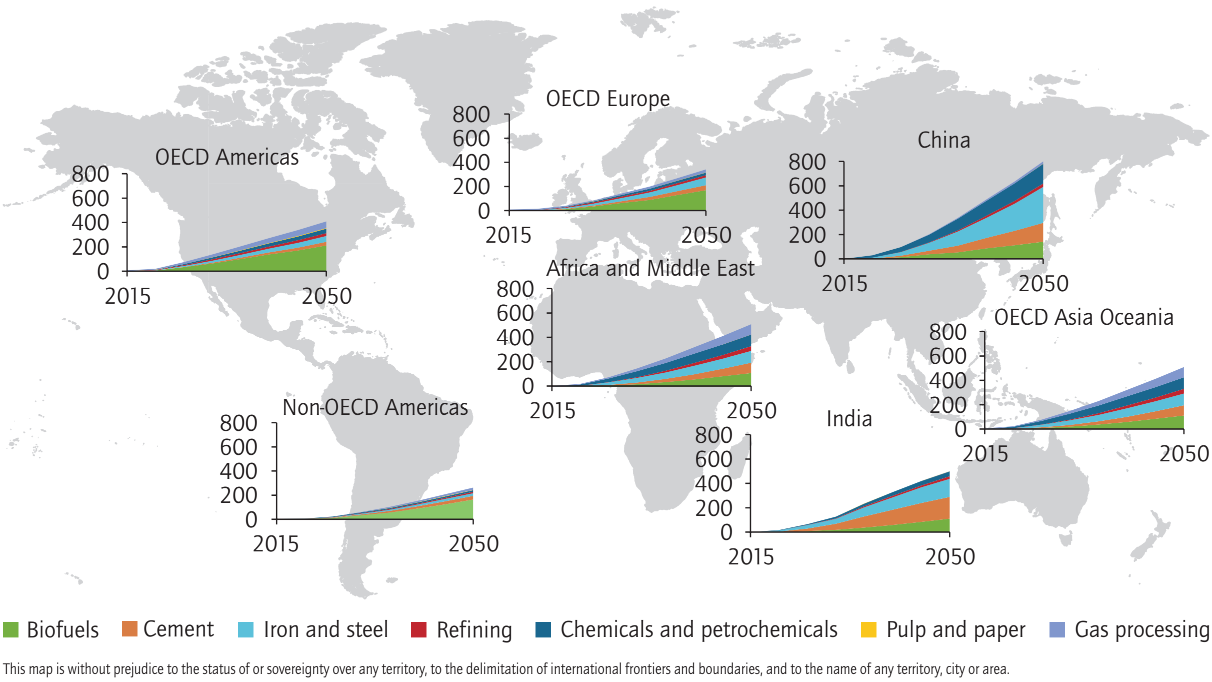
also significant potential to improve technologies and reduce some parts of the cost (*e.g.* Bhown and Freeman, 2011). For example, a novel amine capture technology for CO_2 emissions has been developed by Huaneng/Xi'an Thermal Power Research Institute. It has a lower regeneration heat and hence reduces the power generation penalty. A reduced level of thermal and oxidative degradation was also observed. The reduced power generation penalty and reduced solvent degradation give a modest but tangible cost advantage relative to a conventional 30% monoethanolamine-based solvent (Jones, McVey and Friedman, 2012).

The CO_2 price at which a power plant with CCS is more competitive than a similar plant without CCS can be expressed by the cost of CO_2 avoided, which ranges from USD 40 per tonne of CO_2 to USD 80 per tonne of CO_2. Compared to other dispatchable low-carbon generation options (*e.g.* nuclear, large-scale hydro, and concentrating solar power with energy storage), the LCOE of fossil fuels with CO_2 capture (including estimated transport and storage costs) is reckoned to be competitive.

CCS in industrial applications

In the 2DS, industrial applications of CCS are equally important to the application of CCS in power generation at the global level. However, in some regions, such as the OECD Pacific, and in some non-OECD member countries (*e.g.* India), industrial applications of CCS are far more important than applications in power generation (Figure 8). CO_2 is generated as an unavoidable by-product of the processes by which steel, cement and some chemicals are made. In these processes it is not possible to mitigate these emissions through increased efficiency and renewable energy. Fortunately, in many of these processes, the CO_2 is relatively pure and easy to capture. To achieve emissions reductions of over 50% in these sectors, and to follow a lowest-cost CO_2 mitigation pathway for the economy as a whole, CCS is highly likely to play a major role.

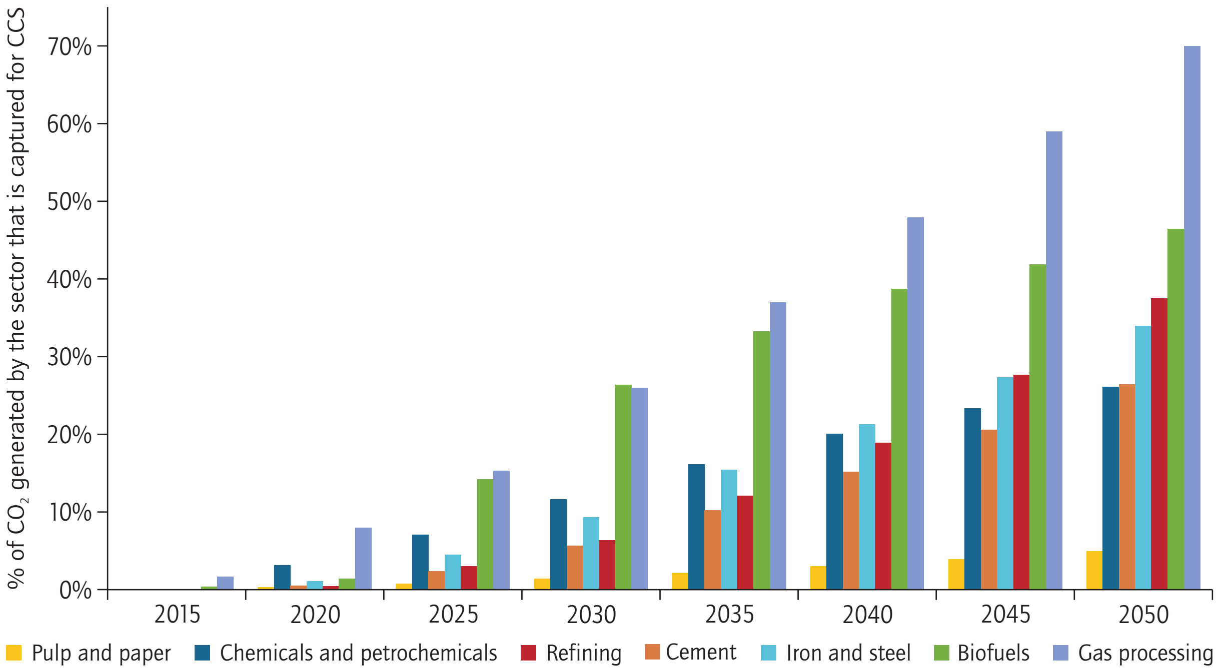
Figure 9: CO_2 captured from industrial applications in the 2DS, by source region for seven key regions



KEY POINT: the industrial sectors in which CCS is deployed in the 2DS scenario vary between regions. These sectors have their own technologies and challenges; a one-size-fits-all approach will not suffice.

Not all sectors deploy CCS at the same speed. While applications such as gas processing and ammonia make up much of the deployment between now and 2025, by 2030 second-phase industrial applications have overtaken them in amount of CO_2 captured and stored. The implication is that by 2025 applications such as iron and steel blast furnaces, cement kilns, and flue-gas scrubbing of refinery flue gases must reach the level of commercial maturity that is seen for first-phase industrial applications today. In today's financial and policy environment this is likely to demand targeted public investments in pilot and demonstration projects and rapid diffusion of the resulting lessons.

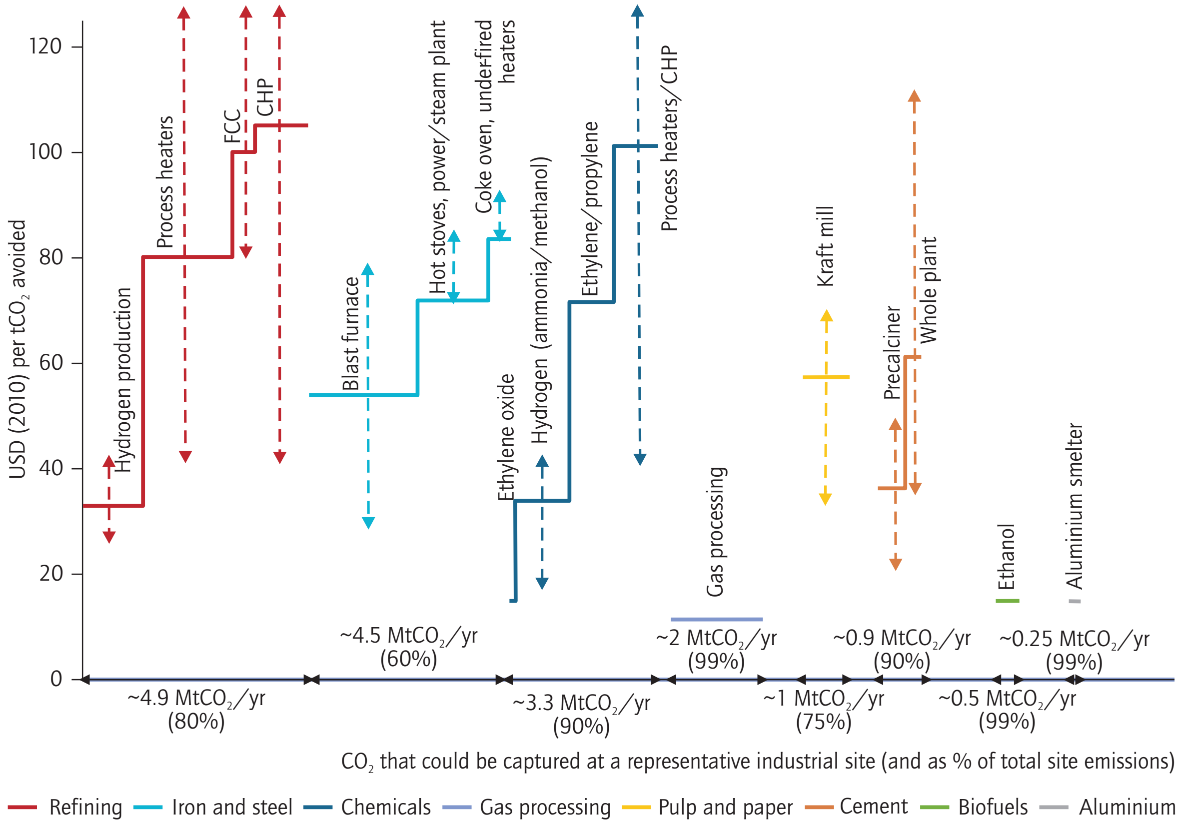
Figure 10: CO_2 captured and stored through CCS in industrial sectors analysed in the 2DS



KEY POINT: the lowest-cost pathway to a 2 °C limit in global temperature rise requires high proportions of global industrial production to be equipped with CCS. In several of these sectors, CCS is the only option for deep CO_2 reductions.

There is much variation in cost estimates for CO_2 capture in industrial applications due to the variety of technologies, the often unique nature of the industrial facilities and the scarcity of analysis in comparison to the power sector. Industrial sites have many site-specific attributes, in particular the availability of excess heat which can avoid the need for additional boilers to provide the steam for solvent regeneration, but narrowing the range of costs for second-phase industrial applications is an urgent task that will support policymaking. Figure 11 shows that in some sectors capture processes with different costs and capture rates must be applied at the same site to capture emissions from multiple sources. A cumulative and stepwise build-up from the cheapest sources in industrial clusters could be envisaged.

Figure 11: Illustration of CO_2 avoidance costs and sizes of CO_2 sources for capture at archetypal industrial sites



Note: arrows represent data given by literature data. Dotted lines are ranges from selected studies.

KEY POINT: there are trade-offs between the quantity and cost of abatement when applying CCS to different industrial sites. There are also significant variations in cost of CO_2 to be captured at a single site. These differences and costs still need to be better understood.

Annex 3. CCS incentive policy frameworks

This annex provides further discussion and detail on incentive policies. It outlines the rationale for incentive policies and the objectives they serve, as well as current examples from a selection of countries and jurisdictions.

As the primary benefit of CCS technology is CO_2 emissions reductions, CCS will only be widely deployed in conjunction with strong policies to reduce emissions. The type of policies that are most effective will change over time, as the technology matures and policy objectives shift. There is no one-size-fits-all policy: different policy instruments serve different objectives (*i.e.* to correct different market failures). Analyses by the IEA and other institutions show that a combination of integrated policies and economic instruments are needed to support the demonstration and commercial deployment of CCS (IEA, 2012f; Goulder and Parry, 2008).

Rather than emissions reductions *per se*, policy emphasis during the early stages will be on promoting learning through the advancement of CCS technology in diverse applications, and in promoting access to (private) capital. During this phase, technology-specific instruments such as capital grants, production subsidies, investment and production tax credits, feed-in tariffs, premium feed-in tariffs, portfolio standards, and credit guarantees can ensure that a desired number of large CCS installations are built and operated to gain knowledge and thereby bring down costs.

Given the immaturity of integrated CCS projects, the need for incentives that are CCS-specific and complementary to emissions reduction policies is critical. In practice, this phase is likely to last well into the 2020s.

As the technology matures, the policy objectives will shift towards emission reductions. During this later phase, technology-neutral incentive mechanisms such as cap and trade schemes, carbon taxes, baseline and credit schemes, feebate systems or emission performance standards will ensure that investments are directed toward the most cost-effective technologies. However, such mechanisms alone cannot ensure the early uptake of CCS in the next decade. Table 5 lists a selection of current or planned incentive mechanisms.

While incentive policies must adapt to fit the commercial maturity level of CCS technology, they must also deliver a level of certainty that encourages private sector investment. One approach to dealing with these contradictory requirements is a "policy gateways" approach consisting of a stable framework composed of defined milestones and associated policies (IEA, 2012g). As each gateway is reached, policies are phased in that are appropriate to the level of maturity of the technology and targeted to address specific market failures. This approach additionally necessitates an outline of how government will react if gateways are missed. Comprehensive sector-specific policy frameworks – whether based on the gateways approach or not – need to be implemented now in order to provide sufficient incentives for demonstration, but also wide deployment beyond the demonstration phase.

As most of the need for CCS in industrial applications will be in trade-exposed sectors, an appropriate incentive framework must deal with issues of international competitiveness. If this issue could be overcome at regional, international or sectoral levels, then moving to genuinely low-carbon production in these sectors will not only deliver some low-cost climate mitigation opportunities but will provide energy-intensive industries with a long-term license to operate in a GHG-restrained world.

An additional instrument that could be of importance for CCS deployment in developing (*i.e.* non-Annex I in the UNFCCC context) countries is the CDM, a project-based international financing mechanism under the Kyoto Protocol. CCS was accepted as an eligible project activity under the CDM in December 2011, at which time modalities and procedures were also adopted that will guide CCS CDM project implementation. While the current price of Certified Emissions Reductions (CERs) is well below the level that could incentivise emissions reduction through CCS, acceptance of CCS in the CDM signifies international acceptance of the technology as a component of global emissions reduction strategies, and could provide direction for development of CCS projects in developing countries, laying a foundation for CCS to be included in future international project-based funding schemes (Levina and Lipponen, 2012).

Table 5: Examples of existing and/or developing policies with potential to incentivise CCS deployment

Policy objective	Type of policy instrument	Examples	
		Jurisdiction	Description
Emissions reductions	Average CO_2 emission reduction standard	United States	Proposed Carbon Pollution Standard for New Power Plants, 27 March 2012.* Under the proposal, power plants incorporating CCS would have the option to spread average CO_2 emissions over a 30-year period to meet the proposed standard, rather than having to meet the standard each year.
	Emissions performance standard	Alberta, Canada	Alberta's emissions intensity reduction policies: Specified Gas Emitters Regulation; pending sequestration offset protocol. CCS will be an eligible activity under the offset protocol.
	Carbon tax	Norway	The carbon price of USD 51 per tonne (/t), introduced in 1991 and imposed on hydrocarbon fuels produced offshore, prompted Statoil to begin its Sleipner CCS project in the North Sea in 1996. Although the injection facility is estimated to have cost USD 100 million to construct, and injection currently costs USD 17/t of CO_2, every year Statoil has avoided paying the tax on an estimated 1 Mt of injected CO_2. Statoil launched a similar project in 2008 with its Snøhvit CO_2 storage project also in the North Sea.
	Command and control	Australia	A large-scale CCS project in Western Australia (WA) will annually be storing 3.3 Mt of CO_2 separated from liquefied natural gas production. It is regulated under the Barrow Island Act 2003 (WA), which is project-specific legislation that was enacted solely to regulate the CCS activities associated with Gorgon project.
	Emissions performance standard	United Kingdom	An emissions performance standard set at a level (450 kilograms of carbon dioxide per megawatt hour) that will ensure that no new coal-fired plants are built without at least partial CCS.
	Emissions performance standard	Canada	The Government of Canada's "Reduction of Carbon Dioxide Emissions from Coal-Fired Generation of Electricity Regulations" will come into effect 1 July 2015. Under these regulations, all new coal-fired units and units reaching the end of their economic life that incorporate CCS will receive a temporary exemption until 2025 from a performance standard based on the emissions performance of natural gas combined cycle generation. The regulations also recognise units that implement CCS before they are subject to the standard.
Technology learning Addressing commercial risk	Capital grants	United Kingdom	The UK CCS Commercialisation Competition makes available GBP 1 billion capital funding, together with additional support through the UK Electricity Market Reforms, to support practical experience in the design, construction and operation of commercial-scale CCS. In March 2013 the government announced two preferred bidders. A final investment decision will be taken by the government in early 2015 on the construction of up to two projects.

Sources: based on IEA, 2012g; IEA, 2012h; Levina and Lipponen, 2012.

* Output-based standard of 1 000 pounds of carbon dioxide per megawatt hour. See http://epa.gov/carbonpollutionstandard/pdfs/20120327factsheet.pdf.

Table 5: Examples of existing and/or developing policies with potential to incentivise CCS deployment (continued)

Policy objective	Type of policy instrument	Examples	
		Jurisdiction	Description
Technology learning ***Addressing commercial risk***	Capital grants	European Union	Recognising the insufficient incentive for CCS by the EU-ETS, the European Commission (EC) introduced a specific mechanism to provide further incentives to CCS. This instrument, referred to as the "NER 300" programme, allocates 300 million EU emission allowances (EUAs) from a New Entrants Reserve to be used to support development of CCS and innovative renewable energy technologies. The reserve is made available until 31 December 2015. However, the first round of NER 300 that included the sale of the first 200 million EUAs did not support any CCS projects in the European Union. In addition, the EC supports CCS demonstration in Europe through the European Energy Programme for Recovery. Six demonstration projects had a fast start aided by a total of EUR 1 billion.
	Capital grants	Japan	Building on a number of R&D projects, Japan is developing an integrated CCS demonstration project at Tomakomai refinery site with a public fund of JPY 50 billion. CO_2 injection is scheduled to start at a rate of over 0.1 $MtCO_2$/yr in 2016.
	RD&D support	China	There is significant activity in both government and industry R&D programmes to explore options for CCS. China's current RD&D efforts emphasise various carbon capture technologies, with an increasing focus on utilisation opportunities. In 2005, China integrated CCS into its national medium- to long-term science and technology development plan, as a cutting-edge technology to achieve near-zero emissions in fossil-based energy development. In 2006, the Ministry of Science and Technology (MOST) launched China's National Basic Research Programme (973 Programme) for the utilisation of GHGs as a resource in EOR and underground storage. In 2007, CCS was mentioned as a key research area for GHG emissions reduction in the National Climate Change Programme. In 2008, MOST launched a CCS technology research programme under the National High-tech Programme 863 (MOST, 2008).
	Contract-for-difference feed-in tariffs	United Kingdom	The United Kingdom has proposed reforms intended to drive decarbonisation of the electricity sector (including through CCS). Provisions related to CCS include feed-in tariffs combined with contracts-for-difference, to provide stable revenue streams to generators of low-carbon electricity. The proposed reforms constitute the first attempt globally to create – as part of the broader reform package – CCS deployment incentives that bridge the gap between CCS-specific demonstration project funding programmes and deployment driven purely by carbon pricing schemes.
	RD&D programme	United States	Extensive RD&D programme, focused on large-scale demonstration projects (both industrial sources and power plants, some of which are moving forward to construction) as well as development of second-generation and transformational technologies.

Sources: based on IEA, 2012g; IEA, 2012h; Levina and Lipponen, 2012.

Abbreviations, acronyms and units of measure

Abbreviations and acronyms

2DS	2 °C Scenario
6DS	6 °C Scenario
BECCS	bioenergy with carbon capture and storage
CCGT	combined cycle gas turbine
CCS	carbon (dioxide) capture and storage
CDM	Clean Development Mechanism
CHP	combined heat and power
CO_2	carbon dioxide
CO_2-EOR	carbon-dioxide enhanced oil recovery
CSLF	Carbon Sequestration Leadership Forum
DRI	direct reduced iron
EC	European Commission
ECBM	enhanced coal-bed methane
EOR	enhanced oil recovery
EPC	engineering procurement construction
ETP	*Energy Technology Perspectives*
EUA	EU emission allowances
GHG	greenhouse gas
HELE	high-efficiency, low-emissions
IDC	interest during construction
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCOE	levelised cost of electricity
LHV	low heating value
MMV	monitoring, measurement and verification
MOST	Chinese Ministry of Science and Technology
NAMA	Nationally Appropriate Mitigation Action
NGCC	natural gas combined cycle
NO_x	nitrogen oxide
OECD	Organisation for Economic Co-operation and Development
PC	pulverised coal
R&D	research and development
RD&D	research, development and demonstration
UNFCCC	United Nations Framework Convention on Climate Change
WEO	*World Energy Outlook*

Units of measure

Gt	gigatonne
$GtCO_2$	gigatonne of carbon dioxide
GW	gigawatt
kg/MWh	kilogram per megawatt hour
kW	kilowatt
kWh	kilowatt hour
Mt	million tonnes or megatonne
$MtCO_2$	megatonne of carbon dioxide
MW	megawatt
MWh	megawatt hour
t	tonne
tCO_2	tonne of carbon dioxide

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