GLOBAL CCS INSTITUTE

THE GLOBAL STATUS OF CCS | 2014

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Cover image: Final calibration on the sulphur dioxide stripper of the SaskPower Boundary Dam Integrated CCS Project, Canada.
Image provided by SaskPower.

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EXECUTIVE SUMMARY

2014-2015 – WATERSHED YEARS FOR CCS

The world's first large-scale carbon capture and storage (CCS) project in the power sector commenced operation in October 2014 at the Boundary Dam power station in Saskatchewan, Canada. Two additional large-scale CCS projects in the power sector – at the Kemper County Energy Facility in Mississippi and the Petra Nova Carbon Capture Project in Texas – are planned to come into operation in 2015 and 2016 respectively. Construction is also underway on the world's first large-scale CCS project in the iron and steel sector, the Abu Dhabi CCS Project in the United Arab Emirates (UAE). These four projects are among the 22 large-scale CCS projects in operation or construction around the world – double the number at the beginning of the decade.

With large-scale CCS power projects now a reality, an important milestone in deployment of the technology has been achieved. This means that it is time to move discussion onto how CCS can best be deployed as part of a least-cost approach to climate change mitigation. We can now move on from arguments about its 'experimental' nature or that it has not yet been applied at scale to fossil fuel power plants.

There are a further 14 large-scale CCS projects in advanced planning, including nine in the power sector, many of which are anticipated to be in a position to make a final investment decision during 2015. Not only does this further reinforce the growing confidence in the (increasing) technical maturity of CCS, it offers the prospect of a 'potential portfolio' of operational large-scale CCS projects around the 2020 timeframe across a range of industries, storage types, fuels and technology suppliers.

Now is the time for actions to help realise the potential of these advanced projects (and for those projects in earlier stages of planning). Furthermore, the data on large-scale CCS projects highlights two other areas requiring increased attention by policymakers – the lack of projects in non-OECD economies (outside of China) and the lack of progress in CCS technology development in high carbon intensive industries such as cement, iron and steel and chemicals.

Numerous international studies continue to show that CCS is essential in meeting global climate targets. We need to realise the potential of CCS projects in the development pipeline and incentivise the development of CCS across a wider range of industries and regions to provide the basis for a rapid expansion in the number and diversity of next generation projects.

For this to happen, the following actions are vital:

RECOMMENDATIONS FOR DECISION MAKERS

- Financial and policy support structures must be provided in the near term to enable transitioning the 'potential portfolio' of planned projects into an 'actual portfolio' of projects operating by 2020.
- Strong, sustainable emission reduction policies that encourage CCS are urgently needed for longer-term deployment and to give investors the policy predictability they need to invest in CCS. These policies must ensure that CCS is not disadvantaged in relation to other low-carbon technologies.
- There is an urgent need for policies and funded programs which encourage the exploration and appraisal of significant carbon dioxide (CO_2) storage capacity, so that broader deployment is not delayed by uncertainty over available storage.

- Substantial effort must be devoted to knowledge sharing, capacity development and the implementation of other policies and legal frameworks during the course of this decade to enable the increasing numbers of large-scale CCS projects needed in non-OECD economies by 2025-30 and beyond.
- CCS is the only technology that can achieve large reductions in CO_2 emissions from industries such as iron and steel and cement. Urgent attention must be given to the development of policies that incentivise the widespread deployment of CCS in such industries.

CCS is essential

Global consumption of fossil fuels continues to increase, driving growth in CO_2 emissions. Even when it is assumed that current policy commitments and pledges by governments around the world to tackle climate change are all implemented, it is expected that fossil fuels will still account for 75% of global energy demand in 2035. Demand growth is expected to be particularly strong in developing countries. In its *World Energy Outlook 2013,* the International Energy Agency (IEA) estimated that on these assumptions energy-related CO_2 emissions will rise by 20% to 2035. This leaves the world on a trajectory consistent with a long-term average temperature increase of 3.6 degrees Celsius (°C), far above the internationally agreed 2°C target.

It is clear that much more needs to be done to limit CO_2 emissions growth. Work is under way through the United Nations Framework Convention on Climate Change (UNFCCC) to reach a new global climate change agreement by the end of 2015. This agreement is vital if greenhouse gas (GHG) concentrations in the atmosphere are to be stabilised at a level that will avoid the worst impacts of climate change.

CCS is a cost-effective technology for achieving large emission reductions from fossil fuel use, and it must play a significant role alongside renewables, energy efficiency, nuclear and other mitigation options in global action on climate change. CCS has a key role in curbing CO_2 emissions from fossil fuel-based power generation. Without investment in CCS in the power sector, total mitigation costs in the sector would increase by US$2 trillion by 2050 (IEA, 2012. *Energy Technology Perspectives*). Further, CCS is the only option available to significantly reduce direct emissions from many industrial processes at the large scale needed in the longer term.

> ***'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.'***
>
> Maria van der Hoeven, Executive Director, IEA
> Foreword to the *Technology Roadmap: Carbon Capture and Storage,* 2013.

CCS power projects are a reality

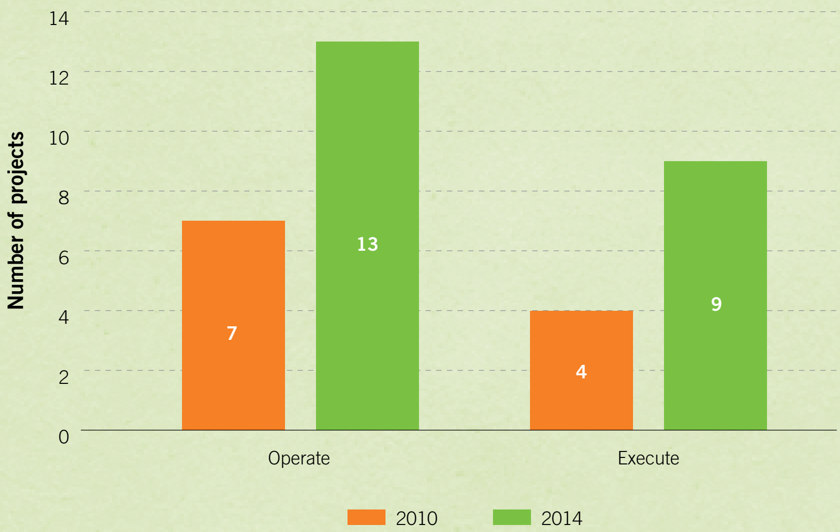
The commencement of CCS operations at SaskPower's Boundary Dam coal-fired power station in October 2014 is a significant step forward. The feasibility of capturing CO_2 from power station flue gas streams has been well established in recent years through a number of pilot and small-scale demonstration plants. The Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project represents the first example of applying CCS in a power station at large scale, and will provide important learnings for future projects as well as a clear demonstration that CCS is a real option to greatly reduce CO_2 emissions from the power sector.

Two further large-scale CCS projects in the power sector are under construction in the United States (US) – at Mississippi Power's Kemper County Energy Facility in Mississippi and the Petra Nova Carbon Capture Project at NRG Energy's W.A. Parish power station in Texas. These are expected to be commissioned in 2015 and 2016 respectively. Importantly, these three power projects will demonstrate different capture techniques (post-combustion in the case of Boundary Dam and Petra Nova, and pre-combustion in the case of Kemper County), and are using capture methods from different technology suppliers.

Construction is also under way on the world's first iron and steel project to apply CCS at large scale, the Abu Dhabi CCS Project at the Emirates Steel plant in the UAE. Iron and steel making is one of the industrial applications for which there are no real alternatives to CCS for greatly reducing emissions. Industrial applications account for about one-quarter of the world's energy-related CO_2 emissions and emissions from these sectors are projected to grow by over 50% by 2050, under a 'business as usual' approach (IEA, 2014. *Energy Technology Perspectives*). Successful demonstration of CCS in sectors such as iron and steel will be vital to future emission reduction efforts.

These four large-scale CCS projects are among the 22 across a range of industries that are now in operation (Operate stage) or construction (Execute stage) around the world, double the number at the beginning of this decade (Figure 1). The total CO_2 capture capacity of these 22 projects is around 40 million tonnes per year (Mtpa) – or equivalent to the total annual CO_2 emissions of countries such as Denmark or Switzerland.

Figure 1 **Number of large-scale CCS projects in the Operate and Execute stages**



To ensure consistency across years, the 2010 record of large-scale operating CCS projects combines the Rangely and Salt Creek EOR Projects. In Institute reporting, these projects were combined and included under the Shute Creek Gas Processing Facility Project from 2011 onwards.

The portfolio of operating CCS projects needs to be broadened

With the exception of the Boundary Dam Project, operating large-scale CCS projects are in sectors where, as part of the industrial process, CO_2 is routinely separated from other gases (such as in natural gas processing) or CO_2 is produced in a relatively pure stream (such as in fertiliser or ethanol production). In such industries, the application of CCS is well understood and could readily be expanded given the right incentive structures and availability of suitable storage sites in reasonable proximity to the industrial plant.

Large-scale CCS projects in the power and iron and steel industries, such as Boundary Dam and those commencing operation in the next two years, are important for broadening the portfolio of CCS into areas where capturing CO_2 is more challenging. There are a further nine large-scale power sector CCS projects in the most advanced stage of development planning (Define stage), which are approaching the point of making a final investment decision. Given the right conditions, all of these projects could be in operation by around the 2020 timeframe. These projects would further expand the scope of power sector CCS application into new capture techniques (including oxyfuel combustion), new plant configurations (such as poly-generation of power with other outputs) and new feedstocks beyond coal (natural gas and biomass). At this stage there are no further large-scale projects contemplated in the iron and steel industry, even though this industry accounts for about 9% of global CO_2 emissions. Nor is any large-scale project planned in the cement industry, which accounts for about 6% of emissions.

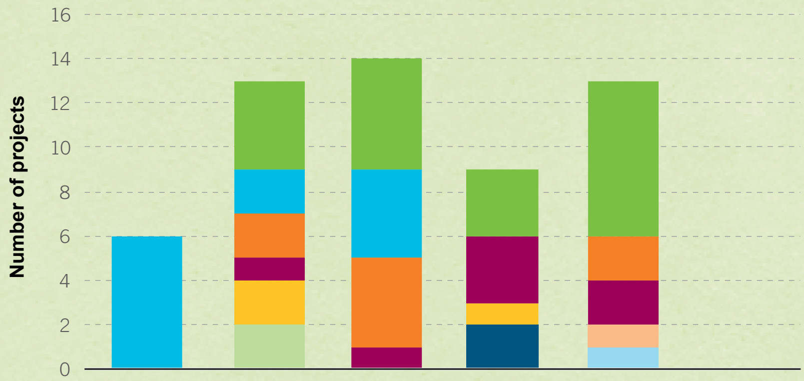
Chemicals and petrochemicals are a rapidly increasing source of emissions. Between 2011 and 2050, CO_2 emissions from these industries in a 'business as usual' scenario are expected to almost triple to 3.7 billion tonnes a year, by which time they are expected to match 'business as usual' emissions from the iron and steel sector (IEA, 2014. *Energy Technology Perspectives*). There are four operating projects in the fertiliser, synthetic natural gas and hydrogen production parts of the chemical industry, with a further two under construction or in advanced planning. Broader experience in applying CCS to the chemicals and petrochemicals industries will be gained through a further five projects under construction or in advanced planning in the ethanol production, refining, coal-to-chemicals and coal-to-liquids sectors. Importantly, two of these projects are in China, where the coal-to-chemicals industry is expanding rapidly.

More widespread experience is also needed in the countries and regions in which CCS is being applied, and in the types of storage being utilised. The present suite of large-scale CCS projects in operation, under construction or in advanced planning is heavily weighted towards projects in North America utilising CO_2 for enhanced oil recovery (EOR).

North America accounts for nine of the 13 operating projects, six of the nine under construction, and six of the 14 in the Define stage (Figure 2). The other 15 projects at these stages of the development lifecycle are spread across nine different countries, but of these countries only China (four), the United Kingdom (UK) (three) and Norway (two) have more than one project in operation, construction or advanced planning.

Overall, including 19 projects in the early stages of development planning (Evaluate and Identify stages), the Global CCS Institute (the Institute) has identified 55 large-scale CCS projects around the world.

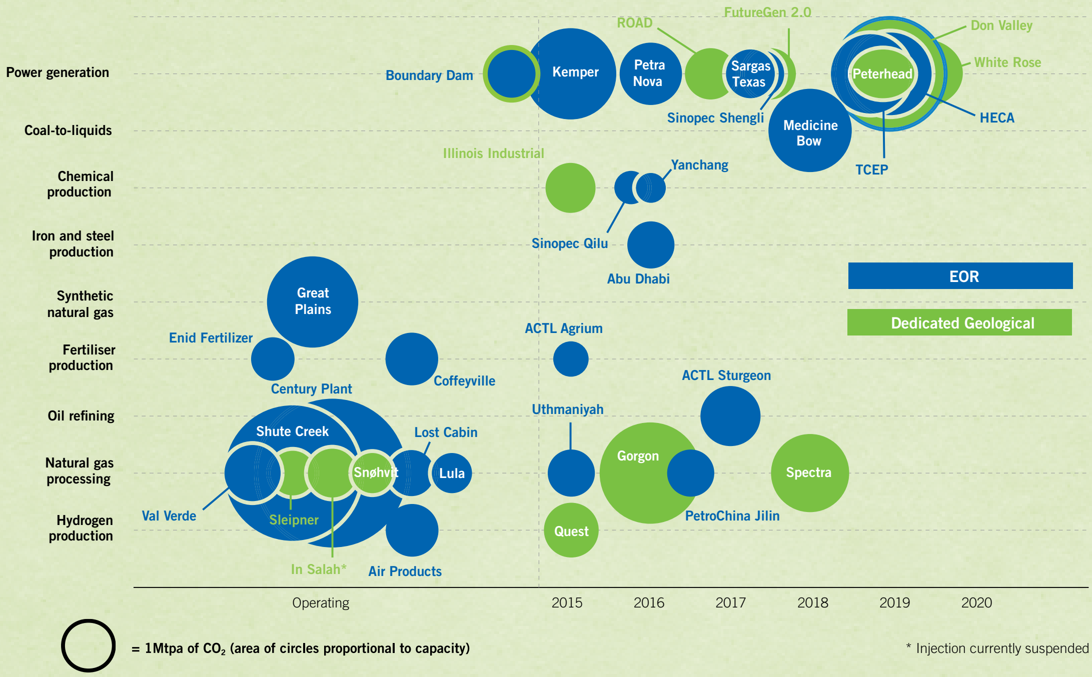
Figure 2 **Large-scale CCS projects by lifecycle and region/country**



	Identify	Evaluate	Define	Execute	Operate	**Total**
United States	0	4	5	3	7	**19**
China	6	2	4	0	0	**12**
Europe	0	2	4	0	2	**8**
Canada	0	1	1	3	2	**7**
Australia	0	2	0	1	0	**3**
Middle East	0	0	0	2	0	**2**
Other Asia	0	2	0	0	0	**2**
South America	0	0	0	0	1	**1**
Africa	0	0	0	0	1	**1**
Total	**6**	**13**	**14**	**9**	**13**	**55**

An important reason for this geographic concentration of projects is the potential in North America for sales of CO_2 for the purpose of EOR. The revenue stream EOR offers has been important in helping to make the business case for all of the operating CCS projects in the US and Canada (Figure 3). EOR is also a feature of the single project operating in Brazil, the two projects under construction in the Middle East, and the four projects in advanced planning in China. In all of the regions where EOR offers revenue potential, it is supporting early deployment of CCS.

Figure 3 **Actual and expected operation dates for large-scale CCS projects in the Operate, Execute and Define stages by industry and storage type**



If CCS is to reach its full potential in emissions mitigation, the majority of CO_2 will eventually have to be stored in dedicated geologic reservoirs, such as deep saline formations. Resource estimates indicate a much greater potential for dedicated geologic storage options than EOR to meet longer-term CO_2 capture and storage requirements.

Valuable experience in deep saline formation storage has been gained from large-scale projects in Norway (the Sleipner and Snøhvit CO_2 Storage Projects) and in Algeria (the In Salah CO_2 Storage Project) and a range of pilot test facilities around the world, such as Lacq in France, Ketzin in Germany and Otway in Australia. Three large-scale CCS projects in construction are pursuing onshore deep saline formation storage – the Quest Project in Canada, the Gorgon Carbon Dioxide Injection Project in Australia and the Illinois Industrial Carbon Capture and Storage Project in the US. These projects will be operational in 2015-16.

A further six projects in the Define stage have confirmed or are exploring storage in deep saline formations or depleted gas reservoirs, including the ROAD Project in the Netherlands, the FutureGen 2.0 Project in the US and all of the UK projects. Anticipated operational dates are in the 2017-20 period. Taken together, the experience gained from these projects will greatly add to the knowledge base on dedicated geological storage. In this context, advancing projects from planning into construction and operation in Europe (where no large-scale CCS project has entered construction in over a decade) will play an important role in establishing a positive perception of CCS both in the region and globally.

Further policy support is vital

Within the next year there is the potential for ten or more projects to be in a position to make a final investment decision. Current policy settings and any new initiatives taken in the next 12-18 months will therefore largely shape the CCS projects portfolio out to 2020. It is important that financial and policy structures in the near term support the transitioning of this ‘potential portfolio’ of planned projects into an ‘actual portfolio’ of operating projects by 2020.

In addition to near-term actions needed to bring planned projects into operation, the future pipeline of projects must be greatly expanded. Important lessons will be learnt from the projects in operation this decade that will help to reduce costs, increase confidence and expand the applications of second- and third-generation CCS technologies in the 2020s and 2030s. But the total absence of any projects in the earliest stage of project planning, except in China, is of concern. This situation must be rectified if CCS is to play its full part as a mitigation option, commensurate with IEA scenarios. As a result, strong sustainable emissions reduction policies that encourage CCS are urgently needed for longer-term deployment and to give investors the longer-term predictability they need to invest in CCS.

Immediate and longer-term policy support is vital. However, a majority of respondents to the Institute’s 2014 Perceptions Survey reported that they had not noticed a material change to their CCS policy environment over the last year. More than three-quarters of respondents cited policy uncertainty as a major risk to their project’s viability, and a similar proportion stated that their project’s viability depends on new government policy settings.

Existing policy support alone over the past five years has not been enough to ‘launch’ the number of large-scale CCS projects anticipated at the start of the decade. In fact, more than 40% of respondents to the Perceptions Survey indicated that the incentives currently in place are inadequate for ensuring projects are not commercially stranded.

The need for supportive policies has been recognised in a number of countries and regions. The UK policy environment continues to promote progress of large-scale projects. The US policy, legal and regulatory environment for CCS/carbon capture, utilisation and storage (CCUS) continues to advance, and projects are also progressing there, particularly when supported by EOR opportunities. The European Commission (EC) is reviewing European Union (EU) CCS policy, against a backdrop of only one project (ROAD) in development planning in mainland Europe. Several developing countries are also progressing policy reviews or including CCS in broader climate change policy considerations. Governments are also supporting efforts through the International Organization for Standardization (ISO) to develop essential supporting technical infrastructure for future CCS development.

Progress must be accelerated in developing countries

It is not surprising that to date, most large-scale CCS projects are in the developed world. This is where key project enablers such as public support programs, marketable opportunities for CO_2, storage assessments and regulatory frameworks are most advanced. However, non-OECD economies will account for the vast majority of growth in energy demand in coming decades. Meeting longer-term climate goals will involve significant capture and storage of CO_2 from facilities in these economies. In its 2012 *Energy Technology Perspectives,* the IEA estimated that 70% of CCS deployment will need to happen in non-OECD countries by 2050 to achieve the 2°C global emission scenario.

Important progress is being made in a number of non-OECD and developing countries in CCS project and policy development. These efforts must continue, and substantial effort devoted to the implementation of policies and frameworks (including knowledge sharing and capacity development programs) during the course of this decade to support the increasing numbers of large-scale CCS projects required in non-OECD economies by 2025-30 and beyond.

Technical challenges and risks are well understood

Capture research, development and demonstration is essential to drive down costs

Carbon capture refers to that part of a CCS project concerned with separating or isolating a relatively pure stream of CO_2 from other gases and liquids, so that it can be transported for use or storage elsewhere. The cost of capture varies greatly depending on the industrial process involved. In industries like natural gas processing, naturally occurring CO_2 is routinely stripped from the methane-rich sales gas component, so there is little or no additional 'capture' cost involved beyond compression if this CO_2 was subsequently to be transported and stored, rather than vented to the atmosphere. By contrast, in industries like power generation or blast furnace steel making, CO_2 is usually a small fraction of the nitrogen-rich exhaust gas stream from the plant, and separating this CO_2 is a complex and costly undertaking. In such industries, capture is by far the largest component of the CCS cost chain.

The three CCS projects in the power sector that have made a positive final investment decision, together with the nine in the Define stage, illustrate that significant progress has been made in tackling these challenges and demonstrating the feasibility of capturing CO_2 at large scale from fossil fuel power stations. The range of projects in the Define stage which are approaching a final investment decision would further expand the types of capture techniques and technologies demonstrated in these applications. Such demonstration of a range of possible capture techniques and technologies is essential to enhance understanding of different operating conditions and to drive further research and development (R&D) in this area.

Cost reduction has been and will continue to be the key focus of much capture R&D and technology improvement. First-generation technologies will be demonstrated in the first-of-a-kind large-scale CCS projects currently being operated or built. The portfolio of R&D capture projects to improve on these technologies is very broad. Although not all the concepts will progress at the same pace nor are they expected to fully transition to pilot and subsequent demonstration, the most promising technologies have the potential to significantly reduce investment and operating costs in the next 10-20 years.

To achieve further improvements in carbon capture, it is critical for governments, researchers and industry to work collaboratively to support next generation large-scale CCS projects. It is equally important to continue R&D and share acquired knowledge to leverage resources to achieve better, faster results to produce future game changing capture technologies needed to accelerate broad CCS deployment. Capture technologies are being developed globally in several programs with support of governments, academia and industry, especially in Europe, North America and Asia. Such international collaboration is key to accelerating the deployment of newer technologies.

Transportation is mostly a scale issue

The transportation of large volumes of CO_2 by pipeline has been practised for decades, particularly in the US. These pipelines have been operated with an excellent safety record, applying internationally adopted standards and codes of practice which continue to be further developed. The technology for CO_2 pipelines is thus well established and CO_2 transportation infrastructure continues to be commissioned and built.

While pipelines are – and are likely to remain – the most common method of transporting the large quantities of CO_2 involved in CCS projects, ship transportation can be an alternative option for a number of regions of the world, especially in regions where onshore and near shore storage locations are not available. Transport of CO_2 by ship already takes place on a small scale in Europe, and larger-scale shipment of CO_2 is likely to have much in common with the shipment of liquefied petroleum gas (LPG), which is now commonplace. Truck and rail transport of industrial and food grade CO_2 has also been undertaken for over 40 years, and may be useful for pilot and small-scale CCS projects.

The main transport issue is scale. For CCS to fulfil its potential in the IEA's least-cost pathway to halve energy-related CO_2 emissions by 2050, the estimated distance of CO_2 transportation infrastructure to be built in the coming 30-40 years is roughly 100 times larger than currently exists.

The costs of CO_2 pipeline transportation differ from project to project due to factors such as pipeline length, volumes of CO_2 and the corresponding pipe diameters, cost of labour, and economic life of the infrastructure. An important option to reduce the cost of CCS is to realise economies of scale by sharing a single CO_2 transportation and storage infrastructure system among several operators of separate CO_2 generating plants. In this sense, it is important to think about CO_2 transport infrastructure through a regional lens (as opposed to point-to-point systems).

Given the scale of CO_2 transportation infrastructure required, experience is needed outside the US in planning, designing and implementation of large-scale CO_2 transport networks connecting multiple CO_2 sources and sinks. Governments can play a role here by providing incentives for projects to invest in CCS transport solutions that will accommodate the future development of other CCS projects and large CO_2 transportation networks.

Early-stage storage site characterisation is important for accelerating CCS deployment

Carbon dioxide is stored in the same kind of porous rock that can contain deposits of crude oil or natural gas. Similarly, the same kind of impermeable cap rocks that keep oil and gas underground and prevent it migrating to the surface can be expected to trap CO_2 over geological timescales.

Today, over 150 sites are injecting CO_2 underground, either for EOR or for dedicated CO_2 storage. EOR represents the majority of these sites and began over 40 years ago in the US. The first dedicated CO_2 storage project started in 1996 at the Sleipner offshore gas field in Norway. The underground storage of natural gas for seasonal and strategic reserves also has several similarities to CO_2 storage and has a long track record that can inform risk management of CO_2 storage sites.

Experience gained from these sites and existing CCS projects, as well as experience from the petroleum industry, gives a high degree of confidence in the feasibility and operation of CO_2 storage. Although all of the required technologies are already available 'off-the-shelf' to develop a large number of secure CO_2 geological storage sites, the geosciences and subsurface engineering communities are still producing considerable innovations to both improve overall solutions and to widen the range of suitable storage sites. Further data from a greater variety of real world large-scale storage scenarios will further inform these efforts.

It can take a considerable period of time, possibly up to ten years, to fully appraise a greenfield site ready for a final investment decision. This is a much longer time frame than is generally required for the capture and transportation elements of a CCS project. In the early phases of project development, storage availability is also the most uncertain element, and may require a significant allocation of resources. The characteristics of a particular storage site may have important influences on the design of the CO_2 capture plant and transportation system.

Given the required scale of CCS deployment post-2020 to meet climate goals, the challenge of finding appropriate storage capacity may increase considerably. Projects may need to investigate several storage targets to mitigate the exploration risk. Accordingly, the importance of undertaking storage-related actions this decade to prepare for widespread CCS deployment post-2020 cannot be overstated.

To lessen the risk of widespread CCS deployment being slowed by uncertainty over available storage, there is an urgent need for policies and funded programs that encourage the exploration and appraisal of significant CO_2 storage capacity.

Public engagement is an important part of the picture in all countries

The most advanced CCS projects have shown they are fully committed to public engagement and long-term outreach activity, not just with their local stakeholders, but also on the international stage. This engagement and outreach is critical for increasing understanding and ensuring acceptance of CCS generally, and with regard to specific projects. The engagement methods ranked most effective by projects are generally direct in nature, such as face-to-face meetings, site visits, formal consultation events and education programs.

The three large-scale power sector CCS projects that have taken a positive final investment decision (and those that will follow) will be vital in establishing a positive perception of CCS as an important part of an effective and efficient CO_2 emission reduction portfolio. Leveraging these milestones in CCS deployment is critical to creating awareness and building enthusiasm to empower communication efforts, not just around CCS technology, but also on climate change and low-carbon energy more generally.

The first-mover projects that have progressed to the most advanced stages of the project lifecycle since the beginning of this decade lie almost exclusively in the Americas and Europe, Middle East and Africa (EMEA) regions. By contrast, most of the large-scale CCS projects in the early stages of project development are in the Asia Pacific region. While the Institute's 2014 Perceptions Survey indicated that around one-third of the projects in the Asia Pacific region are either actively engaged with stakeholders or developing a public engagement strategy, a substantial number are yet to develop such a strategy. This makes those projects that are adopting best practice approaches important and instructive case studies for others in the region.

The majority of CCS social research carried out to date has focused on the developed world, shedding very little light on the role of CCS within developing countries. This is not surprising given the areas of the world where CCS is most developed. However, these results underline the urgent need to improve access to the learnings and experiences of CCS projects and researchers in the developed world. This will help to understand differences in needs in developed and developing regions and allow projects in the latter to benefit from lessons learnt.

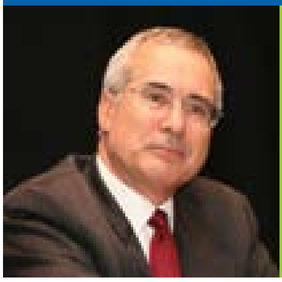
International collaboration is vital to accelerate CCS

While some large-scale CCS projects have been operating for decades, the overall industry is still in its infancy. As with all industries at this stage of development, great benefits can be obtained from knowledge sharing and collaboration along the entire development chain, from early laboratory concept to scalable pilot testing and large-scale projects. Project case studies and comments from leading voices in the CCS and climate change community highlight the value of collaborating with others.

The transfer of large-scale project experience from successfully operating projects to new projects will help to reduce costs and risks, as well as build confidence about CCS among the general public, governments and the finance community. In particular, transferring experience from developed to developing economies will be vital given the future scale of the mitigation task and the role of CCS in helping to achieve mitigation goals in those countries at least cost.

NOTES

[1] INTRODUCTION



This introduction to the *Global Status of CCS: 2014* report has been prepared by Lord Stern of Brentford. Lord Stern is a member of the International Advisory Panel of the Global CCS Institute.

Countries have an important opportunity next year to put the world on a path towards avoiding the immense risks of dangerous climate change.

At the 21st session of the Conference of Parties to the United Nations Framework Convention on Climate Change, due to be held in Paris in December 2015, world leaders should be able to sign an agreement that will mean annual global emissions of greenhouse gases are reduced sufficiently over the coming decades to have a likely, two-in-three, chance of avoiding a rise in global average surface temperature of more than two degrees Celsius (°C) above its pre-industrial level.

In 2010, countries agreed in Cancún, Mexico, that warming should not be allowed to exceed 2°C and made pledges to limit their emissions by 2020.

However, an analysis by the Intergovernmental Panel on Climate Change (IPCC) published earlier this year concluded that current ambitions are insufficient and likely to lead to warming of more than 3°C by the end of this century.

This would result in temperatures not seen on Earth for about three million years and would create huge risks to the lives and livelihoods of perhaps billions of people through impacts such as sea level rise, desertification and changes in extreme weather events around the world.

The IPCC indicated that annual emissions of greenhouse gases, which have been rising at record rates over the last 10 years, would need to peak before 2030 and then decline rapidly for the following decades of the century.

It noted that the budget of greenhouse gases that can be emitted this century while still allowing a two-in-three chance of avoiding global warming of more than 2°C is between 630 and 1,180 billion tonnes of carbon dioxide equivalent (CO_2e).

Given that the world is currently emitting about 50 billion tonnes of CO_2e each year, continued growth would exhaust the budget in less than 20 years.

This has provided clear guidance to countries preparing for the summit in Paris. They will be expected to make commitments early in 2015 for cuts in emissions by 2030 that are consistent with the goal of avoiding global warming of more than 2°C.

The two largest emitters, the United States and China, have begun to show greater urgency in their efforts to tackle climate change.

President Barack Obama and President Xi Jinping highlighted the importance of managing the risks of climate change at their first meeting last year and set up a high-level working group to explore the potential for collaboration.

President Obama has made the fight against climate change a defining part of his second term and is using his executive powers to try to curb emissions by the United States, for instance by introducing stronger regulations for power plants.

The Chinese Government is preparing the 13th Five-Year Plan for the period 2016-20, which is expected to include a goal of reaching a peak in the domestic consumption of coal, the most polluting of fossil fuels.

It will also seek to limit overall annual emissions of greenhouse gases and may introduce a cap.

Other countries are also beginning to take action. A study commissioned by the Global Legislators' Organisation identified 100 countries which have been using laws to tackle climate change.

Such political leadership is generating momentum, but overall the scale and pace of progress is still inadequate.

Some countries remain concerned that cutting greenhouse gas emissions may damage the prospects for economic growth and development.

But the IPCC found that making the necessary emissions reductions for a two-thirds chance of avoiding global warming of more than 2°C would only reduce global consumption by between one and four per cent by 2030.

This estimate excluded a consideration of the wider economic co-benefits from efforts to tackle climate change, such as a reduction in local air pollution caused by diesel in vehicles and coal-fired power plants.

A major report by the Global Commission on the Economy and Climate found that measures which possess these co-benefits could deliver more than half the overall cuts in emission that would be required to keep within the warming threshold of 2°C.

The Commission pointed out that the transition to a low-carbon economy could help countries to achieve more sustainable economic growth as well as reducing the risks of climate change.

One important issue that needs to be resolved in order to reach agreement in Paris is the financial support that the rich countries need to provide to developing nations to help them make the transition to low-carbon economies and to make themselves more resilient to those impacts of climate change that cannot now be avoided.

The agreement in Cancún recognised that the rich countries should be scaling up their support, from both public and private sources, from about US$10 billion per year now to at least US$100 billion by 2020.

These financial flows to poor countries will be essential to ensure that the international agreement in Paris promotes equitable access to sustainable development.

The role of the international financial institutions and the regional and national development banks will also be crucial in delivering the necessary financial support.

But clear and consistent policy-making and strong political leadership will be required to achieve success as well.

The confidence of the private sector, which should provide the investment required to drive the low-carbon transition, is too often being undermined by bad policy-making and uncertainty.

Government-induced policy risk can kill investment and innovation.

Good policies are needed to unleash the creativity that can quickly bring to market a range of new and exciting low-carbon technologies, including renewables and carbon capture and storage.

There is now overwhelming evidence that a transition to a low-carbon economy offers a real opportunity to generate sustainable growth and development for rich and poor countries alike.

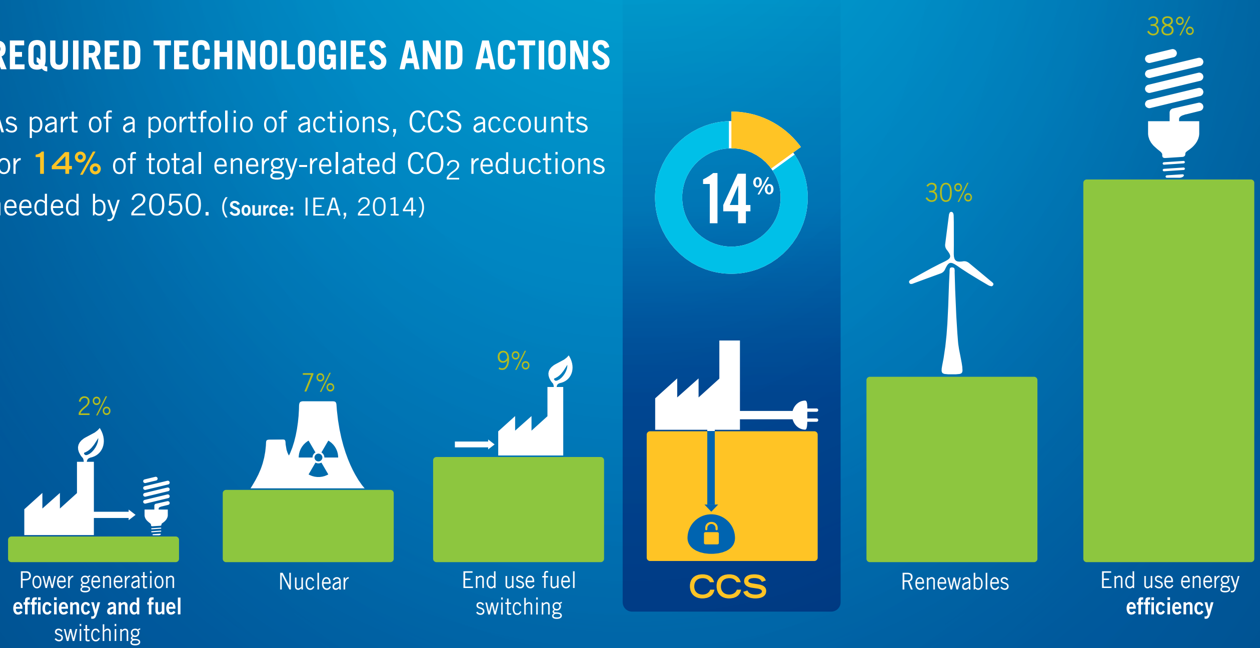
With strong leadership by decision-makers in government and business over the next year, the world can seize this opportunity to create better economic growth and limit climate change.

[2]

CCS IS ESSENTIAL

REQUIRED TECHNOLOGIES AND ACTIONS

As part of a portfolio of actions, CCS accounts for **14%** of total energy-related CO_2 reductions needed by 2050. (**Source:** IEA, 2014)



CHAPTER HIGHLIGHTS

- Fossil fuels will continue to dominate energy consumption patterns.
- Fossil fuel supply remains abundant.
- Carbon dioxide emission trajectories are not compatible with climate targets – delaying action is expensive.
- There cannot be an effective mitigation response to climate change without CCS.
- The value of CCS is increasingly acknowledged by independent studies.

FOSSIL FUELS WILL CONTINUE TO DOMINATE ENERGY CONSUMPTION PATTERNS

Fossil fuels currently supply 80% of the world's energy needs. Global energy demand is projected to be around 40% higher in 2035 than in 2010 – even if current policy commitments and pledges by governments to tackle climate change are all implemented. In this scenario, fossil fuels continue to account for the majority of increased energy demand to 2035, contributing 75% of global energy demand. Energy demand growth over the coming decades will come mainly from the non-OECD countries, especially China and India[1]. Fossil fuels will be relied upon as a primary resource for higher standards of living in these economies, as they have been for the high-income industrial economies.

The global share of power generation derived from fossil fuel sources is projected to be around 57% in 2035 – again based on the assumption that current policy commitments and pledges to tackle climate change are all enacted. While electricity production from fossil sources is projected to be stagnant in the OECD economies over the period from 2010 to 2035, the absolute level of production remains considerably higher than renewable sources (by around 40%). In the non-OECD economies, the use of fossil fuels for electricity production is projected to be twice that of renewable energy sources in 2035. Coal remains the most significant single fuel source in global power generation in 2035 (33% share)[2]. Over 130 gigawatts (GW) of coal capacity was added in 2013 – at least double that of any other fuel[3].

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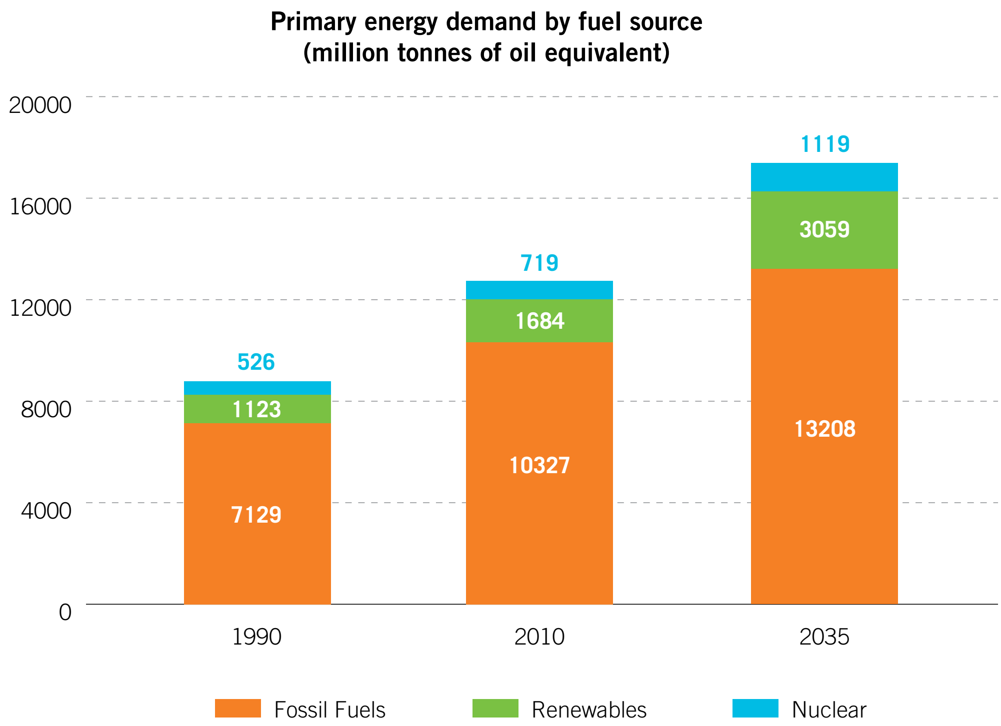
[1] Analysis based on New Policies scenario data from IEA, 2013. *World Energy Outlook 2013*, OECD/IEA, France.

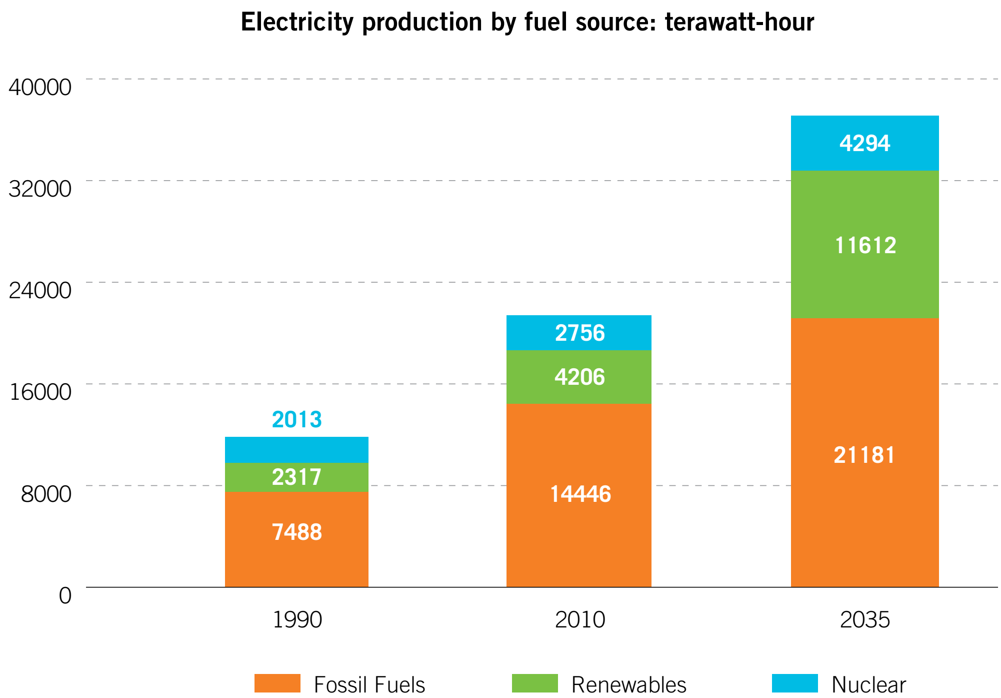
[2] *Ibid.*

[3] IEA, 2014. *Tracking Clean Energy Progress 2014, Energy Technology Perspectives 2014 Excerpt, IEA Input to the Clean Energy Ministerial,* OECD/IEA, France.

Figure 2.1 **Global energy and power demand is underpinned by fossil fuels**



Source: IEA, 2012. *World Energy Outlook (WEO) 2012* and IEA, 2013. *WEO 2013* (New Policies scenario).

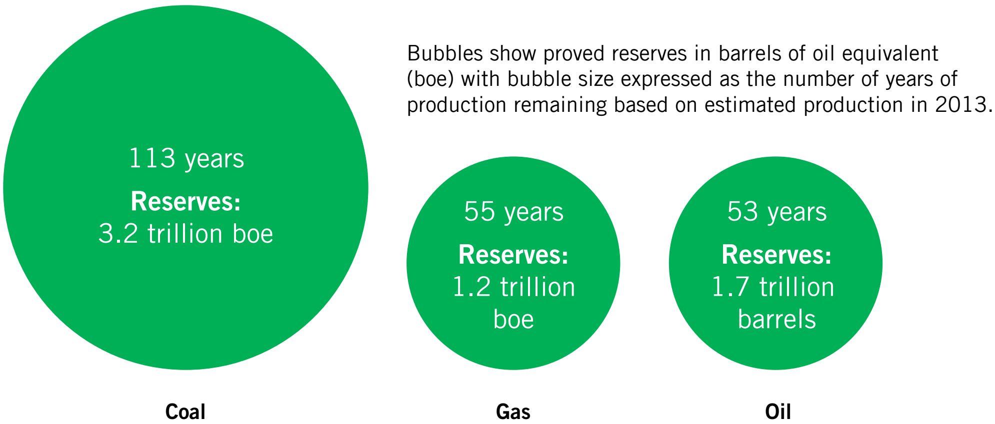


Source: IEA, 2012. *World Energy Outlook (WEO) 2012* and IEA, 2013. *WEO 2013* (New Policies scenario).

FOSSIL FUEL SUPPLY REMAINS ABUNDANT

Proved reserves of hydrocarbon fuels (oil, gas and coal) are estimated at around 6 trillion barrels of oil equivalent, with coal accounting for half. The proved reserves for each fossil energy source are sufficient to meet current demand for many decades (and in the case of coal, for over 100 years). This is little different from the situation in 1990, in spite of a 50% increase in the annual consumption of fossil fuels since that year (to 2011).

Figure 2.2 **Proved reserves of fossil fuels can sustain consumption for many decades**



Source: BP, 2014. *Statistical Review of World Energy.* (Note: one trillion = one thousand billion).

Proved reserves are peer-reviewed estimates of future output, given current knowledge and costs. As knowledge advances over time, ‘resources’ that previously held little or no value are converted into proved reserves and replace interim production. This process of ‘replacement under conditions of increasing knowledge’ has historically been very successful. Indeed, global proved reserves of fossil fuels at the end of 2013 exceeded the cumulative amount of global fossil energy production to date[4]. Proved reserves are not fixed amounts but must be viewed as an inventory and, just like any other inventory, increase not despite interim production but because of it.

CARBON DIOXIDE EMISSION TRAJECTORIES ARE NOT COMPATIBLE WITH CLIMATE TARGETS – DELAYING ACTION IS EXPENSIVE

Projected energy consumption patterns lead to continued increases in annual CO_2 emissions to around 40 gigatonnes (Gt) by 2035 and in a ‘business as usual’ scenario (where current climate pledges are not implemented) to over 50 Gt by 2050 (or more than double CO_2 emissions in the year 2000)[5]. The scientific evidence suggests that on this CO_2 emissions trajectory the world is heading toward an increase in average global temperature of between 3.6 and 5.3 degrees Celsius (°C) (compared to pre-industrial levels), with most of the increase happening this century[6,7]. There is a growing disconnect with the goal, endorsed by over 100 countries in Copenhagen in 2009, for deep cuts in global emissions to hold the increase in global temperature to below 2°C.

[4] Derived using historical data from *BP Statistical Review of World Energy*. See also IEA, 2013. *World Energy Outlook 2013,* OECD/IEA, France.

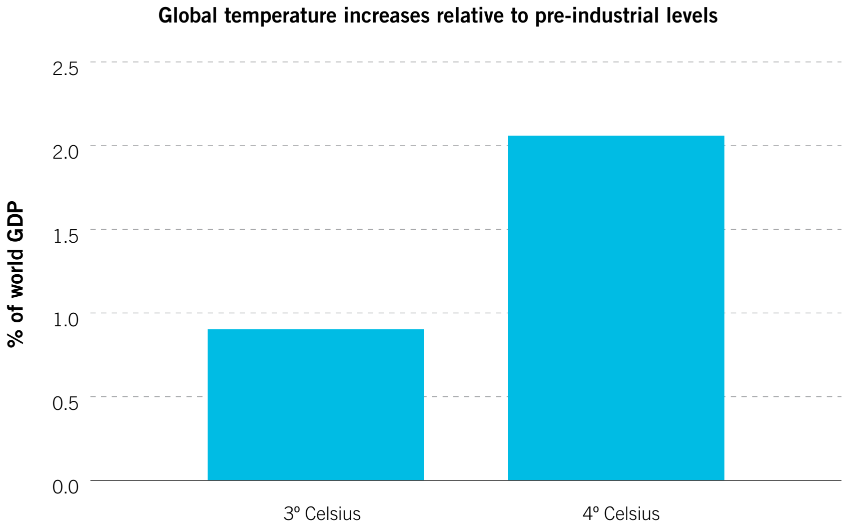
[5] IEA, 2013. *Ibid* and IEA, 2014. *Energy Technology Perspectives 2014: Harnessing Electricity’s Potential,* OECD/IEA, France.

[6] IEA, 2013. *Redrawing the energy-climate map,* OECD/IEA, France.

[7] The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) provides a detailed view of the current state of scientific knowledge on climate change. The Working Group I report on *Climate Change 2013: The Physical Science Basis,* provides a comprehensive assessment of climate change observations throughout the climate system.

We must move quickly to transform the way we generate and use energy. The urgency for action to reduce CO_2 emissions continues to grow as each year passes. A recent report issued by the Executive Office of the President of the United States surveyed the climate economics literature and concluded that delaying action to limit the effects of climate change is costly and that these costs escalate the longer the delay (compared against the same specified climate target).

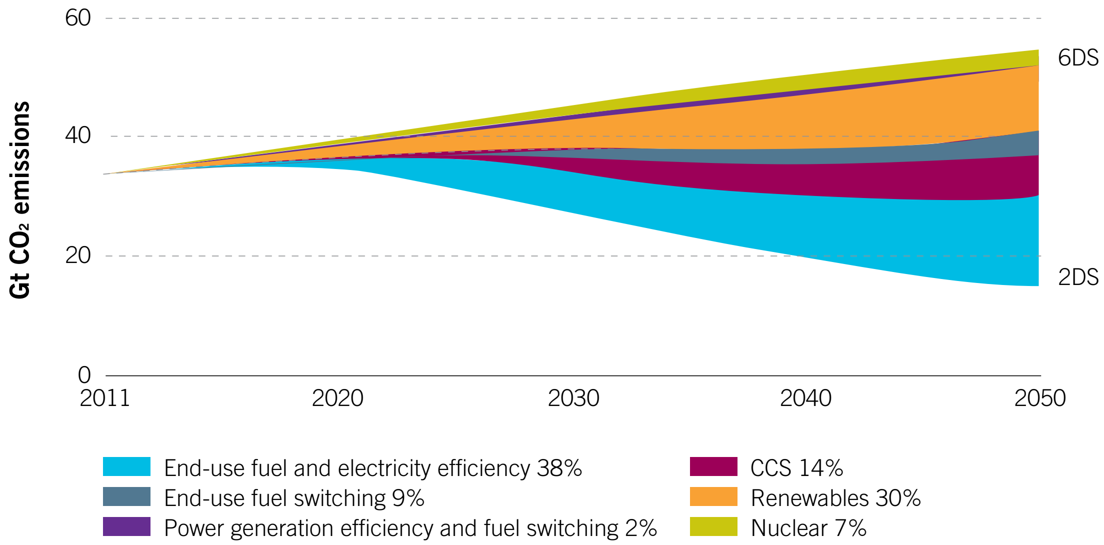
Figure 2.3 **The annual economic damage from temperature increase beyond 2° Celsius increases with delay**



Source: Executive Office of the President of the United States, 2014. *The Cost of Delaying Action to Stem Climate Change.*

Not only are there potentially large costs in delaying action to tackle climate change, there are also significant costs in not tackling such change in an economically efficient manner. Limiting the long-term rise in average global temperature to 2°C involves a substantial reduction in CO_2 emissions. The least-cost pathway to achieve this reduction requires investment in a portfolio of technologies, of which the use of fossil fuels and biomass with CCS is a very important contributor. Modelling by the International Energy Agency (IEA) shows that CCS provides around 14% of the cumulative reductions required through 2050 in a 2°C world compared to 'business as usual'.

Figure 2.4 **CCS contributes 14% of cumulative CO_2 emission reductions through 2050 in a 2°C world compared to 'business as usual'**



Source: IEA, 2014. *Energy Technology Perspectives 2014.*

THE CRITICAL ROLE OF CCS – THERE CANNOT BE AN EFFECTIVE MITIGATION RESPONSE TO CLIMATE CHANGE WITHOUT CCS

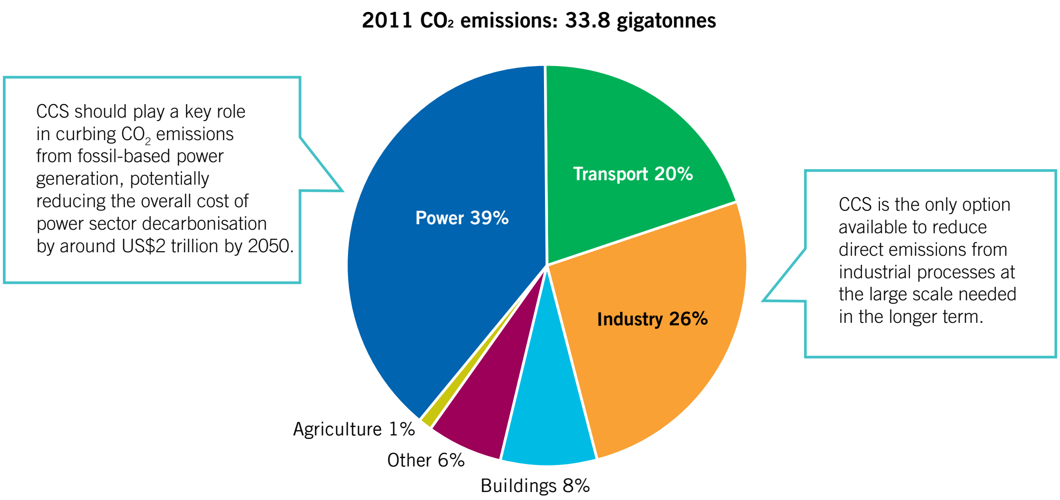
There cannot be an effective, least-cost mitigation response to climate change without CCS.

The criticality of CCS for the efficient transition to a low-carbon future is manifested in the following ways:

- **Electricity generation** – responsible for nearly 40% of CO_2 emissions in 2011. The exclusion of CCS as a technology option in the electricity sector alone would increase mitigation costs by around US$2 trillion by 2050[8]. While it may be possible to reduce emissions in the electricity sector by the amount needed to limit global temperature increase to below 2°C without using CCS, this would necessarily involve using more expensive technologies.

  Much attention is focused on the environmental benefits of fuel switching from coal-to gas-fired power generation. However, the latter is not carbon free and to meet longer-term emissions targets, both coal and gas-fired generating capacity will need to be fitted with CCS. In short, we cannot simply 'gas' our way out of the problem without CCS.
- **Industry** – responsible for a quarter of CO_2 emissions in 2011. In some high-emitting industrial sectors like iron and steel, cement, chemicals and refining, CCS is the only large-scale technology available that can make deep emissions cuts. Under a 'business as usual' scenario, emissions from these sectors are projected to grow by over 50% by 2050[9].

Figure 2.5 **Without CCS, reducing CO_2 emissions through 2050 in a 2°C world is highly unlikely in industry and at best very expensive in power**



Source: CO_2 emissions data from IEA, 2014, *Energy Technology Perspectives 2014.*

The importance of CCS therefore lies in its ability to help solve a sustainability equation that has a number of variables – specifically, the provision of an abundant energy resource in a way that is consistent with reducing CO_2 emissions in line with endorsed climate goals at least cost to economic growth. This is an especially important equation for non-OECD countries, where there is a pressing need to quickly build large amounts of generating capacity to bring electricity to many people who are without it today. As these economies industrialise, it is likely that global CO_2 emissions will increase significantly in the absence of CCS technologies. Further, CCS is a low-carbon complementary technology that can help address the intermittency challenges in renewable energy and thus help expand the latter's global uptake.

[8] IEA, 2012. *Energy Technology Perspectives 2012: Pathways to a Clean Energy System,* OCED/IEA, France.

[9] IEA, 2014. *Energy Technology Perspectives 2014: Harnessing Electricity's Potential,* OECD/IEA, France.

THE VALUE OF CCS IS INCREASINGLY ACKNOWLEDGED BY INDEPENDENT STUDIES

The case is compelling that deployment of CCS in both power and industry is critical to address climate change. A substantial number of independent studies and reports by influential bodies have reinforced this point over the last year.

'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.'

Maria van der Hoeven, Executive Director, IEA
Foreword to the *Technology Roadmap: Carbon Capture and Storage,* 2013.

'A robust finding [of the study] is that the unavailability of carbon capture and storage and limited availability of bioenergy have the largest impact on feasibility and macroeconomic costs for stabilizing atmospheric concentrations at low levels...

...a substantial number of models were not able to produce 450 ppm without CCS. Indeed, the vast majority of situations in which models could not produce scenarios were those in which CCS was assumed to be unavailable.'

Krey, V, Luderer, G, Clarke L, & Kriegler, E 2013, G*etting from here to there – energy technology transformation pathways in the EMF27 scenarios,* Climatic Change, December 2013. The Energy Modelling Forum (EMF) 27 Study on Global Technology and Climate Policy Strategies, 2013. The EMF27 project is a global model comparison exercise that includes a worldwide consortium of research institutes and is led by the Stanford Energy Modeling Forum, the Potsdam Institute for Climate Impacts Research, the International Institute for Applied Systems Analysis, among other institutes.

'Many models could not achieve atmospheric concentration levels of about 450ppm CO_2eq by 2100 if additional mitigation is considerably delayed or under limited availability of key technologies, such as bioenergy, CCS, and their combination (BECCS).'

'Combining bioenergy with CCS (BECCS) offers the prospect of energy supply with large-scale net negative emissions which plays an important role in many low-stabilization scenarios, while it entails challenges and risks (limited evidence, medium agreement).'

Summary report of the IPCC's Fifth Assessment Report (AR5), *Climate Change 2014: Mitigation of Climate Change,* 2014.

'Since CCS is a critical abatement technology in most global mitigation scenarios, including in many of the DDPs (Deep Decarbonization Pathways) developed by the Country Research Teams, countries and businesses need to urgently increase the levels of RDD&D in CCS to test if it can be technically and economically deployed at a large scale. In the absence of CCS, many countries – in particular those relying heavily of fossil fueled power generation – would find it much more difficult to achieve deep decarbonization.'

Pathways to Deep Decarbonization, Interim 2014 Report, Sustainable Development Solutions Network (SDSN) and Institute for Sustainable Development and International Relations (IDDRI), 2014.

NOTES

[3]

LARGE-SCALE CCS PROJECTS

CHAPTER HIGHLIGHTS

- 2014 has been a pivotal year for CCS:
  - the world's first large-scale CCS project in the power sector is operational at the Boundary Dam power station in Saskatchewan, Canada
  - an additional two large-scale CCS power sector projects in the US are expected to come into operation in 2015-16, and
  - construction is underway on the world's first large-scale CCS project in the iron and steel sector in Abu Dhabi, UAE.

- These four projects are among the 22 large-scale CCS projects in operation and construction (Execute stage) around the world – double the number at the beginning of the decade. The total CO_2 capture capacity of these 22 projects is around 40 million tonnes per annum (Mtpa).

- There are 14 large-scale CCS projects in advanced planning (Define stage), including nine in the power sector, many of which are anticipated to be in a position to make a final investment decision during 2015.

- There are a further 19 large-scale CCS projects in earlier stages of planning, bringing the number of large-scale CCS projects identified by the Institute to 55 (total CO_2 capture capacity of around 106 Mtpa).

- The US dominates in terms of large-scale CCS project numbers (19) followed by China (12) and Europe (eight).

- Within the full set of projects in the Operate, Execute and Define stages there is a subset of around 20 projects that is particularly important. These projects have the potential to demonstrate CCS in operation at large scale in the power sector and in new industrial processes, to demonstrate dedicated geological storage of CO_2 (not just EOR) and the use of varying fuel sources and different capture technologies from a range of suppliers.

- Advancing European projects into construction (and operation) will play an important role in establishing a positive perception of CCS globally. All planned large-scale CCS projects in Europe are focused on the power sector using dedicated (offshore) geological storage options.

- There is a lack of large-scale CCS projects in non-OECD economies (outside of China) and limited progress in CCS technology development in high CO_2 emitting industries such as cement, iron and steel and chemicals.

3.1

KEY DEVELOPMENTS IN LARGE-SCALE CCS PROJECTS IN 2014

The Institute has identified 55 large-scale integrated CCS projects from around the world[1]. Summary information on each project is contained in Appendix B while detailed project descriptions can be found on the Institute's website[2].

Section 3.1 of this chapter focuses on projects in operation, construction and at the most advanced stage of development planning, concept definition (or Define)[3].

2014 has been a pivotal year for CCS. Large-scale CCS projects in the power sector are now a reality, demonstrated by:

- the world's first large-scale power sector CCS project – the Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project in Canada (CO_2 capture capacity of 1 Mtpa) – becoming operational in October 2014
- commissioning activities on a new-build 582 megawatt (MW) power plant beginning at the Kemper County Energy Facility in Mississippi (US, CO_2 capture capacity of 3 Mtpa) with CO_2 capture expected to commence in 2015, and
- the Petra Nova Carbon Capture Project at the W.A. Parish power plant near Houston, Texas (US, CO_2 capture capacity of 1.4 Mtpa) entering construction in July 2014, with CO_2 capture anticipated by the end of 2016.

Outside the power sector, the world's first iron and steel project to apply CCS at large scale moved into construction in the UAE in the latter part of 2013. The Abu Dhabi CCS Project (CO_2 capture capacity of 0.8 Mtpa) involves CO_2 capture from the direct reduced iron process used at the Emirates Steel plant in Abu Dhabi and its transportation to the Rumaitha oil field, operated by the Abu Dhabi National Oil Company (ADNOC), for EOR purposes.

Overall, there are now 22 large-scale CCS projects in operation or under construction globally, double the number at the start of the decade (Figure 3.1). Of these, 13 are operational with another nine in construction[4]. The anticipated start dates for the projects under construction are:

- 2015 – the Kemper County Energy Facility, the Illinois Industrial Carbon Capture and Storage Project (US, CO_2 capture capacity of 1 Mtpa), Quest (Canada, CO_2 capture capacity of 1.08 Mtpa), the Uthmaniyah-CO_2 EOR Demonstration Project (Saudi Arabia, CO_2 capture capacity of 0.8 Mtpa) and the Alberta Carbon Trunk Line (ACTL) with Agrium CO_2 Stream Project (Canada, CO_2 capture capacity of 0.3-0.6 Mtpa)
- 2016 – the Gorgon Carbon Dioxide Injection Project (Australia, CO_2 capture capacity of 3.4-4.0 Mtpa), the Abu Dhabi CCS Project and the Petra Nova Carbon Capture Project, and
- 2017 – the ACTL with North West Sturgeon Refinery CO_2 Stream Project (Canada, CO_2 capture capacity of 1.2-1.4 Mtpa).

The total CO_2 capture capacity of these 22 projects is around 40 Mtpa (Figure 3.2).

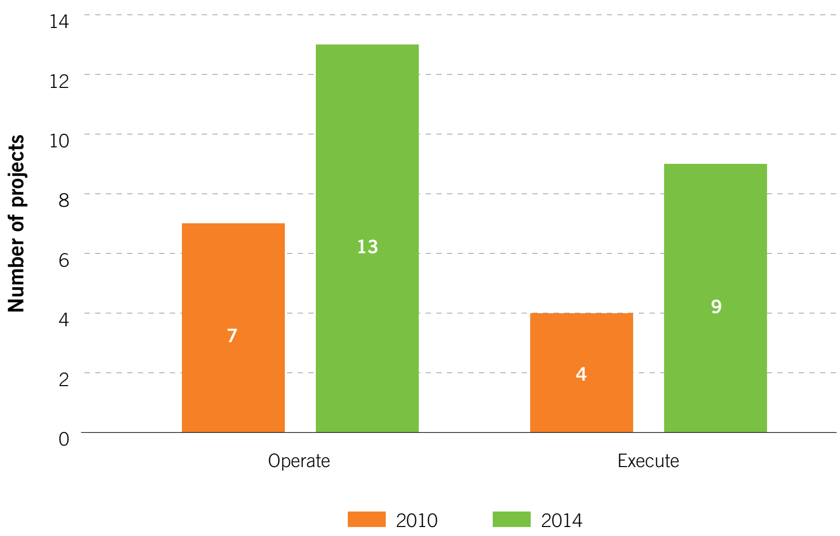
1 Large-scale integrated projects (LSIPs) are CCS projects considered to be at a sufficiently large scale to be representative of commercial-scale process streams. A full definition of the thresholds for projects to be included as an LSIP can be found at www.globalccsinstitute.com/projects/large-scale-ccs-projects-definitions.

2 www.globalccsinstitute.com/projects/large-scale-ccs-projects.

3 An overview of the Project Lifecycle model employed by the Institute to represent the stages in the development of a CCS project can be found at www.globalccsinstitute.com/projects/large-scale-ccs-projects-definitions. Throughout this report the terms construction and Execute are used interchangeably.

4 The 13 operational projects include the In Salah CO_2 Storage Project, which suspended CO_2 injection in June 2011. While In Salah's future injection strategy is under review a comprehensive monitoring program continues. As it is not actually injecting CO_2, In Salah project data is not reflected in the figures that display CO_2 capture capacity in terms of mass.

Figure 3.1 Number of large-scale CCS projects in the Operate and Execute stages[5]



There are a further 14 projects in the Define stage, the most advanced stage of development planning. The work at this stage underpins a final investment decision on whether to proceed into the Execute stage. The portfolio of projects in the Define stage in 2014 represents a robust selection of projects from several perspectives.

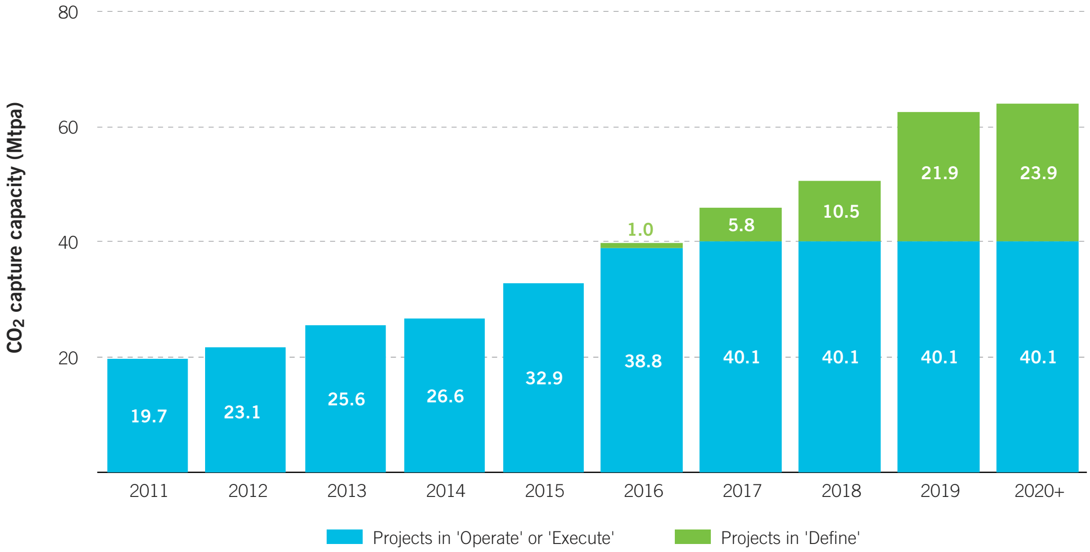
- Many have been recipients of public funding programs developed at the end of the previous decade and have completed their engineering and other studies, with a final investment decision dependent on (additional) funding being secured and/or all permitting approvals being in place. Projects in this category include the Rotterdam Opslag en Afvang Demonstratieproject (ROAD) (Netherlands, CO_2 capture capacity of 1.1 Mtpa), the FutureGen 2.0 Project (US, CO_2 capture capacity of 1.1 Mtpa) and the Texas Clean Energy Project (US, CO_2 capture capacity of 2.7 Mtpa).
- The White Rose CCS Project (UK, CO_2 capture capacity of 2 Mtpa) and the Peterhead CCS Project (UK, CO_2 capture capacity of 1 Mtpa) are benefitting from the UK CCS Commercialisation Programme which made up to GB£1 billion in capital funding available for first-mover CCS projects through a competitive process.

  Additional projects participating in the UK Government's Final Investment Decision Enabling program are negotiating for the opportunity to benefit from an individual Contract for Difference (CfD) to help close the funding gap for further project development.
- There are four projects in China where the engineering and other studies needed to progress to construction are essentially complete. A final investment decision in the next year can be expected, subject to the decision-making processes of the state-owned enterprises responsible for the projects. Two of these projects have implemented a pilot CO_2 capture phase as preparation for progression to larger scale CO_2 capture – these are the Yanchang Integrated Carbon Capture and Storage Demonstration Project (CO_2 capture capacity for the large-scale project of 0.46 Mtpa) and the PetroChina Jilin Oil Field EOR Project (Phase 2) (CO_2 capture capacity for the large-scale project of 0.8 Mtpa).
- There is a balanced spread of projects across most regions as well as across storage options and capture technologies (Figures 3.5-3.7).

Most of the projects in the Define stage should be in a position to make a final investment decision by the end of 2015. The total CO_2 capture capacity of the 14 large-scale CCS projects in Define is around 24 Mtpa. As with any portfolio of projects at such a stage, it should not be expected that all would make a positive final investment decision.

[5] To ensure consistency across years, the 2010 record of large-scale operating CCS projects in all figures combines the Rangely and Salt Creek EOR Projects. In Institute reporting, these projects were combined and included under the Shute Creek Gas Processing Facility Project from 2011 onwards.

Figure 3.2 CO_2 capture capacity of projects in the Operate, Execute and Define stages



Within the full set of projects in the Operate, Execute and Define stages there is a subset of around 20 projects that is particularly important. These projects have the potential to demonstrate CCS in operation at large-scale in the power sector and in new industrial processes (other than natural gas processing and fertiliser production where CCS at large-scale is well established), to demonstrate dedicated geological storage of CO_2 (not just EOR) and different capture technologies from a range of suppliers (Table 3.1).

Table 3.1 **Potential portfolio of large-scale CCS projects: a subset of projects from the Operate, Execute and Define stages that can demonstrate CCS in different industries, geological settings and capture technologies/suppliers**

PROJECT NAME	STAGE	MASS OF CO_2 (MTPA)	PORTFOLIO BENEFIT
Americas region			
Air Products Steam Methane Reformer EOR Project	Operate	1.0	Hydrogen production, industrial separation
Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project	Operate	1.0	Power sector, post-combustion, coal feedstock
Illinois Industrial CCS Project	Execute	1.0	Dedicated geologic storage - onshore deep saline formation
ACTL with North West Sturgeon Refinery CO_2 Stream	Execute	1.2-1.4	Refining sector, pre-combustion
Kemper County Energy Facility	Execute	3.0	Power sector, pre-combustion, coal feedstock
Petra Nova Carbon Capture Project	Execute	1.4	Power sector, post-combustion, coal feedstock
Quest	Execute	1.08	Hydrogen production, industrial separation, dedicated geologic storage - onshore deep saline formation
FutureGen 2.0 Project	Define	1.1	Power sector, oxyfuel combustion, coal feedstock, dedicated geologic storage - onshore deep saline formation
Hydrogen Energy California Project (HECA)	Define	2.7	Power sector (poly-generation facility), pre-combustion, coal feedstock
Texas Clean Energy Project	Define	2.7	Power sector (poly-generation facility), pre-combustion, coal feedstock

PROJECT NAME	STAGE	MASS OF CO_2 (MTPA)	PORTFOLIO BENEFIT
Americas region (continued)			
Sargas Texas Point Comfort Project	Define	0.8	Power sector, post-combustion, natural gas feedstock
Spectra Energy's Fort Nelson CCS Project	Define	2.2	Dedicated geologic storage - onshore deep saline formation
Europe, Middle East and Africa region			
Sleipner CO_2 Storage Project	Operate	0.9	Offshore natural gas processing, pre-combustion, dedicated geologic storage - offshore deep saline formation, direct injection
Snøhvit CO_2 Storage Project	Operate	0.7	Onshore natural gas processing, pre-combustion, dedicated geologic storage - offshore deep saline formation
Abu Dhabi CCS Project	Execute	0.8	Iron and steel sector, industrial separation
Don Valley Power Project	Define	5.0	Power sector, pre-combustion, coal feedstock, dedicated geologic storage - offshore deep saline formation
Peterhead CCS Project	Define	1.0	Power sector, post-combustion, natural gas feedstock, dedicated geologic storage - offshore depleted gas reservoir
ROAD	Define	1.1	Power sector, post-combustion, coal feedstock (plus biomass), dedicated geologic storage - offshore depleted gas reservoir
White Rose CCS Project	Define	2.0	Power sector, oxyfuel combustion, coal feedstock (plus biomass), dedicated geologic storage - offshore deep saline formation
Asia Pacific region			
Gorgon Carbon Dioxide Injection Project	Execute	3.4-4.0	Dedicated geologic storage - onshore deep saline formation
Sinopec Shengli Power Plant CCS Project	Define	1.0	Power sector, post-combustion, coal feedstock
Sinopec Qilu Petrochemical CCS Project	Define	0.5	Chemical sector, pre-combustion, coal feedstock
Yanchang Integrated CCS Demonstration Project	Define	0.46	Chemical sector, pre-combustion, coal feedstock

Important elements of this 'potential project portfolio' include[6]:

- potential for around ten large-scale CCS projects in the power sector to be operational by around the 2020 timeframe
- potential for around ten large-scale CCS projects to have experience injecting CO_2 into geological storage options by around the 2020 timeframe
- potential for CCS to be applied to both coal (of various types) and natural gas feedstocks, and
- potential for all the main CO_2 capture technologies (pre-, post- and oxy-fuel combustion) to be applied at large scale in power generation.

[6] This subset of a 'potential project portfolio' is derived from projects in the Operate, Execute and Define stages. There are other projects in the earlier stages of development planning that in time may advance to Define and then Execute. The key messages that follow are also applicable to these earlier stage projects.

A successful portfolio of demonstration projects will build confidence in CCS by showing the technologies in action across a range of industries, storage types and fuels. A robust portfolio can be a strong catalyst to improving community understanding of CCS as an environmentally friendly technology and reinforce the important role of CCS in reducing global CO_2 emissions. An emerging portfolio of projects is also a critical factor in demonstrating to the financial community that continued progress in CCS is being made. The lessons learnt from such a portfolio – in strengthening regulatory frameworks and identifying avenues for improved technical performance and reductions in costs – would lessen perceived risks associated with the next generation of CCS projects post-2020.

The strength of the CCS projects portfolio to 2020 will be decided to a large extent over the course of the next 12 to 18 months. It is vital that financial and policy support structures in the near term are supportive of transitioning this 'potential portfolio' into an 'actual portfolio' and that CCS is not disadvantaged in relation to other low-carbon technologies.

Once in operation, the portfolio of projects identified above will play a key role in moving forward discussion on CCS, laying to rest arguments about its 'experimental' nature and that it has not yet been applied at scale to large, fossil fuel power plants. Together with advances in capture technologies, the substantial knowledge dividend reaped from a suite of large-scale operational projects will act to reduce costs and strengthen investor and stakeholder confidence.

When this occurs, the necessary pre-conditions must be in place to allow project proponents to quickly transition from current to next generation CCS technologies post-2020.

Establishing the pre-conditions for the widespread deployment of CCS through the 2020s and beyond is a process that must be completed this decade. Momentum must be accelerated. The CO_2 capture capacity of all projects in the Operate, Execute and Define stages of around 65 Mtpa (equivalent to the current CO_2 emissions of Finland or Austria, for example) is multiples below the levels necessary for CCS to play a key role in combating climate change in the longer term. A very substantial increase in new projects entering construction is needed in the next 10-15 years and thereafter.

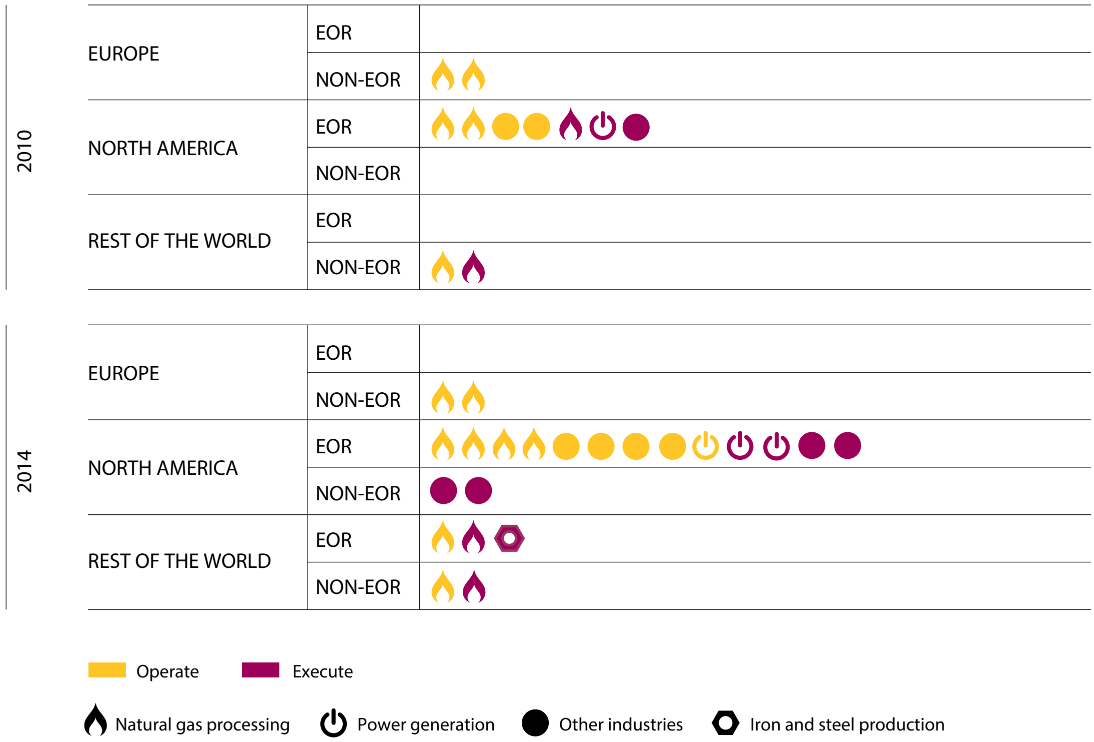
This can only come about through the application of policies that accommodate CCS (and other low-emission technologies) within market mechanisms and that address specific CCS factors, such as development of national laws and regulations (discussed in Chapter Five, Policy, Legal and Regulatory Developments) and policies that encourage the exploration and appraisal of significant storage capacity.

Investors require longer-term policy predictability if they are to invest in CCS. Strong, sustainable emission reduction policies that encourage CCS are urgently needed and necessary for longer-term deployment.

Existing policy support alone over the past five years has been inadequate to attract the necessary private investment needed to 'launch' the number of large-scale CCS projects anticipated at the start of the decade. Current market opportunities can provide added impetus to only a limited number of first-mover projects and to date, there has been a development bias toward projects with access to additional revenue opportunities, such as the use of CO_2 in EOR.

Market opportunities to utilise CO_2 as a commodity is most evident in North America. Of the 22 projects in operation or construction globally in 2014, 16 (around 70%) are using or intend to use the captured CO_2 for EOR (Figure 3.3). Moreover, in many of these projects, CO_2 separation is already part of the industrial separation process, such as in natural gas processing and fertiliser production, requiring much lower incremental cost before transport (compared to CO_2 capture at a power plant for example).

Figure 3.3 Large-scale CCS projects in the Operate and Execute stages by storage type



An examination of projects in the Define stage reveals a number of interesting aspects about past and future project developments.

- Compared to projects presently in operation or under construction, there are proportionately fewer projects where CO_2 separation is part of the industrial process – nine of the 14 projects in Define are in power generation.
- The majority of projects in Define in North America (four out of six) and all in China (four out of four) intend to use captured CO_2 for EOR.

  In North America, three projects in Define have received public funding under Federal programs, of which two intend to use the captured CO_2 for EOR. These 'twin pillars' (public support and market opportunity) offer a positive business case that suggests more projects from North America could move into construction in 2014-15.

  In China, there is optimism that the projects in advanced planning will move into construction in 2014-15, although timing is subject to the decision-making processes of the state-owned enterprises responsible for these projects.
- In Europe, where 'CO_2-EOR suitable' oil fields are less prevalent, projects are focused on dedicated geological storage options, which is much more costly and time intensive to fully characterise than CO_2-EOR systems.

  Coupled with a reliance on carbon price support that has subsequently collapsed, this has resulted in Europe losing the leadership role in CCS development that it aspired to at the beginning of the decade. Despite considerable policy initiatives, no large-scale CCS project has entered construction in Europe in over a decade.

  Nevertheless, European projects can play an important role in the portfolio of large-scale CCS projects, with anticipated start dates towards 2020. All four European projects in the Define stage are in the power sector, employ a range of capture technologies and fuel sources and would validate CO_2 storage in offshore deep saline formations and depleted gas reservoirs. The successful implementation of large-scale CCS projects in Europe will be vital in establishing a positive perception of CCS both in the region and globally.

All but one of the European projects in Define are in the UK. Nevertheless, the ROAD Project in the Netherlands is one of the world's most advanced CCS projects (in development planning) in the power sector and is ready to take a positive final investment decision if additional funding can be secured. As such, the ROAD Project is of vital importance to CCS progress in Europe.

The Peterhead CCS Project and the White Rose CCS Project have both progressed into the Define stage over the past year as CCS efforts are being re-energised in the UK.

Importance of storage characterisation in accelerating CCS

Ultimately every CCS project depends on CO_2 storage. Several aspects of the current storage portfolio of the advanced projects are important for the longer-term deployment of CCS.

While use of CO_2 in EOR remains important in markets where such revenue opportunities are possible, there are a number of projects that will use either deep saline formations or depleted gas reservoirs for CO_2 storage; these projects are particularly important. Deep saline formations are considered to have the greatest potential by far to store the large volumes of CO_2 required for longer-term deployment.

There are three projects in construction pursuing onshore deep saline formation storage – the Quest Project (Canada), the Gorgon Carbon Dioxide Injection Project (Australia) and the Illinois Industrial Carbon Capture and Storage Project (US). These projects will be operational in 2015-16[7].

Of the projects in the Define stage, the FutureGen 2.0 Project (US), Spectra Energy's Fort Nelson CCS Project (Canada, CO_2 capture capacity of 2.2 Mtpa), the ROAD Project (Netherlands) and all the UK projects are evaluating onshore or offshore storage in deep saline formations or offshore depleted gas reservoirs[8]. Anticipated operational dates are in the 2017-20 period.

Based on the assumption that Europe in particular will host a number of large-scale CCS projects over the next decade, knowledge of storage performance should be greatly enhanced by 2030. Whilst theoretical laboratory and pilot-scale field projects have provided significant scientific and technical learnings, large-scale projects are required to demonstrate that sufficient numbers of storage sites will be available across a variety of geological settings that can provide sufficient capacity, injectivity and containment for widespread commercial deployment.

Further data from a greater variety of real-world, large-scale storage scenarios is vital to prove the effectiveness of commercialised, widely deployed CCS and in establishing CCS as an important part of a lowest-cost CO_2 emissions reduction portfolio.

From a project management perspective, there are a number of important characteristics of greenfield storage assessment.

- It can take a considerable period of time to fully appraise a site ready for a final investment decision – experience suggests this can take five to ten years. This is a much longer time frame than is generally required for the capture and transportation elements of a CCS project.
- In the early phases of project development, storage availability is also the most uncertain element – and may require a significant allocation of time and resources early in development planning.
- The characteristics of a particular storage site may have important influences on the design of the CO_2 capture plant and transportation system.

These characteristics of greenfield storage assessment are not restricted to first-mover projects; they will remain as challenges for the next generation of CCS projects. This is unlike the expectation for capture technologies, where over time, costs are expected to reduce substantially due to R&D and learnings from the current generation of projects.

[7] In the case of the (operational) Boundary Dam project, any CO_2 that is not used in EOR will be injected into a deep saline formation near the capture facility through the Aquistore project.

[8] For some UK projects, the potential for EOR is also being examined.

Indeed, given the required scale of CCS deployment post-2020 to meet climate goals, the challenge of finding appropriate storage capacity may increase considerably. Projects may need to investigate multiple storage targets to mitigate exploration risk (not all target sites will be successfully appraised). Accordingly, the importance of undertaking storage-related actions this decade to prepare for wider-scale CCS deployment post-2020 cannot be overstated.

To lessen the risk of widespread CCS deployment being slowed by uncertainty over available storage, there is an urgent need for policies and government funded programs to encourage the exploration and appraisal of significant CO_2 storage capacity. Moreover, efforts to encourage linked storage and transportation infrastructure networks should be incentivised.

The data on large-scale CCS projects also highlights two other areas requiring increased attention by policymakers – the lack of projects in non-OECD economies (outside of China) and the lack of progress (compared to the electricity sector) in CCS technology development in high CO_2 emitting industries such as cement, iron and steel and chemicals.

Importance of CCS in developing countries

It is not surprising that the vast majority of large-scale CCS projects are in the developed world – this is where key project enablers such as public support programs, marketable opportunities for CO_2, storage assessments and regulatory frameworks are most advanced. In this sense, the lack of large-scale CCS projects outside the developed world at this point in time is not something that should be surprising.

However, non-OECD economies will account for the vast majority of growth in energy demand in coming decades. By extension, meeting longer-term climate goals will involve significant capture and storage of CO_2 from facilities in these economies. The IEA has projected that by 2050, non-OECD countries will need to have captured 70% of the cumulative mass of CO_2 captured and stored between 2015 and 2050 to achieve the emission reductions needed to keep the global temperature increase to within 2ºC[9].

This points to the urgent need to devote substantial resources to the implementation of policies and frameworks (including knowledge sharing and capacity development programs) during the course of this decade that can then support the increasing numbers of large-scale CCS projects needed in non-OECD economies by 2025-30 and beyond.

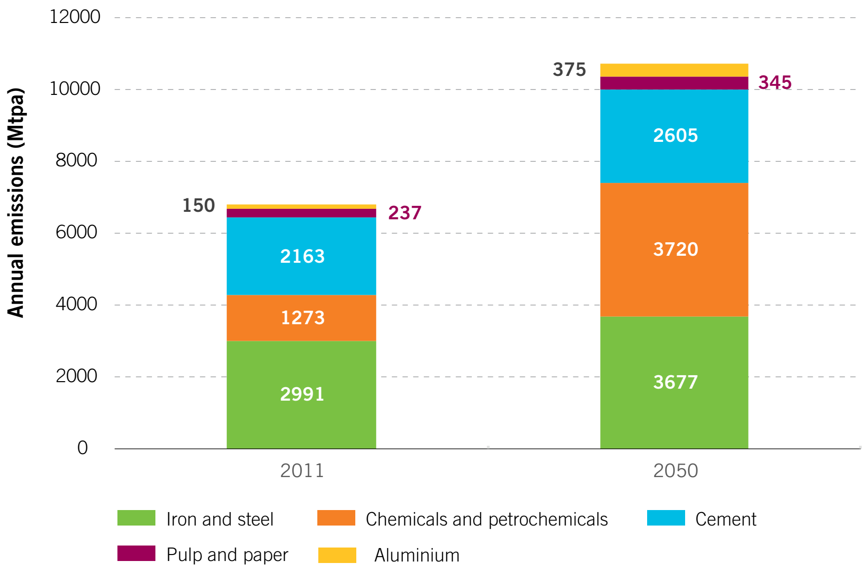
Industrial sector emissions must not be overlooked

Annual CO_2 emissions from the iron and steel, cement, chemicals and refining industries presently total approximately seven gigatonnes, or around 20% of total CO_2 emitted globally each year. Under a 'business as usual' scenario, CO_2 emissions from these sectors could grow by over 50% by 2050 (Figure 3.4). Reducing emissions from these industries is just as important as reductions in the electricity sector, and for many industrial processes deep emission reductions can only occur through abatement options such as CCS[10].

[9] IEA, 2012. *Energy Technology Perspectives 2012: Pathways to a Clean Energy System,* OECD/ IEA, France.

[10] The importance of CCS in industrial sectors is examined by the IEA in *Energy Technology Perspectives 2014: Harnessing Electricity's Potential,* OECD/IEA, France.

Figure 3.4 Industrial sector-specific direct CO_2 emissions to 2050 under a 'business as usual' scenario



Source: IEA, 2014. *Energy Technology Perspectives 2014: Harnessing Electricity's Potential.*

Paradoxically perhaps, many of the large-scale CCS projects currently in operation or under construction are in the industrial sector, mainly natural gas processing and fertiliser production, where the CO_2 is already separated as part of production and is relatively inexpensive to capture compared to heavy industrial processes.

However, these industries are relatively low emitters of CO_2 compared to the iron and steel, cement and chemicals sectors where, with current knowledge, the addition of CO_2 capture technologies would incur significant incremental costs. Significant decarbonisation of the latter three industries is important to help meet global CO_2 emissions reduction goals; however, there is a paucity of large-scale CCS projects in these industries in either operation, construction or the advanced stages of development planning (a case study of a pilot-scale project in the iron and steel industry is contained in Chapter Four, Notable Projects – Japanese Project Case Studies).

The lack of large-scale CCS projects in high-emitting industrial applications is of concern since CCS is the only technology that can help achieve deep reductions in CO_2 emissions in these industries in the longer term. Urgent attention must be given to the implementation of policies that incentivise the development and subsequent widespread deployment of CCS in high-emitting industrial applications.

It is perhaps not surprising that the electricity sector has been the main arena of CCS technology and policy development. Government R&D programs worldwide are generally more robust for the electricity sector than industrial application. Carbon dioxide emissions are much greater in the electricity sector and the 'product' tends to be much more homogeneous than for the industrial sectors – that is, industrial applications of CCS are more varied than power sector applications. Different industrial processes produce different quantities and purities of CO_2 (perhaps distributed over many sites), the extent of redesign of existing facilities to accommodate CCS may vary greatly and, most importantly, the products of the industrial sector can have a high exposure to global competition, making them highly sensitive to relative production costs.

This latter aspect highlights a key area of interaction (and need for reconciliation) between climate policy and industrial policy, as expressed in a recent *Insights Series 2014* paper published by the IEA:

> ***'Enabling trade-exposed sectors to take vital climate change mitigation actions, such as CCS, while retaining a competitive position, is a key challenge for CCS policy in a world with fragmented climate policies. Due to the potential importance of CCS to industrial emissions reductions, it is also a key challenge for achieving deep emissions reductions more broadly.'***
>
> IEA, *Insights Series 2014, CCS 2014 What lies in store for CCS?,* 2014.

This paper discusses a number of policy approaches to encourage CCS in industrial processes, noting that such approaches need to be 'tailor-made' to account for the specific circumstances in each of the key industries.

Importance of international collaboration and knowledge sharing

The foregoing analysis on project developments and enabling factors demonstrates the importance of international collaboration in accelerating the uptake of CCS. Coordinated international collaboration and knowledge sharing platforms can be effective mechanisms to leverage learnings from project and policy experiences and R&D activities to accelerate CCS deployment.

This is often discussed in the context of sharing of learnings in capture technology, where the scope for performance and cost improvement is greatest. However, the scope for international collaboration is much wider. Global collaboration will be important to help accelerate CCS in non-OECD economies and in many industrial processes. The various storage options to be employed by operational projects means coordinated international approaches to sharing learnings, best practices and understanding of storage resources will be particularly helpful. Similar observations about the importance of knowledge sharing can be expressed in the areas of public policy and regulations, public engagement and transportation of CO_2.

Examples of best practices and international developments are being shared through knowledge networks, conferences, workshops and webinars. It is clear that gaining maximum benefit for lsecond-generation CCS projects is dependent on this being as effective as possible and the Institute is fully committed to playing its part.

Figure 3.5 Actual and expected operation dates for large-scale CCS projects in the Operate, Execute and Define stages by industry and storage type

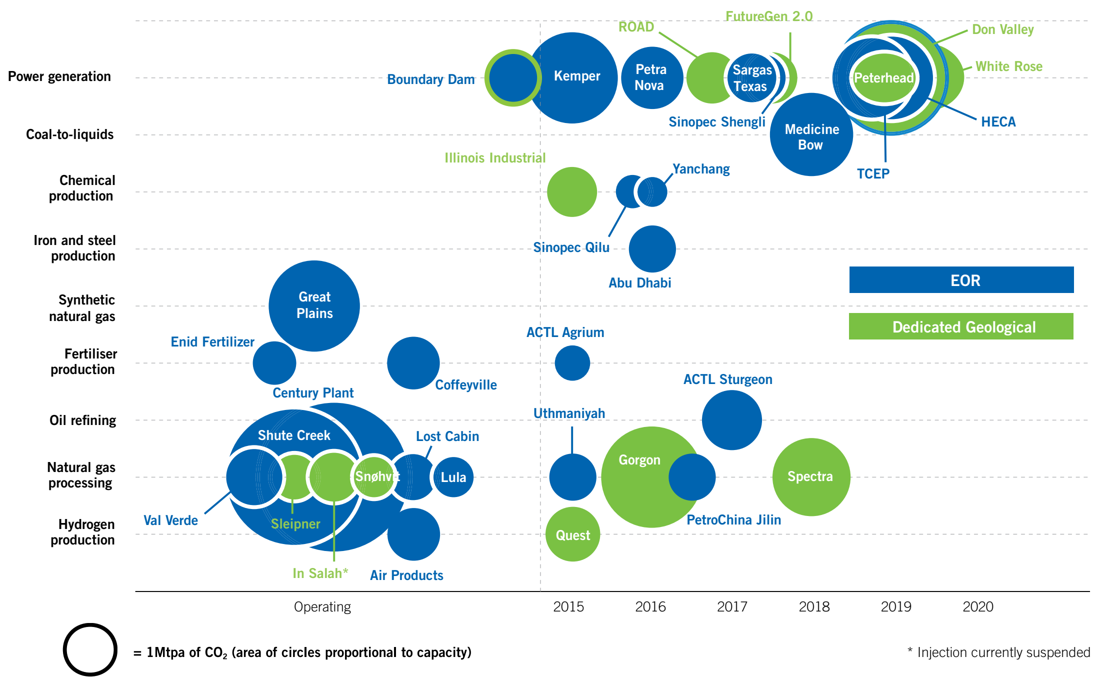


Figure 3.6 Actual and expected operation dates for large-scale CCS projects in the Operate, Execute and Define stages by capture and storage type

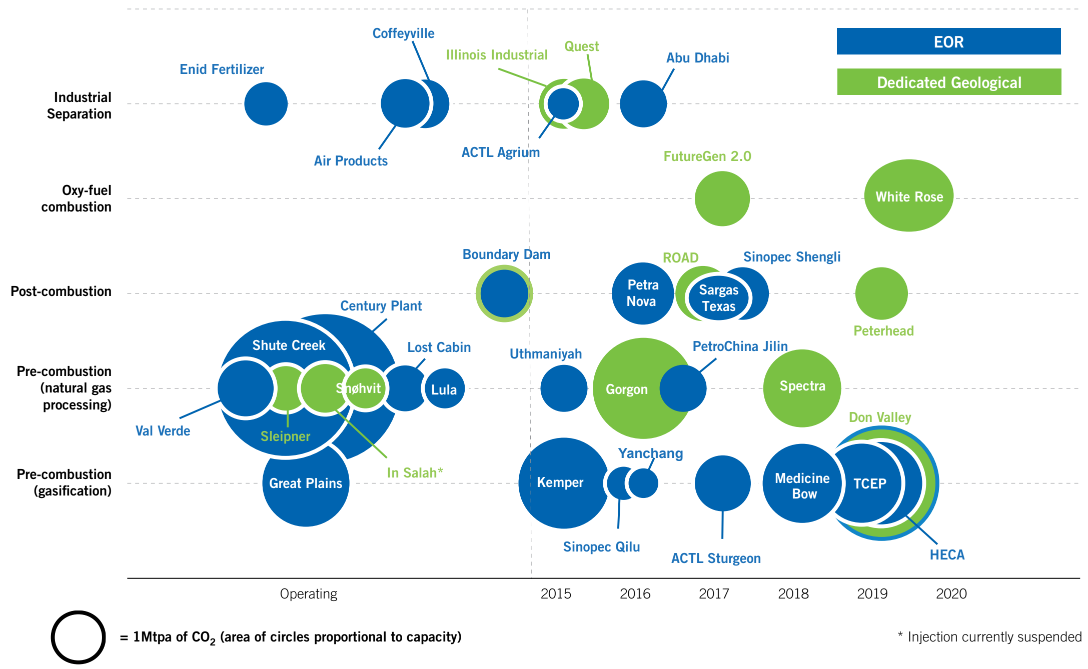
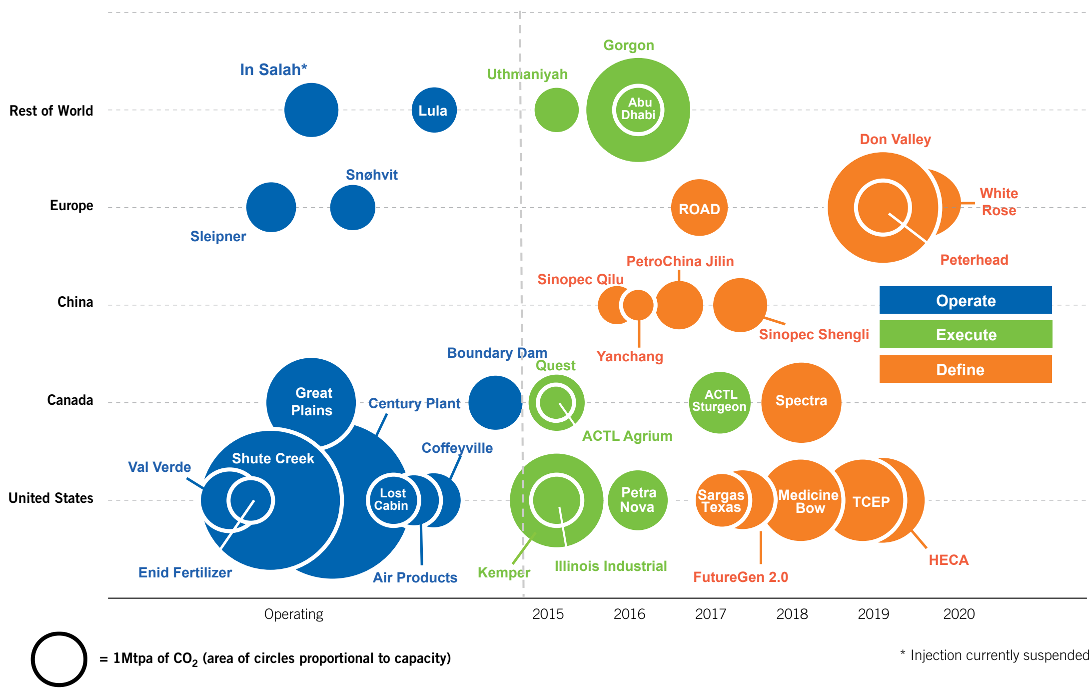


Figure 3.7 Actual and expected operation dates for large-scale CCS projects in the Operate, Execute and Define stages by region and project lifecycle stage

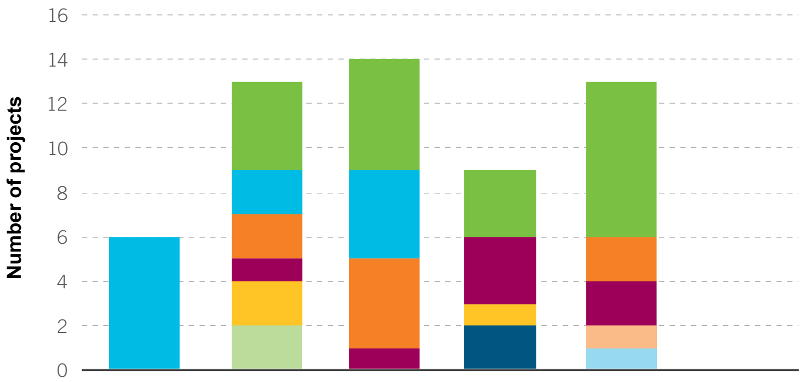


3.2 GLOBAL TRENDS IN LARGE-SCALE CCS PROJECTS

Current status – all projects

The Institute has identified 55 large-scale CCS projects globally (Figure 3.8 and Figure 3.9). Of these, 22 projects are in either operation or under construction. The US continues to have the largest number of projects at 19, including ten projects in either operation or construction. China has a total of 12 projects, four of which are in an advanced stage of development planning and for which hopes are high that a positive financial investment decision may be taken during 2015. Europe has eight projects, two of which are in operation in Norway, five are in the UK and one is in the Netherlands. Canada has seven projects, five of which are in construction or operation. This is the first year that the number of projects in China has exceeded the number of projects in Europe (and reflects a decline in the number of projects in Europe since the release of *The Global Status of CCS: 2013* report).

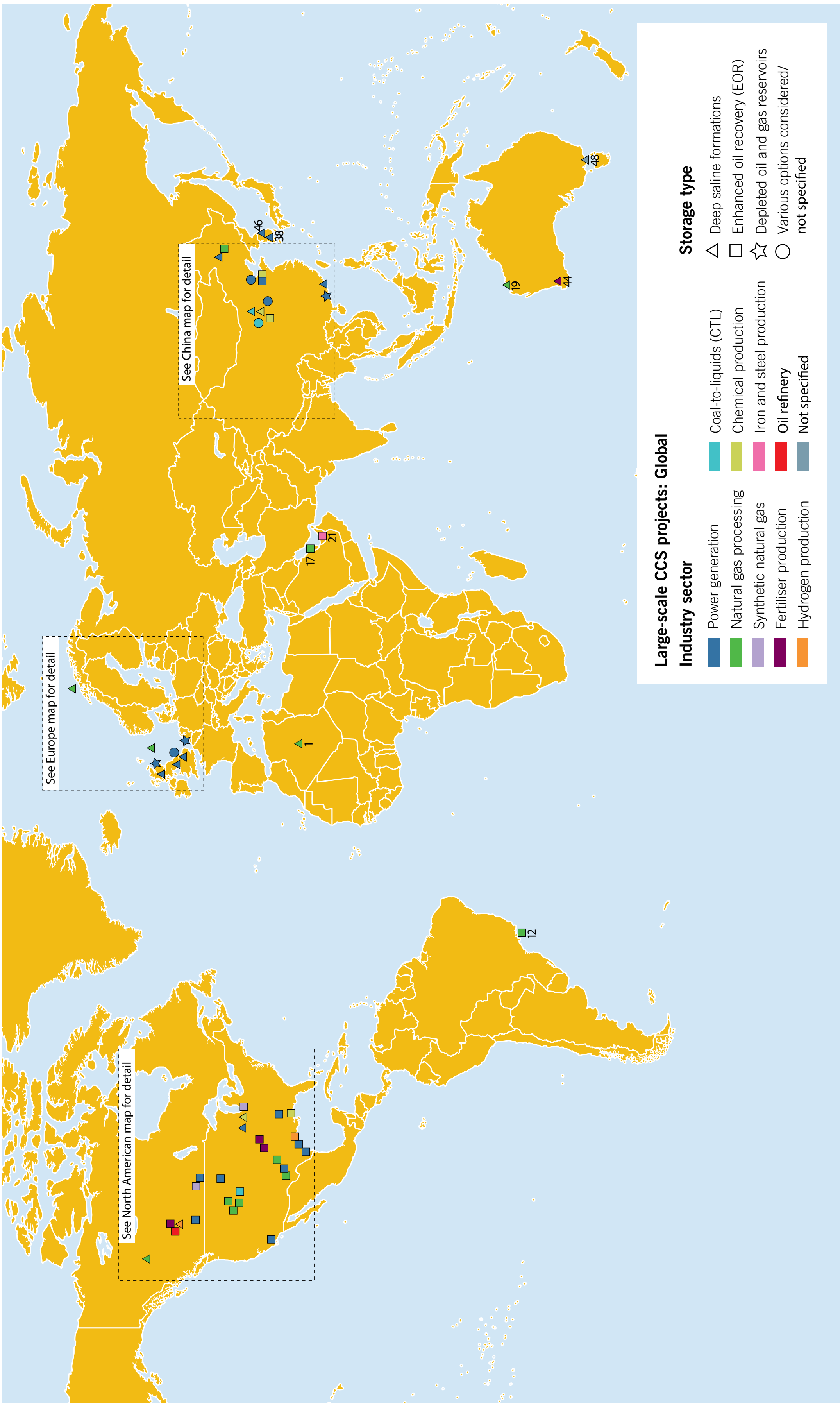
Figure 3.8 Large-scale CCS projects by lifecycle stage and region/country



	Identify	Evaluate	Define	Execute	Operate	Total
United States	0	4	5	3	7	**19**
China	6	2	4	0	0	**12**
Europe	0	2	4	0	2	**8**
Canada	0	1	1	3	2	**7**
Australia	0	2	0	1	0	**3**
Middle East	0	0	0	2	0	**2**
Other Asia	0	2	0	0	0	**2**
South America	0	0	0	0	1	**1**
Africa	0	0	0	0	1	**1**
Total	**6**	**13**	**14**	**9**	**13**	**55**

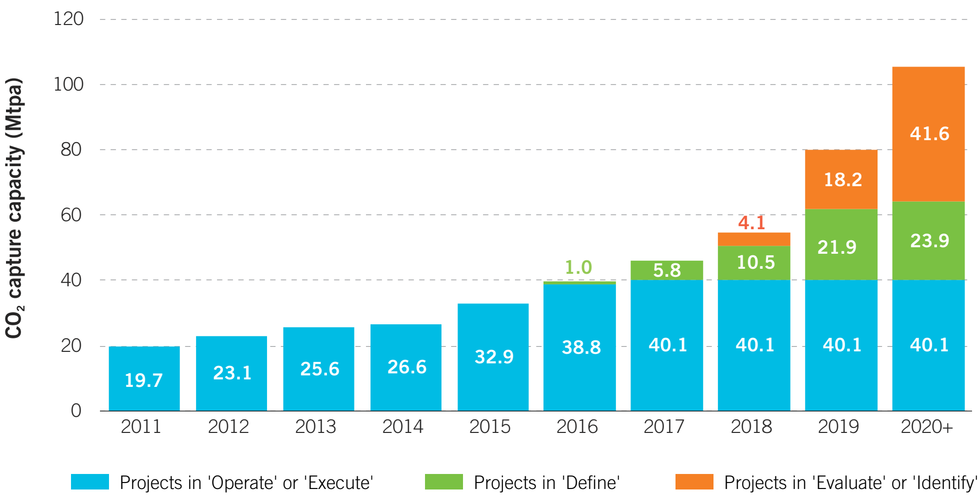
The combined CO_2 capture capacity of all 55 large-scale projects is around 106 Mtpa (Figure 3.10). The regional distribution follows the pattern set by the number of projects – Americas is at 60 Mtpa CO_2 capture capacity, Asia Pacific is at around 27 Mtpa and Europe, Middle and Africa (EMEA) is at around 19 Mtpa. By life-cycle stage, the projects in Operate and Execute have a combined CO_2 capture capacity of around 40 Mtpa, those in Define 24 Mtpa and the remaining projects in the early planning stages 42 Mtpa.

Figure 3.9 World map of large-scale CCS projects[11]



[11] Projects are identified by a reference number that is included in the summary project information provided in Appendix B.

Figure 3.10 CO_2 capture capacity of all identified large-scale CCS projects



Figures 3.11-3.14 illustrate how the 106 Mtpa of combined CO_2 capture capacity is distributed across industry sector and capture and storage type, both globally and by region (the Americas, Asia Pacific and EMEA).

Globally, the power generation and natural gas processing industry sectors account for the majority of CO_2 capture capacity, pre-combustion dominates capture type as does EOR for storage type. The regional breakdowns have a number of similarities and differences to this pattern and are discussed below.

Industry sector

- Americas: The bulk of CO_2 capture capacity is spread across the natural gas processing and power generation industries.
- EMEA: Power generation is by far the the dominant sector.
- Asia Pacific: There is a wider spread of projects covering power generation, natural gas processing, coal-to-liquids and chemical production. The latter two industry sectors are most evident in China with five projects (for a total mass of CO_2 potentially captured of 6.5 Mtpa).

Capture type

- Americas: Pre-combustion capture is the dominant technology and reflects industry composition as well as the number of power projects involving integrated gasification combined cycle (IGCC) plants.
- EMEA: Pre-combustion is the dominant capture technology with a number of planned IGCC plants. The remaining projects employ a range of different capture technologies.
- Asia Pacific: The CO_2 capture technology choice is distributed across a broad portfolio of technologies; however, similar to other regions, pre-combustion technology is the largest component.

Storage type

- Americas: Almost all of the CO_2 capture capacity is intended for use in EOR.
- EMEA: The majority of CO_2 potentially captured is intended for dedicated geological storage in offshore fields (in either deep saline formations or depleted gas reservoirs).
- Asia Pacific: A regional bias to dedicated geological storage but with notable differences within the region. Opportunities to use captured CO_2 for EOR is driving the progress of a number of Chinese CCS projects, with almost one third of the CO_2 capture capacity in China to be stored in this manner. In Australia, on the other hand, all storage is planned in deep saline formations.

Figure 3.11 Global CO_2 capture capacity by industry, capture type and storage option

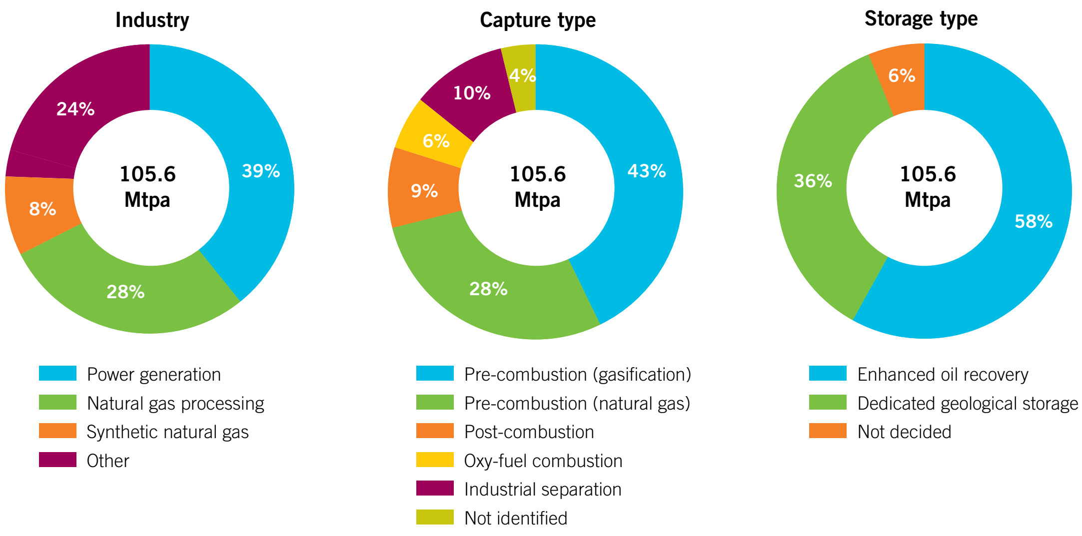


Figure 3.12 CO_2 capture capacity by industry and region

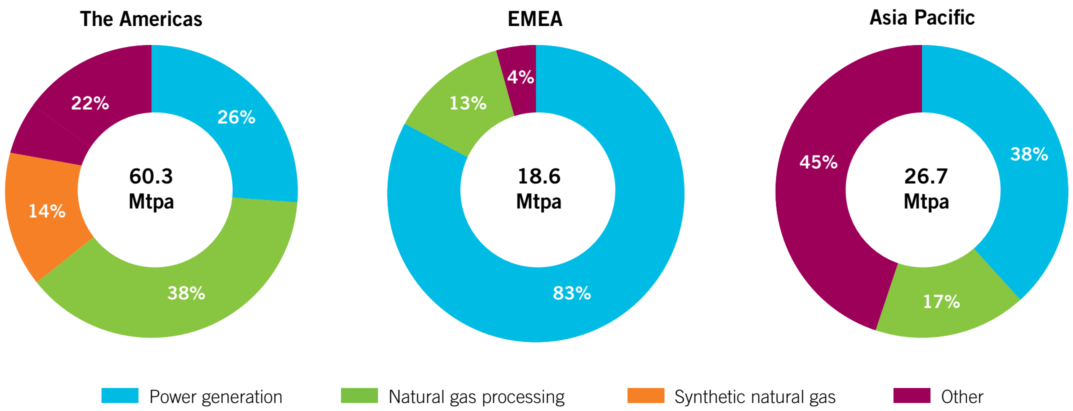


Figure 3.13 CO_2 capture capacity by capture type and region

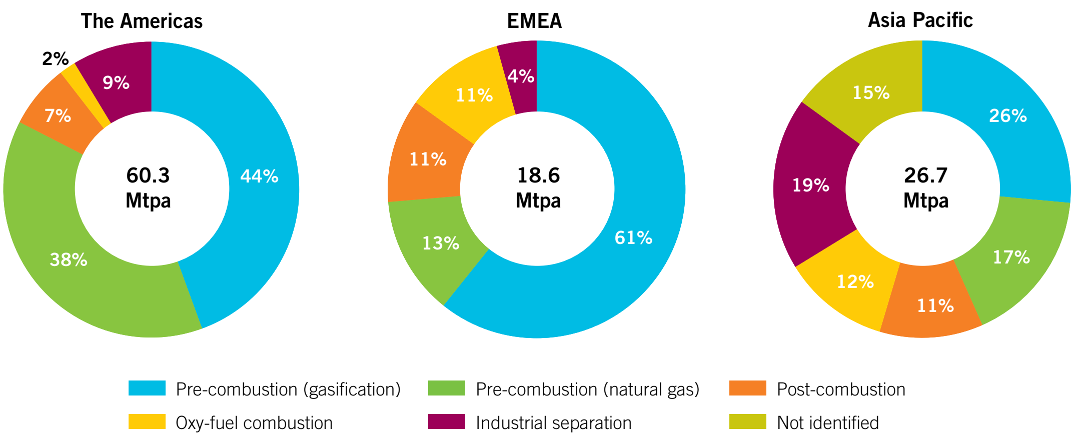
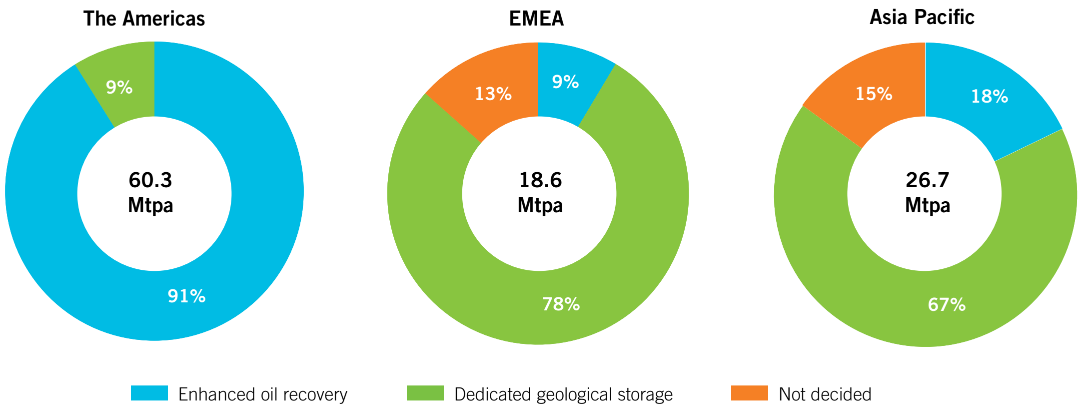


Figure 3.14 CO_2 capture capacity by storage type and region



Key developments since 2013

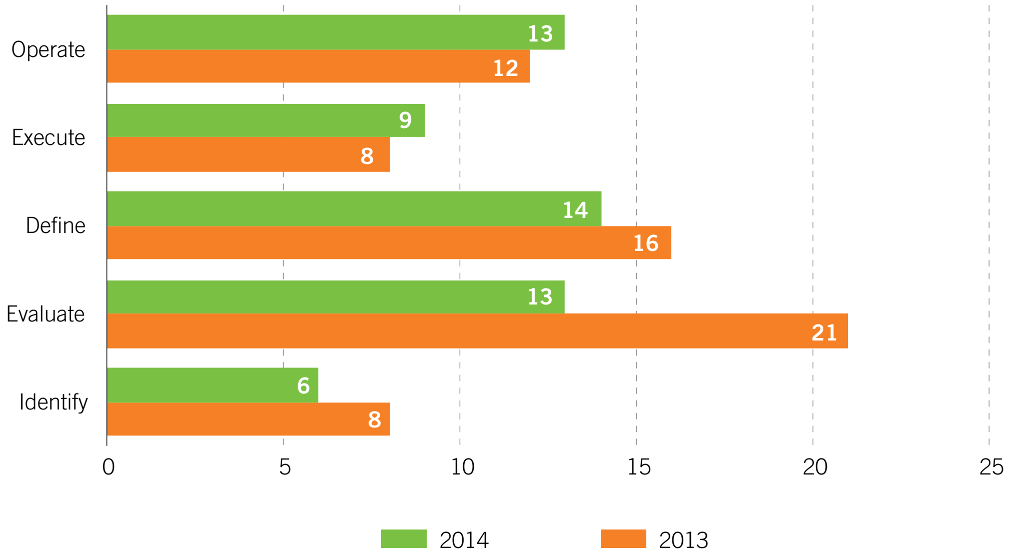
The 55 large-scale integrated projects in this report compares with 65 in 2013. Importantly, there continues to be measured forward movement of projects in operation and construction (Figure 3.15).

The key developments include:

- One project moving from construction into operation – the Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project, the world's first CCS project in the power sector at large scale.
- Two projects moving from Define into construction – the Petra Nova Carbon Capture Project in Texas (formerly the NRG Energy Parish CCS Project), the third large-scale power sector CCS project to have taken a positive financial investment decision, and the Abu Dhabi CCS Project, the first large-scale CCS project in the iron and steel sector.
- Four projects moving into the Define stage – The White Rose CCS Project and the Peterhead CCS Project in the UK, the Yanchang Integrated Carbon Capture and Storage Demonstration Project in China and the Sargas Texas Point Comfort Project in the US (CO_2 capture capacity of 0.8 Mtpa, this being a newly identified project in the power sector in 2014).
- Twelve projects cancelled or put on hold in the course of the past year. Most (seven) of these have been in Europe, with two in the US and one in each of Australia, China and the UAE. Eight of the 12 were in the early stages of development planning, with the remainder being in the Define stage (these being the Porto Tolle Project in Italy, the Low-Impact Steel Project in France, the OXYCFB 300 Compostilla Project in Spain and the Lake Charles CCS Project in the US). Most of the removed projects were in power generation, with post-combustion capture suffering the largest decline. Seven of the removed projects had intended to sequester CO_2 into deep saline formations.
- Two newly-identified projects – the China Resources Power (Haifeng) Integrated Carbon Capture and Sequestration Demonstration Project (CO_2 capture capacity of 1 Mtpa) in China and the Sargas Texas Point Comfort Project noted above.

  Both projects are in the power sector (with post-combustion capture), the CRP (Haifeng) Project is in the Identify stage and is examining offshore geologic storage while the Sargas Project is in the Define stage and is intending to use the CO_2 for EOR.

Figure 3.15 **All identified large-scale CCS projects by project lifecycle and year**



A full inventory of key project developments since the publication of *The Global Status of CCS: 2013* report is contained in Appendix A.

A comprehensive set of supplementary information that provides a detailed breakdown of projects by geographical trends, industry, capture technology and transport and storage types is found at: http://www.globalccsinstitute.com/publications/global-status-ccs-2014-supplementary-information-presentation-package.

3.3 GEOGRAPHICAL TRENDS IN LARGE-SCALE CSS PROJECTS

The Americas

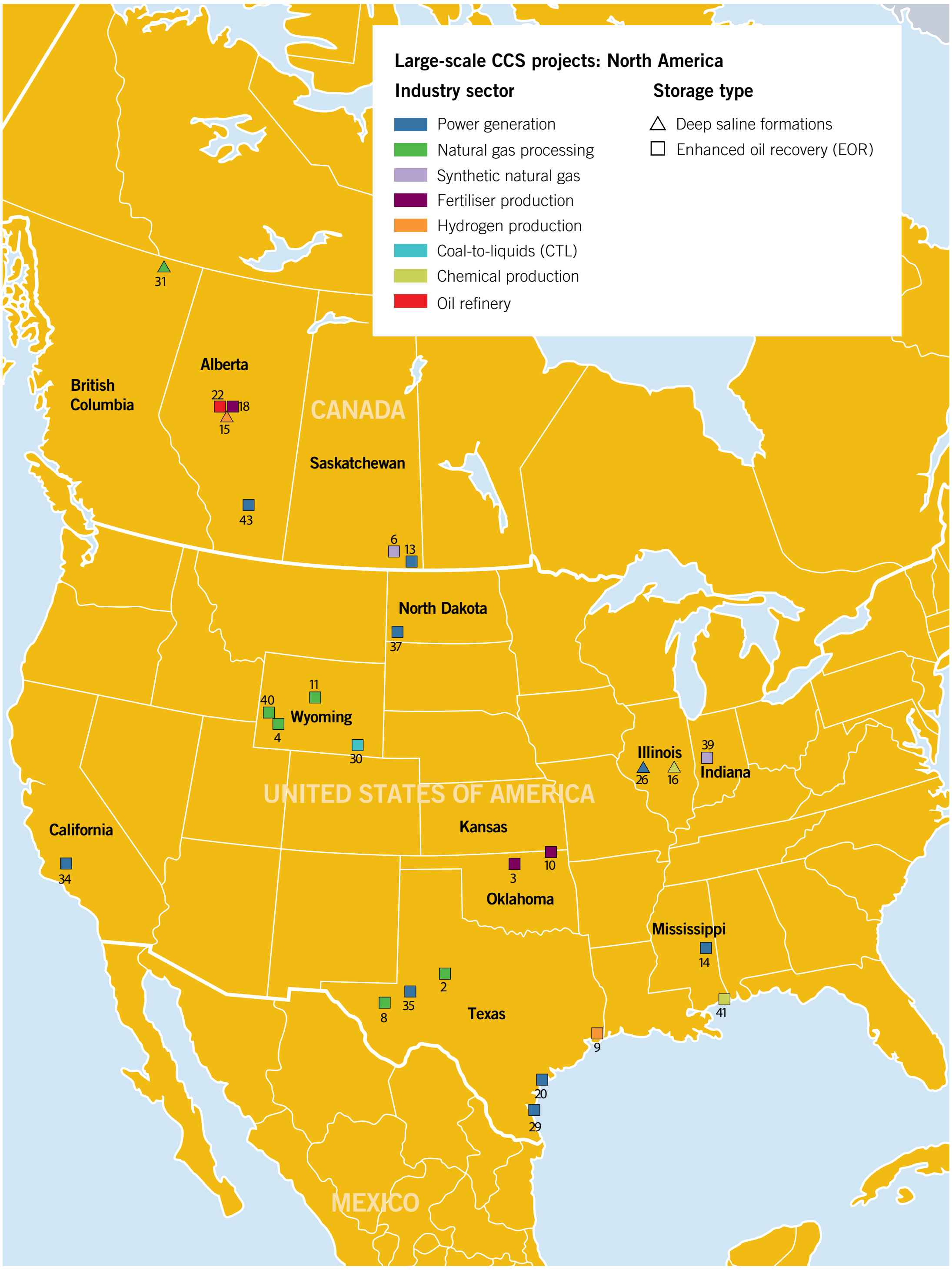
North America is the front-runner in large-scale CCS/CCUS projects, with EOR providing added support to the commercial pathway. One large-scale CCS project in the power sector commenced operation in 2014, another will commence operation in 2015 and a third is anticipated to begin operation by the end of 2016. All three projects integrate CCUS with coal-based power systems. Three other large-scale CCS projects in industries outside the power sector are anticipated to begin operation in 2015.

While a number of projects in the Define stage have strong hopes of progressing into construction, there have been challenges associated with project timelines, costs and retention of skilled talent. Furthermore, a limited number of new projects are in the pipeline as developers take a wait-and-see approach for the necessary policy action to support deployment.

In addition to project activity in the US and Canada, Mexico has begun significant efforts to lay the foundation for CCUS project developments and the Institute is engaged with the country's CCUS capacity building efforts. As project activities in Mexico further develop, they will be featured in coming reports.

The Petrobras Lula Oil Field CCS Project (Brazil, CO_2 capture capacity of 0.7 Mtpa) continues to operate successfully.

Figure 3.16 Map of large-scale CCS projects in North America



United States

Supported by significant funding from the US Department of Energy (DOE), the US has the most robust portfolio of large-scale CCS/CCUS projects in terms of public and private investment dollars, number of projects (19) and technology configurations. Nearly all projects include CO_2-EOR as the preferred storage type, with only two involving CO_2 storage in saline formations.

Two projects are expected to move from construction into operation in 2015:

- Archer Daniels Midland's Illinois Industrial Carbon Capture and Storage Project received an Underground Injection Control (UIC) Class VI permit in September 2014 from the US Environmental Protection Agency (EPA) and, in the absence of appeals to the Environmental Appeals Board, CO_2 capture and storage could begin in the first part of 2015.

  This project involves the compression/dehydration of CO_2 already separated in a corn to-ethanol plant and its storage in a deep saline aquifer adjacent to the producing plant. The Illinois Industrial CCS Project will integrate its facilities with the existing 1,000 tonnes of CO_2 per day facility under the Illinois Basin-Decatur Project (IBDP) to achieve a total CO_2 injection capacity of 3,000 tonnes per day or approximately 1 Mtpa of CO_2.

- Mississippi Power's Kemper County Energy Facility has experienced construction delays and is scheduled to start operation in 2015.

  The 582 MW (net) project will use Transport Integrated Gasification (TRIG™) technology (a coal-gasification method designed for lower-rank coals) developed by Mississippi Power's parent company Southern Company and KBR in conjunction with the US DOE. The plant will capture 65% of total CO_2 emissions, or approximately 3 Mtpa. By-product sales, including CO_2, are expected to generate approximately US$50 million to US$100 million annually.

The Petra Nova Carbon Capture Project (a joint venture between NRG Energy and JX Nippon Oil & Gas Exploration of Japan) recently entered construction and will retrofit carbon capture facilities to an existing coal-fired power plant near Houston, Texas. It will capture 1.4 Mtpa of CO_2 for EOR purposes. Anticipated start-up is in the latter part of 2016.

A number of projects are in the Define stage, including:

- In January 2014 the US DOE issued its Record of Decision to provide financial assistance to the FutureGen Industrial Alliance. The US DOE action would provide approximately US$1 billion in cost-share for its FutureGen 2.0 Project. The project reached a further major milestone in August 2014 when the US EPA issued four UIC Class VI permits to the Alliance (effective October 14, 2014 in the absence of appeals to the Environmental Appeals Board).

  Key aspects of the FutureGen 2.0 Project include the capture of approximately 1.1 Mtpa of CO_2 at a repowered electricity generating unit at the Meredosia Energy Center in Illinois. The captured CO_2 would be injected into the nearby Mount Simon saline formation to a depth of approximately 1,220 metres.

- The Texas Clean Energy Project (TCEP) and the Hydrogen Energy California (HECA) Project are both poly-generation projects with significant revenues from the sale of a range of products (power, fertiliser and CO_2) and both continue to work toward final investment decisions. Carbon capture for each of these facilities is around 2.7 Mtpa, mostly for use in EOR.

- The Sargas Texas Point Comfort Project is planning to construct a 500 MW natural gas combined cycle (NGCC) power plant with carbon capture at the Port of Port Lavaca-Point Comfort. Storage targets for the captured CO_2 (around 0.8 Mtpa) are oil fields in South Texas where the captured CO_2 would be used for EOR. The project is progressing to late stage development, and agreements with power and CO_2 customers are in process.

The Kentucky NewGas project in Muhlenberg County, Kentucky, a project in the earlier planning stages, has been cancelled. Project developer, Peabody Energy, officially advised the Commonwealth of Kentucky in 2013 that it had ceased further development work on the project.

In September 2014, Leucadia National Corporation announced that it was not proceeding with further development of the Lake Charles project.

Canada

Canada's federal and provincial governments have committed significant funding for CCS, which could lead to as many as seven large-scale CCS projects in Canada, with the western provinces of Alberta and Saskatchewan seeing most of the country's project activity.

In October 2014, SaskPower launched the world's first operational large-scale power facility equipped with carbon capture technology – the Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project. The application of capture facilities will reduce CO_2 emissions from a rebuilt (coal-fired) Production Unit 3 at the Boundary Dam power station by up to 90% and capture 1 Mtpa of CO_2. The CO_2 captured will be used primarily for EOR at the Weyburn oil unit. Any CO_2 from the project that is not used in EOR will be injected into a nearby deep saline formation through the Aquistore project.

Other Canadian projects in construction continue to advance, including the Quest Project and the ACTL 'Project', which will connect to two industrial sources of CO_2: the Agrium Fertiliser Plant CO_2 Stream and the North West Sturgeon Refinery CO_2 Stream. Operations for the Quest Project and the Agrium CO_2 Stream Project are expected to start in 2015. The Quest Project is particularly important as the captured CO_2 will be sequestered in a deep saline geological formation at a depth of around 2 km below ground level. This complements the other projects in North America presently in construction or Define stages that will also sequester in deep saline formations (the Illinois Industrial CCS, FutureGen 2.0 and Fort Nelson CCS projects). These projects include a range of instrumentation and monitoring schemes that will help inform future commercial measurement, monitoring and verification (MMV) requirements and regulatory framework development.

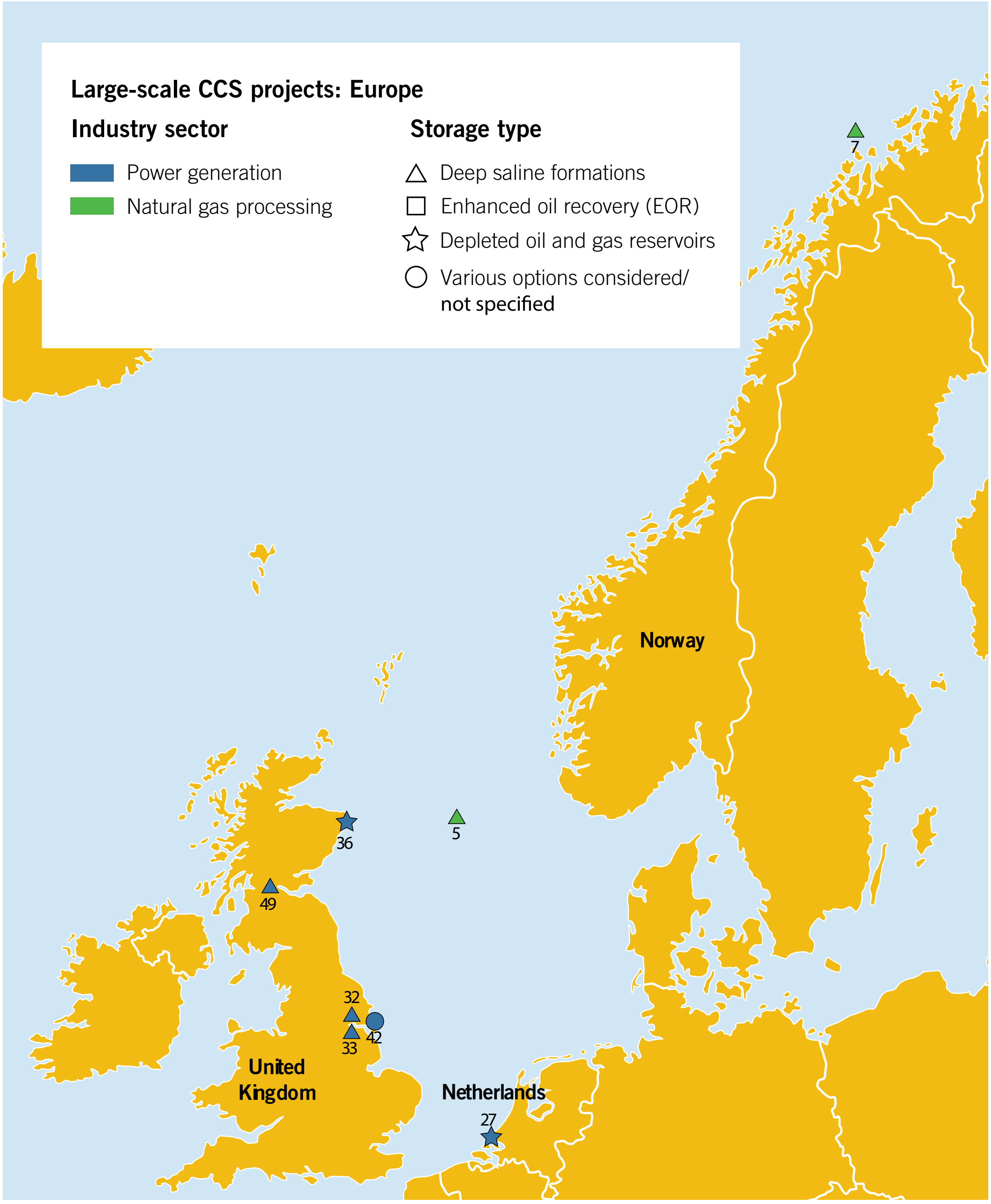
Europe and the Middle East

Europe

Large-scale CCS developments in Europe are now entirely focussed on the North Sea. There are currently eight projects in the region, spread across three countries.

	Evaluate	Define	Execute	Operate
Norway				2
United Kingdom	2	3		
Netherlands		1		

Figure 3.17 Map of large-scale CCS projects in Europe



Norway, and more recently the UK, have developed policy frameworks that rank among the world's most supportive towards CCS. This is reflected in Europe's only two operating CCS projects being located in Norway, and five of the remaining six CCS projects under development in Europe being located in the UK.

The Sleipner and Snøhvit projects offshore of Norway (both operated by Statoil) have been operational since 1996 and 2008 respectively. Since 1996, over 16 million tonnes of CO_2 has been permanently sequestered deep undersea by the two projects[12]. In April 2014, Statoil's new Gudrun field commenced operations. The field is located about 55 km north of the Sleipner installations, and all processing of oil and gas from Gudrun takes place on the Sleipner installations, leading to the sequestration of CO_2 from the new field into the Utsira Formation.

[12] http://www.statoil.com/en/TechnologyInnovation/NewEnergy/Co2CaptureStorage/Pages/SleipnerVest.aspx and http://www.statoil.com/en/TechnologyInnovation/NewEnergy/Co2CaptureStorage/Pages/Snohvit.aspx

The ROAD Project in the Netherlands is the only project in development planning in mainland Europe. It is of vital importance to CCS progress in the region. The project is ready to take a positive final investment decision and commence construction if additional funding can be secured. EU Energy Commissioner Günther Oettinger has hosted a number of meetings with project stakeholders and European Member States looking to raise monies to cover the current funding gap faced by the project, which is largely related to operating costs. These discussions are ongoing, although Norway has committed €15 million (125 million Norwegian kroner) to an EC initiative that is seeking to close the financing gap[13].

In the UK, the CCS Commercialisation Programme has made up to GB£1 billion in capital funding available for first-mover CCS projects through a competitive process. Through this Programme both the White Rose CCS Project and the Peterhead CCS Project have announced that contracts for Front End Engineering Design (FEED) have been agreed with the UK Government, moving these two projects from the Evaluate to the Define stage.

- The White Rose CCS Project is planned to be the first large-scale oxyfuel project in the world with the ability to use biomass fuel for co-firing with coal. This means that in addition to capturing nearly 90% of its carbon emissions, under the right circumstances it could reach zero or even negative emissions. The White Rose proposal is significant in that it also includes the development of a large capacity pipeline – the Yorkshire Humber CCS Trunkline – which will have capacity to enable additional carbon capture projects in the area, which hosts approximately one-fifth of the UK's current CO_2 emissions[14].

  In July 2014, the EC announced that the White Rose CCS Project had been awarded up to €300 million in funding as part of the second call of the NER300 funding programme[15].
- The Peterhead CCS Project is also globally significant in that the project proponents (Shell U.K. Limited with strategic support from Scottish and Southern Energy) are developing the world's first large-scale gas CCS project in the power sector with geologic storage.

Both of the above projects will undertake FEED studies through 2014 and 2015 and (depending on the outcome of these studies) could be in position to move forward at the end of 2015.

Beyond the CCS Commercialisation Programme, the UK Government is also discussing support for additional early projects through its Final Investment Decision Enabling program. Any such support will be limited to issuing a CfD, and funding will not be available to support development or capital costs.

The third CCS project in the Define stage in the UK, the Don Valley Power Project in South Yorkshire, plans to use pre-combustion technology at a new-build IGCC power plant. The Project is the only UK CCS project to benefit from funding under the European Energy Programme for Recovery (EEPR) of €180 million. In July 2014, the project developer, 2Co Energy, announced it was in advanced negotiations to sell the Don Valley Power Project to the privately owned Norwegian company Sargas. It is intended that the sale be completed during 2014.

As part of the Tees Valley City Deal announced by the British Prime Minister in December 2013, the Local Enterprise Partnership, Tees Valley Unlimited, has been awarded GB£1 million, alongside industry contributions, to carry out:

- pre-FEED analysis on capture, transport and storage from multiple industrial sources in Teesside, and
- development of possible business and investment models for industrial CCS in Teesside.

While not a large-scale project tracked by the Institute, this work represents a welcome development in the critical area of industrial CCS.

Since the release of The *Global Status of CCS: 2013* report, seven projects within Europe have either been put on hold or cancelled. A fuller analysis and description of these projects is given in Appendix A.

[13] http://www.regjeringen.no/en/dep/oed/press-center/press-releases/2014/Strong-commitment-to-CCS.html?id=770964

[14] http://www.2coenergy.com/don_valley_power_project.html

[15] Article 10a(8) of Directive 2003/87/EC established a mechanism for the financing of commercial demonstration CCS projects and demonstration projects of innovative renewable energy technologies covering €300 million allowances from the new entrants reserve of the EU Emissions Trading System.

- Four projects removed were at the early stages of development planning – the Industrikraft Møre AS Norway Project and the Full Scale CO_2 Capture Mongstad (CCM) Project (both in Norway), the Teesside Low Carbon Project (UK) and the Getica CCS Demonstration Project (Romania). All of these removed projects were in the power sector.
- Three projects removed were in the Define stage – the OXYCFB 300 Compostilla Project (Spain), the Porto Tolle Project (Italy) and the Low Impact Steel Project (France). Both Compostilla and Porto Tolle were EEPR-supported CCS projects in the power sector. The project proponents for Porte Tolle (Enel S.p.A.) and Compostilla (Endesa Generación SA and CIUDEN) will continue with the pilot initiatives that were created to support the large-scale project proposals – a capture facility in Brindisi (Porte Tolle) and the capture and storage pilots for Compostilla. These will produce valuable data to help support the wider development of CCS in Europe.

The reasons for projects not proceeding are varied although a common theme appears to be a lack of funding to enable work to continue and an inability to achieve closure for the financial structure of the project.

Middle East

The Middle East accounts for around 50% of the world's proved oil reserves and 45% of the world's proved gas reserves. For the six Gulf Cooperation Council (GCC) countries – Bahrain, Kuwait, Oman, Qatar, the Kingdom of Saudi Arabia and the United Arab Emirates – the respective shares are 30% and 23%[16]. Fossil fuels account for almost all of the region's primary energy supply.

Energy consumption has increased by over 80% in the GCC region since 2000. This has been accompanied by a similar increase in annual CO_2 emissions from these countries (to around 800 million tonnes)[17]. The rapid rise in CO_2 emissions is related to robust economic growth in the region and the need for energy supply/electricity generation to support this development.

In light of the above, various policies and measures are being put in place by a number of economies in the Middle East to reduce CO_2 emissions. These actions include:

- introduction of renewable energy sources
- fuel switching in industry and transport
- use of combined heat and power
- reduction of electricity generation, transmission and distribution losses (and in generation replacement of steam turbine technologies with advanced systems), and
- promoting energy efficiency programs in domestic and industrial settings.

These actions highlight several 'strategic pathways' in which high CO_2 mitigation levels are planned to be achieved in the Middle East – through widespread diffusion of low-emission technologies aimed at a substantial reduction in energy intensity, mitigation efforts that cover all major emitters, and technology transfers.

With fossil fuels to remain a major contributor to energy supply in the region, it is also recognised that CCS will need to become a key mitigation activity. CCS activities are very much at an early stage of development. A summary of key CCS activities in the GCC countries is described below.

United Arab Emirates (UAE)

Masdar is Abu Dhabi's renewable energy company, working to advance the development, commercialisation and deployment of clean energy technologies and solutions. Masdar is wholly owned by the Mubadala Development Company PJSC, the strategic investment company of the Government of Abu Dhabi, and is dedicated to the Emirate's long-term vision for the future of energy and water.

[16] Reserves data is sourced from *BP Statistical Review of World Energy 2014.*

[17] Bedrous, M A 2013, 'Energy sector: mitigation options of climate change', Table 1, in I A Gelil, M El-Ashry & N Saab (eds), *Arab environment 6. Sustainable energy: prospects, challenges, opportunities,* Arab Forum for Environment and Development with Technical Publications and Environment & Development Magazine, Lebanon, pp. 132-155.

Through the UAE, Masdar has pioneered the deployment of many renewable energy projects both in the UAE and around the world. The world's first iron and steel project to apply CCS at large scale is now under construction in the UAE. The Abu Dhabi CCS Project involves the capture of approximately 0.8 million tonnes of CO_2 per annum from the direct reduced iron (DRI) process used at the Emirates Steel factory in Abu Dhabi and its transportation to the Rumaitha oil field, operated by the ADNOC group company, for the purpose of EOR. The project is being managed by a joint venture between ADNOC and Masdar. Injection of CO_2 is planned for the first quarter of 2016. Both joint venture partners consider this a flagship project and its success will be a catalyst for future CCS projects aimed at providing the growing demand of CO_2 within the UAE for EOR.

Kingdom of Saudi Arabia

Saudi Arabia is evaluating the use of CO_2 injection and has planned a series of programs at various scales in mature fields such as Ghawar. The Uthmaniyah CO_2-EOR Demonstration Project involves the capture of 0.8 million tonnes of CO_2 per annum from the Hawiyah NGL (natural gas liquids) Recovery Plant, which is then transported 70 km to the injection site in the Uthmaniyah production unit of the Ghawar field. The project objectives include determination of incremental oil recovery (beyond water flooding), estimation of sequestered CO_2 and addressing primary risks and uncertainties, including migration of CO_2 within the reservoir. The project duration is expected to be four to five years, starting in 2015. The design of the project includes a comprehensive monitoring and surveillance plan.

Saudi Arabia is increasing its experience in the research, development and demonstration of CCUS. Much of the research and development work is related to capturing and storing of CO_2 from both point and mobile sources. Several institutions in Saudi Arabia are engaged in CCS research, including the King Abdulaziz City for Science and Technology (KACST), King Fahd University of Petroleum & Minerals (KFUPM), King Abdullah University of Science and Technology (KAUST), Saudi Aramco, and the King Abdullah Petroleum Studies and Research Center (KAPSARC).

KAPSARC has adapted an early stage approach to conduct research focused on CCS technologies, economics and policies. One of its inaugural projects *'CCS Implementation Strategies for the Kingdom of Saudi Arabia'* aimed to develop a robust CCS implementation strategy through a first order assessment of the potential for CCS to be deployed in Saudi Arabia.

Additionally, several leading Saudi universities and research centres, including KACST, KFUPM and KAUST, are conducting basic technical research on CO_2 capture and storage. For example, the Technology Innovation Centre for CCS (KACST-TIC CCS) at KFUPM has been awarded KACST baseline funding of SAR10 million per year (US$2.7 million per year) for a five-year period (2011–15). The ongoing research of the KACST-TIC CCS has been focusing on oxy-fuel combustion, mobile capture, site assessment and measurement, and MMV of CO_2 storage. KACST-TIC CCS has extensive collaboration with the private sector (Saudi Aramco, Aker Solutions) and institutions (TNO in the Netherlands and MIT and Carnegie Mellon in the US).

Saudi Aramco has been actively engaged in carbon management initiatives within the oil industry. Saudi Aramco's Carbon Management Technology Roadmap includes CO_2 capture from fixed sources, CO_2 reduction from mobile sources, industrial applications, CO_2 storage and CO_2-EOR. A comprehensive research framework has been developed for CCS, including CO_2 capture (mobile capture, oxy-fuel combustion, and chemical looping combustion), storage, and EOR technologies.

Aside from CO_2-EOR, there are initiatives on CCUS as Clean Development Mechanism (CDM) project activities under the Kyoto Protocol Mechanism. The CCUS projects below have submitted prior consideration to the Designated National Authority (DNA) and UNFCCC as per CDM Modalities and Procedures:

- Carbon Dioxide Capture & Injection Facilities, Uthmaniyah (Saudi Aramco)
- Carbon Dioxide Recovery Project in Saudi Arabia (Rabigh Refining and Petrochemical Company – Petro Rabigh)
- Construction of liquid-CO_2 plant in Saudi Arabia (Saudi Industrial Gas Company – a subsidiary of the Linde Group), and

- SAFCO-V Project carbon dioxide utilisation at urea production facility (Saudi Arabian Fertilizer Company).

Saudi Arabia is also constructing the world's largest CO_2 purification and liquefaction plant at the Jubail United Petrochemical Company, a manufacturing affiliate of SABIC (Saudi Basic Industries Corporation). The plant is designed to compress and purify around 1,500 tonnes per day of raw CO_2 coming from two nearby ethylene glycol plants. The purified gaseous CO_2 will be transported through the piping corridor of the Royal Commission of Jubail to three SABIC-affiliated companies for enhanced methanol and urea production. It is estimated that around 500,000 tonnes of CO_2 emissions will be saved each year. The plant will also be capable of producing 200 tonnes per day of liquid CO_2 of food grade quality, which will be stored and thereafter supplied by truck to the beverage and food industry. Mechanical completion is set to be achieved in 2015.

Saudi Arabia, along with Norway, the Netherlands and the UK, established the Four Kingdoms initiative in 2008. It aims to explore the potential for collaboration on CCS between countries committed to its deployment – a workshop was held in Saudi Arabia in 2011 and a second took place in 2012. Both Saudi Arabia and the UAE are members of the Carbon Sequestration Leadership Forum (CSLF). Saudi Aramco also sponsored the IEAGHG Weyburn-Midale monitoring and storage project in Canada.

Qatar

Qatar has several CCS-related initiatives, the most significant being the establishment of the Qatar Carbonates and Carbon Storage Research Centre (QCCSRC). This is a US$70 million, 10-year research partnership established in 2012 between Shell, Qatar Petroleum, Qatar Science and Technology Park and Imperial College London to build Qatar's capacity in CCS and cleaner fossil fuels.

The Qatar Fuel Additives Company is constructing a CO_2 recovery plant of around 500 tonnes per day of CO_2 capacity at its methanol production plant near Doha. The CO_2 is captured from combustion exhaust gas emitted in the methanol production process and would in turn be used as feedstock to boost methanol production. Construction of the plant is slated for completion in the last part of 2014.

Qatar University's Gas Processing Centre (GPC) released a Carbon Capture and Management Roadmap in 2012 and is conducting a CO_2 capture research project which will evaluate the performance of different chemical solvents in capturing CO_2 from the flue gas of a simulated natural gas-fired power plant.

CO_2-EOR in the Middle East

It is important to note that the CO_2-EOR programs in the Middle East, unlike those in other parts of the world, are not focused on near term, full-scale implementation to maximise incremental oil recovery. This is still 20-30 years away. Present CO_2 injection programs form part of a longer-term carbon management roadmap for these economies, supporting the development of EOR technology for global carbon management and for its use domestically in the future. It is believed that careful reservoir management, new drilling technologies and state-of-the-art information gathering can significantly extend the conventional production life for many fields in the Middle East. In some countries CO_2-EOR programs can help replace traditional gas-EOR programs, leaving more gas available for domestic consumption.

Asia Pacific

China

China is especially important for CCS development in view of its large carbon emissions footprint. China is making significant strides in progressing both pilot and demonstration projects, R&D activities and CCS has been included in several national strategic plans.

China's electricity generation is heavily coal based. At the same time, demand for crude oil has been increasing rapidly. These twin factors have influenced power generators to seek arrangements with energy companies to conduct CCS/CCUS projects. CO_2-EOR is also considered to have significant strategic value for China in terms of energy security. Of the 12 identified large-scale CCS projects in China, four are confirmed as CO_2-EOR and these are also the most advanced in development planning. Many of the remaining projects, which either are planning on geologic storage of CCS or have not yet identified a storage option, are at the very earliest stage of the project lifecycle (the 'Identify' stage).

Key projects in China in the Define stage include the following:

- In Mid-Western China, the Yanchang Petroleum Group is developing the Yanchang Integrated Carbon Capture and Storage Demonstration Project, which in total intends to capture more than 0.4 Mtpa of CO_2 per annum from coal-to-chemicals conversion facilities located in Shaanxi Province. The captured CO_2 would be used for CO_2-EOR for Yanchang's low permeability oil fields. Northern Shaanxi's geological structure (Ordos Basin) is considered to have considerable potential for CO_2 storage.
- In Eastern China, the Bohai Gulf Basin hosts another major Chinese oil field – the Sinopec Shengli Oil Field. Sinopec is planning two large-scale projects which would utilise CO_2 for EOR. These include 1 Mtpa of CO_2 per annum from a coal-fired power station (the Sinopec Shengli Power Plant CCS Project) and 0.5 Mtpa of CO_2 'captured' from a Sinopec fertiliser facility in Zibo city, Shandong Province (the Sinopec Qilu Petrochemical CCS Project).
- In North-Eastern China, the Songliao Basin accommodates two large oil fields – Daqing and Jilin. The China National Petroleum Company (CNPC) plans to capture 0.8 Mtpa of CO_2 from a new natural gas processing facility in Songyuan for EOR in the Jilin oil field (the PetroChina Jilin Oil Field EOR Project – Phase 2).

In Southern China, the Pearl River Basin is a major natural gas producing area and has many depleted gas reservoirs. A newly identified project, the China Resources Power (Haifeng) Integrated Carbon Capture and Sequestration Demonstration Project, intends to capture 1 Mtpa of CO_2 from a new-build coal-fired 1 gigawatt (GW) power station. The CO_2 could be transported through existing gas pipeline infrastructure to reservoirs in the South China Sea for geological storage and/or CO_2-EOR. The project is at an early stage of development planning.

The Lianyungang IGCC Project has been removed from the Institute's listing of large-scale projects as it has not progressed since first announced by the Chinese Academy of Sciences three years ago and is effectively 'cancelled'.

On 13 April 2013, China and the US signed *'the US-China Joint Statement on Climate Change'* in which the US-China Climate Change Working Group (CCWG) was announced. The CCWG launched five action initiatives with *'carbon capture, utilization and storage'* included as one of the five.

On 22 April 2014, the CCWG organised the first workshop on carbon capture, utilisation and storage in Beijing to strengthen information exchange between the two countries and identify opportunities for specific CCUS cooperation. Representatives from a variety of organisations including China Shenhua Group, China Huaneng Group, Shaanxi Yanchang Petroleum Group, China Power Investment Group, Sinopec, Shanxi International Energy, Summit Power Company and Southern Power Company attended the workshop.

Another major outcome is from the 5th Round of the US-China Strategic and Economic Dialogue (S&ED). Out of a total of eight climate change-related projects, four joint demonstration CCUS projects under the CCWG Framework were announced on 8 July 2014 (Table 3.2).

Table 3.2 US-China CCUS Collaboration Projects

Collaboration contents	China	US
Post-combustion CO_2 capture and CO_2-EOR	Shengli Oil Field Company of Sinopec Corporation	Schlumberger Carbon Services Co. and University of Kentucky
CCUS-clean energy demonstration and CO_2-EOR	Yanchang Petroleum Group	Air Products and Chemicals, West Virginia University and University of Wyoming
Coal-based IGCC with CCUS and CO_2-EOR	Huaneng Clean Energy Research Institute	Summit Power Group

Coal-fired oxy-combustion to separate CO_2 for CCUS	Shanxi International Energy Group	Air Products and Chemicals

The collaborative projects cover post-combustion, pre-combustion, oxyfuel and coal-to-chemical (poly-generation) CCUS. Another outcome under the CCWG framework is that China and the US will collaborate on *'capacity building, training, information exchanges, site visits, technology evaluations, and feasibility studies'*.[18]

Such collaboration reaffirms the strategic importance of global coordinated efforts in CCS/CCUS and knowledge sharing.

Figure 3.18 Map of large-scale CCS projects in China

Australia

The Gorgon Project is one of the world's largest natural gas projects and the largest single-resource development in Australia. Based on Barrow Island, Western Australia, the Gorgon Project includes an LNG facility with three processing units designed to produce 15.6 million tonnes of LNG per year from offshore gas fields. It also includes a natural gas plant for delivery of domestic gas to the mainland and the wells and facilities required for the Gorgon Carbon Dioxide Injection Project (in which the

[18] U.S. Department of State, *Report of the U.S.-China Climate Change Working Group to the 6th Round of the Strategic and Economic Dialogue* (15-July-2014) < http://www.state.gov/r/pa/prs/ps/2014/07/229308.htm >.

captured reservoir CO_2 will be injected into the nearby Dupuy Formation, more than 2 km below the surface). It is expected that over 100 million tonnes of CO_2 will be injected over the life of the project.

The Gorgon Carbon Dioxide Injection Project commenced its multi-year injection well drilling campaign in the latter part of 2013. Nine wells are expected to be directionally drilled at three drill centres. Commissioning of the Gorgon Project will be phased over a two year period anticipated to commence in 2015. Commissioning of the CO_2 injection system is anticipated to occur 6-12 months into this process. Injection of CO_2 is expected to commence in 2016.

The CarbonNet Project in Victoria is investigating the potential for establishing a large-scale CCS network, bringing together multiple CO_2 capture projects in Victoria's Latrobe Valley, transporting CO_2 via a common-use pipeline and injecting it deep into offshore underground storage sites in the State's Gippsland region. The project is continuing with feasibility studies examining CCS potential in the Gippsland Basin. Currently the project is working on the development of a business case and in the coming year is working towards drilling a well to collect rock and fluid samples and to confirm previous geological models.

The South West Hub Project in Western Australia involves the large-scale capture, transport and storage of CO_2 from various industrial sources. To date, the project has completed the early preparatory phase of storage characterisation with a 2D seismic survey (2011) and a deep stratigraphic well, Harvey-1. A 3D seismic survey was completed in April 2014 and covered around 115 square kilometres over the area of the Harvey-1 well. The storage feasibility study for the capture and hub concept is ongoing. The integration of survey and well data will enable a high resolution model of the underlying geology, including the potential reservoirs and seals for CO_2 storage. Community engagement activities around the seismic survey are a focus for the project team and an analysis of this work is currently being completed. Other studies regarding CO_2 transport and baseline monitoring are also being undertaken.

The Surat Basin CCS Project has been removed from the Institute's listing of large-scale projects as the project is evaluating options of lesser scale.

[4]

NOTABLE PROJECTS – JAPANESE PROJECT CASE STUDIES

One of the drilling units used to drill a survey well at the Tomakomai Project.

CHAPTER HIGHLIGHTS

- Projects at the pilot scale have made a significant contribution to the global development of CCS.
- The early focus of pilot scale projects has been on capture though the US DOE has supported seven Regional Carbon Sequestration Partnerships.
- While Japan does not have a large-scale CCS project, it has an extensive CCS development program underway at lesser scale.
- Four Japanese CCS projects are showcased – the Tomakomai CCS Demonstration Project, COURSE 50, the EAGLE Project and the Osaki CoolGen Project.

4.1 THE IMPORTANT ROLE OF NOTABLE PROJECTS

The Global Status of CCS: 2013 report highlighted a number of 'notable' pilot and demonstration CCS projects. These tended to be projects that were either not of a sufficient scale to be considered as large-scale projects or were not fully integrated. Nevertheless, these projects have provided valuable information to assist in the design and development of large-scale CO_2 capture plants and to advance the understanding of the behaviour of CO_2 in the subsurface.

Many of these notable projects have similar objectives, which can be grouped as follows:

- demonstrating the technical feasibility of a particular technology
- gaining operational experience and economic information, and
- gathering data to support the development of large-scale projects.

Globally, the focus of these notable projects has been on capture technology, though the US DOE has supported an extensive storage program of seven sequestration partnerships across the country. By way of example, a non-exhaustive representation of pilot test projects is referenced below[1]. By their nature, these projects usually have specific objectives and a defined life span.

Notable CO_2 capture pilot projects

- Europe: Ferrybridge, Aberthaw, Renfrew (UK), Wilhelmshaven, Schwarze Pumpe (Germany), Lacq, Le Havre (France), Buggenum, Rotterdam (Netherlands), Technology Centre Mongstad, Brevik (Norway), Puertollano, Ponferrada (Spain), Brindisi (Italy), Karlshamn (Sweden).
- Americas: Plant Barry, Mountaineer, Pleasant Prairie, National Carbon Capture Center (US), Shand (Canada).

[1] The listed projects include those that are completed, operational or under construction.

- Asia Pacific: Tomakomai, EAGLE, Osaki CoolGen, COURSE 50 (Japan), Shanghai Shidongkou, Guodian, Huazhong, HuaNeng GreenGen (China), Boryeong, Hadong (Korea), Callide, Hazelwood (Australia).

Notable CO_2 storage pilot projects

- Europe: Lacq, Ketzin, Hontomin.
- Americas: Seven Regional Carbon Sequestration Partnerships (US), Miranga (Brazil).
- Asia Pacific: Tomakomai, Nagaoka (Japan), Otway (Australia).

Many of the pilot capture activities are supported by capture technology vendors, often with co-funding from public sources. The vendors are very active in these pilot projects to test capture technologies at a scale relevant to the industry, including how a particular capture system can be best integrated into the host facility.

Notable projects may also include potential large-scale projects that are currently being scoped and for which greater detail is necessary prior to formal listing as a large-scale integrated project. An example of this type of project is the Australia-China Post-Combustion Capture (PCC) Project.

The Institute has prepared descriptions for over 30 notable projects, including references to published materials that provide additional information on test results (where possible). These descriptions can be found at www.globalccsinstitute.com/projects/notable-projects.

Focus on Japanese Notable Projects

Previous Institute Status Reports have highlighted notable projects in regions where there are also large-scale CCS projects (Europe, US, China and Korea). Importantly, Japan has several notable projects. While Japan does not have a large-scale CCS project, it has established a very active program of projects at lesser scale, including pilot plants for testing advanced capture technologies in power and iron and steel. It is also embarking on the demonstration of an integrated CCS project (CO_2 capture capacity of 100,000 tonnes per annum).

Case studies of four important notable CCS projects in Japan are described below.

4.2 THE TOMAKOMAI CCS DEMONSTRATION PROJECT

Project proponents	The Government of Japan through the Ministry of Economy, Trade and Industry (METI). Execution of the project is to be undertaken by Japan CCS Co., Ltd. (comprising 35 companies).
Location	Tomakomai area, southern Hokkaido, Japan.
Project status	In construction. A three year CO_2 injection program is scheduled for 2016-18 with monitoring continuing for another two years until 2020.
CO_2 capture source	CO_2 is to be sourced from a hydrogen production unit at Idemitsu Kosan's Hokkaido Refinery at Tomakomai port.
Capture method and type	Industrial separation – absorption chemical solvent-based process.
Storage type	Dedicated geological storage – deep saline aquifers. Two separate near shore reservoirs have been identified as storage sites.
CO_2 stored	100,000 tonnes or more of CO_2 per annum is to be injected over the period 2016-18.

The Tomakomai CCS Demonstration Project was endorsed by METI in February 2012 based on an evaluation of geological conditions in the Tomakomai area which indicated it was suitable for CO_2 storage. The project aims to demonstrate an overall CCS system from capture to storage as a foundation for commercialising CCS from 2020.

Design and construction of the facilities, drilling of wells and preparation for operations began in 2012 with CO_2 injection planned to begin in 2016. Carbon dioxide injection is planned to take place for three years to 2018 after which environmental monitoring will continue for two years post injection.

The emission source for the project is a hydrogen production unit (HPU) at Idemitsu Kosan's Hokkaido Refinery situated at Tomakomai port. The HPU will supply PSA (Pressure Swing Adsorption) off-gas to a new-build capture plant via a 2.5 km pipeline. At the capture plant, gaseous CO_2 of 99% purity will be produced by an amine scrubbing process at a rate of 100,000 tonnes per annum or more from the PSA off-gas. The gaseous CO_2 will then be sent to the CO_2 injection facility next to the capture plant where it is compressed and injected into two different offshore reservoirs by two deviated injection wells.

One of the Tomakomai Project's target reservoirs is the Takinoue Formation, an aquifer around 2,400-3,000 metres below the seabed. This is a Miocene saline aquifer composed of volcanic and volcaniclastic rocks of about 600 metres thickness. The Takinoue Formation is covered by 1,100 metres of mudstone layers which act as a cap rock. The other target reservoir is the sandstone layer of the Moebetsu Formation, situated 1,100-1,200 metres below the seabed. This is a Lower Quarternary saline aquifer of 100 metres thickness. It is covered by a 200 metre thick mudstone layer. While the well heads for both injection wells are located onshore, the injection point for the Moebetsu Formation is located 2.9 km offshore and the injection point for the Takinoue Formation is located 4.1 km offshore.

An extensive monitoring program is planned. Behaviour of the injected CO_2 will be observed through repeated 3D and 2D seismic surveys together with various seismic sensors (ocean bottom cable, ocean bottom seismometer and onshore seismometer). Reservoir temperature and pressure will be monitored at the injection wells and three observation wells. A suite of marine environmental surveys will also be undertaken. Monitoring activities will continue for two years after the planned end of CO_2 injection in 2018.

4.3 COURSE 50

Project proponents	COURSE 50 comprises six companies – Kobe Steel, JFE Steel Corporation, Nippon Steel Corporation, Nippon Steel & Sumikin Engineering, Sumitomo Metal Industries and Nissin Steel – the New Energy and Industrial Technology Development Organisation (NEDO) and a joint implementation that also involves the Research Institute of Innovative Technology for the Earth (RITE) and several universities.
Capture method and type	Two technologies are being evaluated: 1. Chemical absorption – a new liquid absorbent has undergone performance testing. 2. Physical adsorption – development of a Pressure Swing Adsorption (PSA) technology has undergone testing.
Location and CO_2 capture source	Chemical absorption technology was tested at a pilot plant (CO_2 capture capacity 30 tonnes per day) at Kimitsu iron works (Nippon Steel & Sumitomo Metal Corporation), Chiba Prefecture. Physical adsorption technology was tested at bench scale (CO_2 capture capacity initially 3 tonnes per day expanded to 6 tonnes per day) at Fukuyama iron works (JFE Steel Corporation), Hiroshima Prefecture.
Project status	Phase 1, Step 1 Japanese Fiscal Year (JFY) 2008-12. Phase 1, Step 2 JFY 2013-17.

The 'Cool Earth 50' initiative, announced by the then Prime Minister Abe in May 2007, sought to achieve compatibility of environmental protection and economic growth through the utilisation of energy-saving technologies. In support of this initiative, the Japan Iron and Steel Federation (JISF) established 'COURSE 50' or 'CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50' under the support of NEDO.

COURSE 50 aims to develop technologies to reduce CO_2 emissions by approximately 30% through:

a) the reduction of CO_2 emissions from blast furnaces, and

b) the separation and capture of CO_2 from blast furnace gas, and establishing the technologies by around 2030 with the final goal of industrialising and transferring the developed technologies by 2050.

As for (a) above, COURSE 50 aims at a 10% CO_2 emission reduction by developing reaction control technologies for the 'hydrogen reduction of iron ore' to reduce the amount of coke used in blast furnaces.

As for the separation and capture of CO_2 from blast furnace gas, COURSE 50 aims to develop technologies to enable a 20% reduction in emissions through the application of CCS. Both chemical absorption and physical adsorption technologies are being evaluated.

A pilot plant with a CO_2 capture capacity of 30 tonnes per day was built at the Kimitsu iron works of Nippon Steel & Sumitomo Metal Corporation in 2010 to undertake performance testing of a new chemical liquid absorbent (which is being developed by Nippon Steel & Sumikin Engineering and RITE). The plant was operated for around 9,000 hours over a three year period.

To conduct testing of physical adsorption, a CO_2 capture bench-scale plant was constructed at the Fukuyama iron works of JFE Steel Corporation. Carbon dioxide capture capacity of the bench-scale plant was initially 3 tonnes per day and then was expanded to 6 tonnes per day.

Development of technologies for CO_2 separation and capture from blast furnace gas is planned to continue at a scale of around several dozen tonnes per day by 2020 (Phase 1), then advanced to CO_2 capture capacity of hundreds of tonnes per day between 2020-30 (Phase 2) with planned wide-spread deployment from 2030 onwards.

4.4 THE EAGLE PROJECT

Project proponents	Electric Power Development Company (J-POWER), the New Energy and Industrial Technology Development Organisation (NEDO), an independent administrative agency under METI.
CO_2 capture source	Gases generated during the coal gasification process at J-POWER's 150 tonnes per day (coal feed rate) oxygen-blown coal gasification pilot plant.
Capture method and type	Pre-combustion capture (gasification) – CO_2 capture from coal gasification gas, testing both chemical absorption and physical absorption methods.
CO_2 capture capacity	Approximately 24 tonnes per day.
Location	J-POWER Wakamatsu Research Institute, Fukuoka Prefecture.
Project status	Testing completed. Three stages of pilot testing were conducted between 2002 and the end of JFY 2013.

The EAGLE (Coal Energy Application for Gas, Liquid and Electricity) Project sought to research and establish technologies for an integrated gasification combined cycle (IGCC) oxygen-blown coal system. The project was jointly run by NEDO and J-POWER.

Construction of the EAGLE pilot plant's 150 tonne per day (coal-fed) oxygen-blown gasifier and other key facilities commenced at J POWER's Wakamatsu Research Institute in 1998 and were completed in 2001.

The oxygen-blown gasifier developed by the project used a single chamber with two-stage swirling flow to achieve high efficiency gasification. The oxygen feed was varied according to coal type to ensure reliable syngas characteristics. Purification of the syngas is achieved through a cold gas clean-up process, prior to the separation and capture of CO_2 through the application of pre-combustion technologies.

Three stages of pilot testing were completed under the EAGLE Project:

- Stage 1 (JFY 2002-07): System verification, testing of oxygen-blown coal gasifier and gas purification technologies, and verification of operations across a range of coal types.
- Stage 2 (JFY 2007-10): Testing of chemical absorption CO_2 capture technologies, expanded range of useable coal types and research into trace elements behaviour.
- Stage 3 (JFY 2010-13): Optimisation trials of chemical absorption CO_2 capture technologies. Testing of physical absorption CO_2 capture technologies.

Stage 3 of the EAGLE pilot indicated an energy saving for the physical absorption technologies tested relative the chemical absorption technologies applied in Stage 2.

A large-scale test and demonstration of the oxygen-blown gasification and carbon capture technologies tested and developed under the EAGLE Project is planned under the Osaki CoolGen project.

4.5 THE OSAKI COOLGEN PROJECT

Project proponents	The Osaki CoolGen Corporation was established in 2009 under joint funding by J-POWER and the Chugoku Electric Power Company.
CO_2 capture source	Gases generated during the coal gasification process at Osaki CoolGen Corporation's 166 MW oxygen-blown coal gasification demonstration plant (coal feed rate of 1,180 tonnes per day).
Location	Chugoku Electric Osaki power station at Osakikamijima, Hiroshima Prefecture.
Capture method and type	Pre-combustion capture (gasification) – CO_2 capture from coal gasification gas, testing both chemical absorption and physical absorption capture methods.
Project status	Construction of the oxygen-blown IGCC unit began in March 2013, with the first stage of testing anticipated to commence in JFY 2016.

The Osaki CoolGen Project will leverage knowledge and expertise gained from the EAGLE Project to demonstrate at large scale oxygen-blown integrated coal gasification combined cycle (oxygen-blown IGCC) technologies, including CO_2 separation and capture technology.

Construction has commenced on a 166 MW oxygen-blown IGCC plant at the Chugoku Electric Power Osaki power station in Osakikamijima, Hiroshima. The oxygen-blown (coal) gasifier will use a single chambered, two-stage swivel entrained bed gasification system. Air separation will be performed using a cryogenic process and syngas purification will be performed in the sulfur removal and recovery facilities, followed by CO_2 separation. The plant will have a coal processing capacity of 1,180 tonnes per day. Testing is anticipated to commence in JFY 2016.The test program of the Osaki CoolGen Project is planned to occur in three stages:

1. JFY 2016-18: the first stage would test the basic performance, operating characteristics and economics of the oxygen-blown IGCC system at large scale.
2. JFY 2019-20: the second stage would involve retrofitting the IGCC plant with CO_2 separation and capture technology (construction starting in JFY 2016), and then to verify the system's basic performance, equipment reliability, operating characteristics and environmental performance. An evaluation of the IGCC system using the chemical absorption and physical absorption methods evaluated under the EAGLE Project is planned.
3. JFY 2020-21: the third stage (construction starting in JFY 2018) is planned to test the scope for efficiency improvements by combining fuel cells with the oxygen-blown IGCC system (with CO_2 separation and capture). This stage would verify the gas purification technology and the potential for using coal gas in fuel cells (as well as performing the verification testing of an integrated gasification fuel cell (IGFC) combined cycle power generation system).

The Government of Japan, through the Ministry of Economy, Trade and Industry, is supporting one-third of project costs.

[5]

POLICY, LEGAL AND REGULATORY DEVELOPMENTS

CHAPTER HIGHLIGHTS

- The next 18 months are critical for future climate change commitments if we are to avoid the risks of rising global surface temperatures.
- The international policy agenda, including the IPCC 5th Technical Assessment Report, has acknowledged that CCS is a critical component of a least-cost portfolio approach to mitigating climate change.
- Despite this, regional/national policy settings are often fragmented and are not incentivising an acceleration in CCS project development.
- From a policy perspective, the 2014 Perceptions Survey indicates project proponents strongly believe policy uncertainty is a major risk to projects and that project viability is dependent on new government policy settings.
- The most important policy enablers that have consistently appeared in recent surveys include access to direct subsidies and off-take arrangements offering guaranteed prices.
- From a legal and regulatory perspective, the 2014 Perceptions Survey indicated that existing legal and regulatory regimes continue to provide important support to projects with CO_2-EOR storage options.
- Projects in all jurisdictions continue to highlight issues surrounding transboundary movement, market mechanisms and liability as 'unaddressed'. These particular issues have been consistently rated as 'unaddressed' in previous Perception Surveys.
- Non-OECD jurisdictions, particularly in Asia, which has a number of large-scale projects evaluating geological storage options, will require increased legislative activity in the near term to support project development.

5.1 DEVELOPMENTS IN INTERNATIONAL POLICY AGENDAS

The United Nations Framework Convention on Climate Change (UNFCCC)

The UNFCCC is the key forum in which discussions take place on global actions to address climate change and national commitments are made to assist in meeting emissions reduction targets. The next 18 months will be important for determining international and national support settings for CCS activities as the world works towards a new global climate change agreement. This period will drive the short to medium-term institutional settings in which CCS will need to be further developed, and perhaps more importantly, the longer-term arrangements that will need to provide for its commercial deployment.

The UN Secretary General's recent summits on climate change, including the Abu Dhabi Ascent and the 2014 Climate Summit, signify the importance Mr Ban Ki-moon places on heads of state supporting the UNFCCC processes to ensure that an effective, global response to addressing climate change can be delivered at the Conference of the Parties to the Convention in Paris at the end of 2015 (COP 21). Clearly, the rate of future progress of CCS is strongly linked to such an outcome.

The UNFCCC agenda strongly complements and influences sovereign national policy settings in support of clean energy technologies through its various negotiating elements, including:

- technology development and transfer (pursued under the 'Technology Mechanism')
- public and private climate financing (pursued under the 'Financial Mechanism')

- the establishment and operation of carbon markets (pursued under the Kyoto Protocol's carbon markets), the establishment of a 'New Market Mechanism', and potential integration of national schemes implemented as unilateral or linked systems
- non-market approaches (pursued under the 'Non-Market Mechanism'), and
- knowledge sharing and education.

Since COP 19 in Warsaw, the UNFCCC's subsidiary bodies have implemented a number of decisions arising from that meeting:

- The Ad Hoc Working Group on the Durban Platform for Enhanced Action (ADP) continues to lead discussions on two negotiating tracks (pre- and post-2020 ambitions) underpinning a potential new climate change agreement which is planned to be adopted at COP 21 in Paris.
- The Subsidiary Body for Implementation (SBI) and the Subsidiary Body for Scientific and Technological Advice (SBSTA) continue to jointly steward CCS relevant agendas, such as the development and transfer of technology; carbon markets and non-market approaches; and the issue of long-term finance.

The work programs of all subsidiary bodies overlap and are complementary to each other.

Ad Hoc Working Group on the Durban Platform for Enhanced Action (ADP)

The ADP is the principal negotiating track for the 2015 Agreement. This Agreement will be a legal instrument that could culminate in a new universal climate change agreement, with an aim of complementing (or eventually superseding) the second commitment period (1 January 2013 to 31 December 2020) of the Kyoto Protocol. Its work program is split into two components:

1. post-2020 ambitions (Work Stream – WS1), and
2. pre-2020 ambitions (Work Stream – WS2).

The ADP's recent work program facilitates discussions on the agreed elements of the 2015 Agreement (mitigation, adaptation, finance, technology, capacity building and transparency of action and support) with a view to adopting formal text by May 2015 as the basis of negotiations at COP 21.

The ADP convened three important meetings in the lead-up to COP 20, scheduled to take place in Lima, Peru from 1-12 December 2014. In its most recent meetings, the ADP has primarily focused on achieving progress in three areas:

1. nationally determined contributions (NDC)
2. upfront information from countries, and
3. identifying the concepts or bullet points which could form the skeleton agreement.

There are high expectations that parties will be in a position to announce their obligations to address climate change (referred to as Intended Nationally Determined Contributions – INDC) by the first quarter of 2015, with many parties, including the US, recently reaffirming they are on track to meet this date.

Effort under WS2 largely occurs through Technical Expert Meetings (TEMs). The purpose of the TEMs is to examine clean energy technology options and help governments understand how various technologies can enhance domestic mitigation efforts in the pre-2020 period (although clearly the dialogue is also relevant for the post-2020 period).

A series of TEMs were held throughout 2014, including on renewable energy, energy efficiency and CCS. A formal meeting report with recommendations from the CCS TEM held in October 2014 will be forwarded to the COP for consideration. The Institute expects that the report will provide an important focus on CCS as a major mitigation technology in the lead up to COP 20 and 21, and deliver an important set of recommendations on how the UNFCCC system can better support CCS developments.

The Technology Executive Committee/Climate Technology Centre and Network

Technology transfer is an important agenda item within the UNFCCC. The development, deployment and diffusion of technology solutions is considered central to the emission mitigation efforts of developed and developing countries alike.

The Technology Mechanism is the UNFCCC's principal channel to facilitate action on technology development to assist in mitigation activities. Its Technology Executive Committee (TEC) is the policy advisory body to the COP (which includes supporting the ADP and SBSTA deliberations), and its work is complemented by the implementation of actions of the Climate Technology Centre and Network (CTCN).

The TEC recently adopted a two-year rolling work program (2014-15) that includes the creation of six task forces:

1. technical needs assessments
2. enablers and barriers
3. adaptation
4. linkages between the Technology Mechanism and the Financial Mechanism
5. mitigation, and
6. emerging and cross-cutting issues.

The TEC hosted a number of workshops in 2014, including a thematic dialogue on climate finance of technology (19 August 2014) and national systems of innovation in developing countries (13-14 October 2014). It intends to host further thematic dialogues on mitigation technologies in 2015.

The CTCN recently announced that it is ready to receive requests for assistance by developing countries. The CTCN has also appointed over 90 Nationally Designated Entities (NDEs), nominated by the parties (developing countries), who serve as the interface between developing country requests for assistance and the CTCN, and nine Network members, including the Institute.

The CTCN will respond to developing country requests for technology development and transfer assistance on CCS matters, as evidenced by the Institute's recent membership to its Climate Technology Network.

The Financial Mechanism/Green Climate Fund

The Green Climate Fund (GCF) is an operating entity of the Financial Mechanism. The GCF supports projects, programs, policies and other activities in developing country Parties to the UNFCCC. The GCF will ultimately provide climate financing to developing countries for both mitigation and adaptation activities, including a mix of public and private sector projects and programs.

The Fund is governed by the GCF Board. The assets of the GCF will be administered by a trustee in accordance with the relevant decisions of the GCF Board. The World Bank was invited by the COP to serve as the interim trustee of the GCF, subject to a review after three years of operation.

In May 2014, the GCF announced that it is also fully operational and the World Bank is helping the GCF Board pursue financial sponsors. The GCF Board has prioritised 14 'Initial Result Areas', including low-emission energy access, and small-medium and large-scale low-emission power generation.

Once the GCF is funded it will consider claims by developing countries to support CCS projects as cited in its *Governing Instrument,* which states on the issue of eligibility: *'The Fund will finance agreed full and agreed incremental costs for activities to enable and support enhanced action on … technology development and transfer (including carbon capture and storage) …'*.

The GCF Board has also established a number of committees to help oversight the GCF, including the Private Sector Advisory Group (PSAG), a panel that provides advice on Fund engagement with the private sector.

BOX 5.1

Role of the Institute in UNFCCC processes

The Institute serves as an accredited observer to the GCF, an accredited network member of the CTCN, is awaiting a decision to become an accredited observer to the IPCC, and is a member of the TEC's cross-cutting working group. Upon request, the Institute assisted in organising the CCS TEM event in October 2014. Throughout 2014, the Institute participated as an accredited observer in all of the technology relevant meetings, including the TEC, CTCN Advisory Board, SBSTA, SBI, ADP, and the GCF.

This extensive engagement complements the Institute's status as a UNFCCC observer (since 2011) and positions the Institute at the centre of global climate negotiations, where it can advocate for the vital role of CCS as part of a portfolio of measures to combat climate change.

Carbon Sequestration Leadership Forum (CSLF)

The Ministerial communiqué following the 5th meeting of the CSLF Ministers in Washington, DC in November 2013 clearly emphasised the importance of CCS in tackling climate change and the need to increase implementation momentum. The CSLF has 23 members, including 22 countries and the EC that account for a large portion of global CO_2 emissions. Therefore, action taken by CSLF member countries can have a significant impact on climate change mitigation.

Specifically, the communiqué stated:

> **"We, the Ministers and Heads of Delegation of the CSLF Members, are convinced that the research and development (R&D), demonstration and global deployment of Carbon Capture and Storage (CCS) must be accelerated… We are committed to taking necessary actions individually and collaboratively to promote the further development and deployment of CCS.**
>
> **Building on valuable experience gained during the past decades, the next seven years are critically important for creating the conditions for CCS to be ready for large-scale deployment by the end of the decade. Our common goal is to ensure that the conditions are right for all CCS projects currently under construction or in advanced stages of planning to be completed, and we must increase the number of new large CCS demonstrations by 2020 to expand commercial deployment in the 2020's."**

5.2

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

A number of best practice guidelines and national standards and codes already apply to a range of CCS activities. The next step is to compile these sources into formal international standards. This process was initiated in 2011 when the Standards Council of Canada submitted a proposal to the ISO to develop internationally agreed standards for CCS.

Expected benefits of standardisation include:

- helping facilitate the deployment and integration of procedures, systems, and technologies needed to safely implement and operate CCS projects
- enabling knowledge sharing, innovation, cooperation and coordination
- helping achieve public acceptance of CCS as a safe and reliable climate change mitigation technology

- achieving greater consistency across multiple interests and different abilities of professional disciplines, sectors, and levels of administrative responsibility within the national and transnational context
- increasing preparedness, continuity management, culture and best practices within governments and organisations working in the field of CCS, and
- reducing risks and consequences of accidental, intentional and natural events.

The ISO is a global system with a collection of around 19,000 standards and has over 160 national members. The ISO 'develops' standards though panels of experts within a technical committee.

In 2012 the ISO established a Technical Committee (TC) on Carbon Dioxide Capture, Transportation, and Geological Storage (ISO/TC 265) to oversee the standardisation of the design, construction, operation, environmental planning and management, risk management, quantification, monitoring and verification, and related activities in the field of CO_2 capture, transportation and storage.

ISO/TC 265 is chaired by Canada, which also provides the Secretariat (twinned with China) and has met four times since its establishment, including in Paris (June 2012), Madrid (February 2013), Beijing (September 2013) and Berlin (April 2014).

The Membership of ISO/TC 265 has several layers:

- eighteen participating ('P') countries that provide national delegations, identify experts to contribute and have an obligation to vote. The 'P' members are supported by in country 'mirror committees' which typically rely on localised expertise to formulate their country positions on key negotiating issues,
- nine observing ('O') countries that can make contributions should they choose to do so, and
- ten liaison ('L') organisations that bring expertise and help with wider acceptance but do not have voting rights (this group includes the Global CCS Institute).

Within ISO/TC 265, there are six working groups (WGs) led by various 'P' countries that are developing a variety of formally endorsed ISO outputs, ranging from Technical Reports (informational products) to draft Standards. The six WGs include:

- WG1: Capture (Japan convening)
- WG2: Transportation (Germany convening)
- WG3: Storage (Canada/Japan co-convening)
- WG4: Quantification and Verification (China/France co-convening)
- WG5: Cross-Cutting Issues (France/China co-convening), and
- WG6: EOR Issues (US/Norway co-convening).

All WGs have approved New Work Item Proposals (NWIPs) and are currently progressing six projects including:

- WG1: A Technical Report on capture, due for completion by 2016
- WG2: An ISO Standard for CO_2 pipelines transportation due by 2016
- WG3: A Technical Report on geological storage due by 2017
- WG4: A Technical Report on quantification and validation due by 2016
- WG5: An ISO Standard for a cross-cutting issue (common vocabulary) due by 2014, and
- WG6: An ISO Standard for CO_2 storage using EOR due by 2017.

All WGs have convened at least twice to date, and have conducted multiple teleconference calls on related work items.

As it is possible for ISO/TC 265 committee members to propose NWIPs, the US and China co-presented on behalf of WG5 at the 4^{th} Technical Committee meeting in April 2014 a proposal concept for a new Technical Report on lifecycle risk management for integrated CCS projects. It was agreed that WG5 will continue to develop the preparation of this NWIP for further consideration and ultimately a vote by the Technical Committee at the next meeting.

The next Technical Committee meeting is scheduled for 28-29 January 2015 in Birmingham, Alabama and will be hosted by the American National Standards Institute at Alabama Power headquarters. It is expected that all six WGs will meet prior to the Technical Committee meeting.

5.3 INTERNATIONAL MARINE AGREEMENT

The Institute's *Global Status of CCS* reports have previously highlighted the amendments made to the London Protocol in 2006 and 2009. This international agreement, which seeks to *'protect and preserve the marine environment from all sources of pollution'*, was initially amended in 2006 to allow captured CO_2 to be disposed of in sub-seabed geological formations. The amendment entered into force for all Contracting Parties to the London Protocol in February 2010. A later amendment, adopted by the Parties in 2009, sought to remove a further barrier to the technology contained in Article 6 of the Protocol. This article, which precludes the export of wastes under the Protocol, effectively prohibited the movement of CO_2 across marine borders for the purposes of geological storage. A new paragraph was adopted by the Parties to allow for the export of CO_2 for storage, subject to a number of conditions. However, for this amendment to enter into force two-thirds of the Protocol's Parties are required to ratify it.

The *Global Status of CCS: 2012* report noted that only two Parties to the Protocol, Norway and the UK, had ratified the Article 6 amendment. Despite significant work to complete revised Guidelines to accommodate transboundary migration and the development of Guidance to cover responsibilities for 'arrangements or agreements' for export, there have been no further ratifications. As such, the (transboundary) export of CO_2 for the purposes of offshore storage is still not permitted under the Protocol.

At the 8th Meeting of the Contracting Parties to the London Protocol, held in October 2013, the Secretary-General of the International Maritime Organisation, Mr. Koji Sekimizu, made the following statement in his opening speech:

> **"The London Protocol currently is the only global framework to regulate carbon capture and sequestration in sub-seabed geological formations… However, it remains a serious concern that, to date, only two of the 43 London Protocol Parties have accepted the 2009 amendment, which is a long way from satisfying the entry-into-force requirements. The importance of securing its entry into force cannot be over-emphasized, if the threat of acidification of the oceans from climate change is to be minimized."**

While several Parties have indicated that they are preparing submissions for ratifying the amendment, their number remains far below the necessary number to satisfy the entry-into-force requirements. The Institute, in recognising the importance of London Protocol ratification to provide for the implementation of transboundary CCS projects, is strongly supportive of actions by the Contracting Parties that increase the total number of ratifications for it to enter into force as soon as is practicable.

5.4 REGIONAL POLICY, LEGAL AND REGULATORY DEVELOPMENTS

The Americas

CO_2-EOR is the primary driver for CCUS deployment in the Americas and much of the current policy, legal and regulatory landscape is focused around efforts to build on existing oil and gas regulations at both the federal and state or provincial levels. Many of the required elements to support commercial deployment are in place or under development, however, there are no comprehensive CCS/CCUS frameworks, and policies to incentivise new large-scale CCS projects remain inadequate.

United States

The US policy, legal and regulatory environment for CCS/CCUS continues to advance at the Federal, state and regional levels but remains fragmented. Federal action on CCS has focused on the regulatory environment with the US Environmental Protection Agency (EPA) taking the lead with proposals to advance President Obama's Climate Change Action Plan.

Legislative leaders in coal producing states (including Heidi Heitkamp: Democrat – North Dakota and Senator John D. Rockefeller: Democrat – West Virginia) have proposed bills to support CCS policy action and incentives, however, the bills have not passed out of the Congressional committees. States with EOR opportunities (e.g. Texas, Wyoming, North Dakota and Mississippi) continue to be the most active in driving policies to advance CCUS deployment, and California leads on establishing GHG limits that could include CCS/CCUS under its cap-and-trade program.

US EPA Performance Standards for New and Existing Power Plants[1]

The EPA, using its authority under the *Clean Air Act,* has issued proposed standards, regulations or guidelines to address CO_2 emissions from both new and existing natural gas and coal-fired power plants that will have major implications for states, electric utilities, energy companies, financial institutions, and others, including companies engaged in CCS development and deployment.

New, Modified or Reconstructed Sources – Clean Air Act section 111 (b)

On 8 January 2014, the EPA published a proposed rule that sets limits on CO_2 emissions from new coal and natural gas-fired power plants. Existing technology should enable new natural gas-fired plants to meet the emissions standards. To comply with the proposed standard, new large natural gas generating units (~ 100 megawatts of electrical output or larger) could emit no more than 1,000 pounds (454 kg) of CO_2 per megawatt-hour (MWh), which can be achieved with combined cycle technology. Smaller natural gas units would need to achieve 1,100 pounds (499 kg) CO_2/MWh.

New coal plants, including the higher efficiency ultra-supercritical boilers and integrated gasification combined cycle (IGCC) units, have two compliance options, both of which would require CCS:

1. one option requires CCS soon after start-up to achieve a 12-month average emission rate of 1,100 pounds (499 kg) CO_2/MWh, or
2. alternately, CCS could be used within seven years of start-up to achieve a seven-year average emission rate of 1,000-1,050 pounds (454-476 kg) CO_2/MWh (requiring about 40% CO_2 capture)[2]. This longer compliance period was intended to encourage CCS technology advances and allow for more start-up time.

Compliance with the standard is only based on quantities of CO_2 captured and the EPA has emphasised that the proposal does not involve regulation of any downstream recipients of captured CO_2. However, captured CO_2 must be transported to a storage site that complies with reporting obligations under the EPA's GHG Reporting Rule, Subpart RR, which requires storage site owners or operators to submit a monitoring, reporting and verification (MRV) plan to the EPA for review and approval[3].

As the EPA explains in its New Source Performance Standards (NSPS) proposal, the practical impact would be that owners and operators of projects injecting CO_2 that are permitted under Underground Injection Control (UIC) Class II for EOR operations – and receive CO_2 captured from power plants to meet the proposed NSPS – will also be required to submit, and receive approval from the EPA for, an MRV plan and report under Subpart RR.

The question remains as to whether the EPA's proposed NSPS will have any significant impact

[1] http://www2.epa.gov/carbon-pollution-standards/regulatory-actions

[2] The 40% reference is from Congressional Research Office report, *EPA Standards for Greenhouse Gas Emissions from Power Plants: Many Questions, Some Answers,* November 2013.

[3] Geologic storage sites permitted for long-term storage under the EPA's Underground Injections Control (UIC) Program Class VI (Geological Sequestration) regulations also report under Subpart RR.

on CO_2 emissions or CCS deployment. Current market conditions in the US (e.g. low electricity demand growth, abundant natural gas, and the pressures and costs associated with other regulatory compliance requirements for coal plants) make it unlikely that any new coal plants would be built in the near term. Between now and 2018, the US Energy Information Administration (EIA) forecasts only four potential coal plants compared to more than 200 natural gas plants. Legal challenges (including from adversely affected states) to the proposed NSPS are underway. Given current legal challenges, it is not expected that the EPA will publish its final rule before 2015. A key issue relates to whether the EPA can lawfully determine that partial CCS is 'adequately demonstrated' and can therefore be selected as a best system of emission reduction under section 111 of the *Clean Air Act.*

Given these considerations, it seems the EPA's NSPS regulatory action alone may not be sufficient to drive CCS deployment. For a sustainable CCS business case, further policy action is needed to advance the technology and put in place adequate incentives and regulatory frameworks necessary to attract private sector investment.

Existing Power Plants – Clean Air Act section 111 (d)

On 2 June 2014, the EPA issued a proposed rule to establish CO_2 emission limits on a state-by-state basis for existing fossil fuel power plants. Each state goal would take the form of an average rate of emissions per net MWh of electricity (pounds CO_2/MWh) across all power plants within a particular state. Under the proposed rule, the EPA would require states to meet CO_2 emission targets through four 'building blocks', including:

1. heat rate improvements at coal-fired power plants
2. increased use of existing natural gas combined cycle units
3. preservation of nuclear capacity and increased use of renewable energy, and
4. increased demand-side energy efficiency.

The proposal provides flexibility for states to determine their compliance pathways, which can come from any or all of the four building blocks, as well as other emission reduction measures not considered by the EPA (which could include CCS). The EPA's proposal will essentially require states to set a cap on emissions from their power sector, or alternatively, impose a price on carbon.

This flexibility is responsive to comments from states that would like to integrate existing state GHG emissions reduction programs with the proposed rule's framework (e.g. California or the Regional Greenhouse Gas Initiative of the north-eastern states). Although flexibility afforded to states may allow for several compliance pathways, it may prove difficult to translate that flexibility into clear market signals for various technologies, including CCS.

The EPA indicates that it expects to issue a final rule by June 2015. States will be required to meet an interim emission rate in 2020 and the full reduction required by the emission guideline in 2030. State compliance plans are due to be submitted to the EPA by 30 June 2016, however, states that are going to participate in multi-state compliance programs (e.g. cap-and-trade) can get an extension until 30 June 2018 to submit their plans.

Legal challenges are underway to block the EPA's proposed rule. A dozen states, led by West Virginia, have sued the EPA (West Virginia v EPA, 14-1146). These states maintain that a US Supreme Court ruling prohibits the EPA from issuing power plant rules under 111 (d), when it has already regulated them under a separate section.

US EPA Guidance on Transitioning from Class II to Class VI Wells[4]

In December 2013 the EPA released draft guidance for comment on transitioning Class II wells for oil and gas operations, including EOR, to Class VI wells for geologic carbon storage. According to the draft, owners or operators of Class II wells that inject CO_2 for the primary purpose of long-term storage would be required to apply for and obtain Class VI well permits if the UIC program director

[4] http://water.epa.gov/type/groundwater/uic/class6/gsguidedoc.cfm

determines there is increased risk to underground sources of drinking water. If a determination is made that a Class VI permit is needed, a number of requirements must be fulfilled, both at the time of re-permitting and during future operations, including:

- well construction and operation
- geologic storage site testing and monitoring
- post-injection site care, and
- emergency and remedial response.

The EPA is expected to publish its final rule towards the end of 2014.

US EPA exempts Class VI CO_2 Injection from Resource Conservation and Recovery Act (RCRA) Hazardous Waste Regulations[5]

In December 2013, the EPA conditionally excluded CO_2 captured from power plants and industrial sources and injected into UIC Class VI wells from RCRA hazardous waste regulation in a pre-publication version of the rule. The EPA has determined that CO_2 injected into Class VI wells does not present a substantial risk to human health or the environment and should be exempted from the regulation.

Canada

Similar to the US, CO_2-EOR is the primary policy, regulatory and legal driver for CCUS in Canada. The Government of Canada and the provinces have been engaged in updating their existing regulatory frameworks rather than developing a comprehensive framework.

The Government of Canada has not taken any recent action on CCS, however, its emissions reduction policy (finalised in September 2012) – *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations*[6] – is due to come into effect on 1 July 2015. It requires all coal-fired units to retire after 50 years of being in operation, or be refitted with CCS technology to achieve a performance standard equivalent to emissions from a combined cycle natural gas plant. Temporary exemptions are offered until 2025 for plants that incorporate CCS and incentives are available for existing plants incorporating CCS earlier than necessary.

The Government continues to work with the provinces through the Federal-Provincial CCS Network to establish GHG emissions reduction targets and build on a solid CCS regulatory foundation from the oil and gas sector. Current provincial CCS regulatory efforts have focused on a review of existing CCS frameworks and considerations of whether additional policy and regulatory measures are needed.

In October 2013, the Alberta Government concluded its consultation period on its final draft *CCS Regulatory Framework Assessment* (RFA) report[7]. The two-year process evaluated Alberta's CCS regulatory regime and considered best practices adopted in jurisdictions around the world. Over 70 conclusions and recommendations were made and sought to *'ensure the highest levels of protection for public safety and the environment'* in the creation of a regulatory model. It is expected that Alberta Energy will publish a summary of the feedback and finalise the report in 2014.

Mexico

CO_2-EOR is the primary driver for CCUS in Mexico and the government is currently active in advancing the policy, legal and regulatory frameworks needed to implement CCUS. Led by the Ministry of Energy (SENER), Mexico issued its *CCUS Technology Roadmap*[8] in early 2014 and is currently undertaking a

[5] http://www.epa.gov/waste/nonhaz/industrial/geo-sequester/faqs.htm
[6] https://www.ec.gc.ca/lcpe-cepa/eng/regulations/detailreg.cfm?intReg=209
[7] http://www.energy.alberta.ca/Initiatives/3544.asp
[8] http://www.sener.gob.mx/res/gef/CCUS%20Technology%20Roadmap%20in%20Mexico/MRTPUBLICAINGLES%20v2.0.pdf

review of its CCS regulatory framework. At the conclusion of the review, specific regulatory framework recommendations are expected. The World Bank project on *Development of a Regulatory Framework for Carbon Capture, Utilization and Storage in Mexico* will also support specific recommendations. SENER is also advancing a national proposal for CO_2-EOR projects that is aligned with its CCUS Technology Roadmap. Further information is included in the Mexico case study in Chapter 6 (CCS in Developing Countries).

BOX 5.2

Institute engagement and collaboration on CCS/CCUS policy in the Americas

The Institute advocates for sustainable policies and regulations that will incentivise broad CCS/CCUS deployment. A key Institute area of activity is engaging policy makers, legislative leaders and targeted stakeholders from various groups with a stake in CCS/CCUS deployment. The Institute regularly holds roundtables, forums, regulator networks, and workshops to build CCS/CCUS policy momentum. Many of these activities are conducted in partnership with high-profile group organisations such as the Environmental NGO Network on CCS (ENGO Network on CCS), the Atlantic Council and other policy groups with an interest in advancing CCS. In May 2014, the ENGO Network on CCS (US chapter) issued an important set of US policy recommendations in support of CCS at a high-level Congressional forum.

Europe and the Middle East

Europe

There have been a number of CCS-related policy, legal and regulatory developments in Europe in 2014, the most important being the review of the application of the European Union (EU) Directive 2009/31/EC (CCS Directive) on the geological storage of CO_2. This process will allow the European Commission (EC) to evaluate the performance of its key regulatory framework, as well as seek input into policy development to support the uptake of CCS technologies. The review process is expected to be completed by March 2015 and, where necessary, the EC may then propose a revision of the Directive or other CCS measures.

The future policy context for low-carbon technology developments in Europe over the next decade is largely found in the 2030 climate and energy framework and the European Energy Security Strategy Communications. Released in 2014, these Communications include further details of the approach the EC is seeking to adopt in relation to a future framework for shaping the EU's climate and energy policies after 2020 and for greater self-sufficiency in its energy supply.

The speed and approach taken to translating this policy framework into legislative proposals will be subject to the strategic choices of the new European Commissioners who are expected to take office around November 2014. Such choices are likely to include:

- the nature of EU-wide GHG emissions reduction targets
- how Member States will react to the proposal to develop national plans for competitive, secure and sustainable energy
- the reform of the EU Emissions Trading System (ETS), and
- which type of innovation support should be designed after 2020 (expanded NER300 or New Innovation Facility).

CCS Directive 2009/31/EC Review

The most important piece of legislation that impacts CCS in the EU is Directive 2009/31/EC (CCS Directive) on the geological storage of CO_2, which is also one of the most comprehensive examples worldwide of CCS-specific legislation. Article 38 of the CCS Directive requires the EC to review the application of the CCS Directive. The EC has a deadline of 31 March 2015 to submit the next Implementation Report to the European Parliament (EP) and European Council, and report on the implementation of the CCS Directive.

The EC launched the review process in May 2014 and appointed independent consultants to undertake a stakeholder consultation. The review process extends beyond the provisions of Article 38 of the Directive and requires an assessment of the CCS Directive's effectiveness, relevance, efficiency, coherence and EU-added value.

The stakeholder consultation has received input in the form of 105 completed questionnaires and 16 written submissions. The (large) majority of comments received suggested that there has not been enough experience of the CCS Directive to justify high-level changes and that key issues for the uptake of CCS in Europe are linked to CCS enabling policies rather than the Directive itself.

With respect to the Directive itself, the following specific issues have been highlighted:

- the feasibility of retrofitting of power plants for CO_2 capture
- Emissions Performance Standards (EPS)
- the role played by integrated transport and storage infrastructure in Europe ahead of establishing capture projects to maximise social benefits, and
- in the case of storage – the definition of 'permanent', transfer of responsibility for a storage site, financial security, financial mechanisms and the criteria for establishing and updating the monitoring plan.

The Institute participated in the review process and submitted a formal written response to the consultation in July 2014 (Box 5.3)[9].

BOX 5.3

Storage Directive 2009/31/EC Review – the Institute's Submission

The Institute recognises the importance of the CCS Directive and affirms the importance of legal and regulatory frameworks for ensuring project deployment.

The Institute believes that a detailed assessment of the CCS Directive, of the nature proposed under the Directive, is premature at this point in time. The Institute makes this statement on the basis that there has been insufficient experience of the full spectrum of the Directive's provisions by European projects to date.

The Institute does, however, consider that early European CCS demonstration projects offer important project-level perspectives of national regulatory models and the overarching European regime that may be pertinent to the review. These are most evident in issues arising from post-closure stewardship (transfer of responsibilities, liabilities). Addressing these issues in a manner that accommodates the risk profiles of governments and first-mover project developers is critical to ensure the progression of CCS in Europe.

Policy efforts to accelerate the momentum of CCS projects in Europe must address the following issues:

- Strong, sustainable technology-neutral emissions reduction policies to support longer-term deployment – this is critical to reduce uncertainty and provide the longer-term predictability required by project developers.
- Strengthened incentive mechanisms to support the immediate demonstration effort – in the short term, financial support measures are needed that enable projects to progress faster

[9] http://www.globalccsinstitute.com/hub_show/173768

BOX 5.3

Storage Directive 2009/31/EC Review – the Institute's Submission

through the development pipeline and enter construction. First-mover projects incur higher risks and upfront costs than later projects; appropriate recognition of this should be taken into consideration in the framing of financial and policy support.

- It is important that the benefits and value of CCS are continually asserted and that CCS is not disadvantaged in relation to other low-carbon technologies in policy considerations and government support.
- Europe can create a positive pathway for CCS demonstration by advancing plans for storage site selection and encouraging linked transportation and storage solutions that reduce project costs and timelines.

Transposition of the Directive

In February 2014, the EC issued a report on the implementation of the CCS Directive[10]. The report highlights a number of specific implementation issues, including the permitting of CO_2 storage, obligations for operation of storage sites, closure and post-closure obligations, financial guarantees and transboundary issues. The report highlights that proper and consistent implementation of the CCS regulatory framework across Europe is of paramount importance. The report also highlighted the selection, operation, closure and post-closure of storage sites, as well as the assessment for retrofitting large combustion plants for CO_2 capture, as particularly significant for boosting public confidence in CCS technologies.

While the formal transposition deadline of 25 June 2011 was missed by all but one Member State and the EC issued infringement cases for non-communication against 26 Member States, the February 2014 report shows that all Member States notified the transposing measures to the EC by 2013. Based on an assessment conducted by the EC on the transposition of the Directive into national law, a second stage of the infringement procedure was commenced in late 2013. Reasoned Opinions were issued to six Member States (Austria, Cyprus, Hungary, Ireland, Sweden and Slovenia) in November 2013 and to Poland in April 2014, for partial non-communication of transposing measures. In July 2014, the EC announced that it had closed infringement procedures against Cyprus, Hungary and Ireland.

Although not a member of the EU, Norway is a party to the Agreement on the European Economic Area (EEA Agreement), and has announced its intention to transpose the EU CCS Directive into national legislation and regulation. In April 2014, Norway launched a stakeholder consultation with a view of transposing the Directive; this consultation was concluded in May.

The 2030 Framework and related policy developments

In January 2014, the EC released a non-legislative text in the form of a Communication[11] to address 2030 climate and energy targets, detailing the main messages that the EC seeks to include in future EU energy and climate polices. In this document, the EC proposed a GHG emission reduction target for domestic EU emissions of 40% in 2030 compared to 1990 levels and a 27% EU-wide renewable energy target.

While the renewable energy target is binding at EU level, it would not be binding for Member States individually, therefore leaving greater flexibility for Member States to choose the most cost effective manner to achieve GHG reduction targets. As part of this Communication, it is proposed that each Member State report on the approach set out to achieve GHG domestic objectives after 2020 in their national plans for competitive, secure and sustainable energy, including Member States choices on low-carbon technologies policies.

Another key element of the framework is the reform of the EU Emissions Trading Scheme (EU ETS) which has been re-stated in the Communication as the cornerstone of longer-term emissions

[10] http://ec.europa.eu/transparency/regdoc/rep/½014/EN/1-2014-99-EN-F1-1.Pdf
[11] COM(2014)15 http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0015

reduction in the EU and, as such, should remain as one of the central instruments to bring about the transition to a low-carbon economy. Within this context, the EC has published a legislative proposal[12] to introduce a Market Stability Reserve (MSR) in the EU ETS, with the aim of improving its functioning in the long term.

In July 2014, the EC released a further Communication on a non-binding EU-wide 30% energy efficiency target by 2030[13], in order to increase the EU's energy security and reduce the EU's dependence on energy imports.

In parallel, the EC opened a stakeholder consultation to consider the post-2020 rules to protect against the risk of 'carbon leakage'. The consultation was concluded at the end of July 2014 and will feed into further work on the 2030 framework regarding the determination of a system of free allocation post-2020 to ensure the competitiveness of Europe's energy intensive industries[14]. The Institute participated in one of three stakeholder workshops held during the consultation process, addressed to discuss means of directing further revenues from the ETS in the form of an expanded NER300. Given that no further sales are possible under the present NER300 initiative (as the second call was concluded in July 2014), it is expected that an expanded NER300 system or a New Innovation Facility will be explored in the post-2020 period.

Member States have agreed unanimously to reach an agreement in October 2014 on the 2030 framework by European heads of state.

Security of energy supply comes into greater focus

An increased focus on EU energy dependency issues has recently driven the European energy agenda to focus on how to strengthen Europe's security of supply and re-stated the path towards a low-carbon, competitive and energy-secure Europe. At the end of May 2014, the EC published a Communication on the *European Energy Security Strategy*[15], which sets out areas where concrete actions should be implemented to respond to energy security concerns. Of the eight key pillars identified in the strategy, one is focused specifically on maximising the use of indigenous sources of energy, including the exploitation of conventional oil and gas resources in Europe.

The document suggests that coal and lignite fuel sources have a long-term future in the EU where CCS is used and that *'CCS [also] offers the potential to further improve gas and oil recovery that would otherwise remain untapped'.* As key actions, the EC indicates that Member States should *'support demonstration projects for carbon capture and storage, particularly those co-financed by the NER 300 Programme and the European Energy Programme for Recovery, such as the ROAD project'.*

Related CCS reports and communications

In March 2013 the EC launched a Consultative Communication on *The Future of Carbon Capture and Storage in Europe*[16], which considered the status of CCS in the EU and the barriers which have impacted its deployment to date. In addition to this analysis, the Communication also welcomed stakeholder views on a range of opportunities for promoting CCS demonstration and wider deployment. Stakeholder responses highlight several conclusions, including a desire to ensure CCS is included in the EU's 2030 energy and climate policy framework. The Institute provided a written response to this Communication[17].

In January 2014, the European Parliament passed a report advocating for the future of CCS technology titled *Developing and applying carbon capture and storage technology in Europe*[18]. The report was passed in Parliament by a vote of 524 to 141 with 25 abstentions. The report highlights a

[12] COM(2014) 20 http://ec.europa.eu/clima/policies/ets/reform/docs/com_2014_20_en.pdf

[13] http://ec.europa.eu/energy/efficiency/events/doc/2014_eec_communication_adopted.pdf

[14] http://ec.europa.eu/clima/consultations/articles/0023_en.htm

[15] COM(2014) 330 final. http://ec.europa.eu/energy/doc/20140528_energy_security_communication.pdf

[16] COM(2013) 180 final. http://ec.europa.eu/energy/coal/ccs_en.htm

[17] http://www.globalccsinstitute.com/publications/european-commission-CCS-consultation-paper-global-CCS-institute-submission

[18] European Parliament 2013, *Report on implementation report 2013: developing and applying carbon capture and storage technology in Europe (2013/2079(INI)),* European Parliament, Brussels, Belgium.

number of factors considered to be critical in encouraging the widespread deployment of the technology and calls on the Commission to undertake activities in a number of key areas. Several issues in particular are highlighted in the report, including:

- the need for the Commission and Member States to 'raise ambitions' for the technology, and
- the strengthening of regulation and funding support.

CCS re-energised in the United Kingdom

There have been a number of encouraging developments for CCS in the UK, with important amendments passed on energy policy and progress in the UK CCS Commercialisation Programme.

UK Energy Act 2013

On 18 December 2013, the *UK Energy Act 2013* received Royal Assent and became law in the UK. The Act provides the legislative framework aimed at supporting the wide-scale electricity market reforms and investments being made in the UK to replace ageing energy infrastructure. There are two critical parts of the Act influencing CCS deployment in the UK.

The first is the establishment of an Emissions Performance Standard (EPS) which enforces the UK policy that no new coal-fired power plant should be consented unless equipped with CCS technology. Operators of all new fossil-fuel plants in the UK will have to operate within an annual emission limit, equivalent to 450 g (one pound) of CO_2 per kilowatt hour (kWh) of electricity for a plant operating at base-load. The *UK Energy Act 2013* also provides three-year exemptions from the emissions limit duty for operators developing CCS projects. The CCS exemptions are available until the end of 2027 and commence for three years from the start of operation of the CCS system.

The second is the eligibility of CCS projects for a Contract for Difference (CfD). CfD's are long-term contracts that provide a stable revenue stream for developers of eligible low-carbon electricity generation. Generation using CCS is explicitly included within this category under the 2013 Act. Each CfD has a set 'strike price' (a price per unit of electricity generated) which is set at the level determined to be necessary to support the particular technologies or projects supported by the scheme. The strike price for UK CCS projects will be determined initially on a case-by-case basis, with a progressive move to competitive allocation in line with the development of the technology.

UK CCS Commercialisation Programme – making steady progress

In addition to the longer-term funding support and incentive mechanisms being built into the UK Electricity Market Reforms, including the EPS and CfDs, the UK Government established the UK CCS Commercialisation Programme which made up to GB£1 billion capital funding available for first-mover CCS demonstrations through a competition process. In the past year the UK Government has announced that FEED contracts under the Programme have been successfully agreed with the White Rose CCS Project and the Peterhead CCS Project. In addition, in July 2014, the EC announced that the White Rose project was to be awarded up to €300 million in funding as part of the second call of the NER300 funding program.

Next Steps in CCS: Policy Scoping Document

In August 2014, the UK Government published a scoping document designed to gather stakeholder feedback on the approaches required to progress to the next phase of CCS project development in the UK[19]. The *Policy Scoping Document* summarises the policies and actions that the Government has taken to date to support CCS deployment in the UK and identifies key areas requiring further development for the second phase of the UK CCS Commercialisation Programme[20].

[19] https://www.gov.uk/government/publications/ccs-policy-scoping-document.

[20] See also House of Commons, Energy and Climate Committee, *Carbon Capture and Storage: Government Response to the Committee's Ninth Report of Session 2013-14,* September 2014. In this response document, the UK government reiterates the critical importance of CCS technology and its commitment to working with the CCS industry to deliver cost-competitive CCS by the 2020s

In addition to offering GB£1 billion capital funding for first-mover CCS projects through a competitive process during the first phase, the Government is considering how to support industry to build on the infrastructure which could be put in place by these projects. The *Policy Scoping Document* covers a wide range of policy issues, including financial incentives to CCS, transport and storage infrastructures, and prospects for industrial CCS, bio-CCS and CCUS.

Middle East

The following update on the progress of CCUS in the Gulf Cooperation Council (Box 5.4) has been provided by Dr I-Tsung Tsai, Assistant Professor in Engineering Systems and Management at the Masdar Institute, Abu Dhabi. Dr Tsai authored the study, *Carbon Capture, Utilization and Storage Regulation in the Gulf Cooperation Council Countries: A Review on the Current Status,* which was presented at the United Nations Economic and Social Commission for Western Asia (UN-ESCWA) Expert Group Meeting on CCUS in Abu Dhabi, in November 2013.

BOX 5.4

Current progress of CCUS in the Gulf Cooperation Council

The Gulf Cooperation Council (GCC) is in the early stage of CCUS development and deployment. While both CO_2-storage and CO_2-EOR have great potential in the GCC given the region's vast geological formations for CO_2 storage and enormous oil and gas production, at this moment major activities have been focusing on validating the feasibility of commercial-scale carbon capture in the local context.

Saudi Arabia is constructing the world's largest CO_2 purification and liquefaction plant in Jubail to bring 1,500 tonnes per day of raw CO_2 coming from two ethylene glycol plants to three Saudi Basic Industries Corporation (SABIC)-affiliated companies for enhanced methanol and urea production. The country is in the process of developing several similar CCS projects, including some pilot projects for CO_2-EOR.

The Qatar Fuel Additives Company plans to install a CO_2 capture plant in its methanol production plant by autumn 2014. Meanwhile, Qatar Petroleum has a joint venture with Shell and some academic institutions to establish the Qatar Carbonates and Carbon Storage Research Centre (QCCSRC). Bahrain has a project that captures flue gases from an existing petrochemical plant for urea and methanol production.

Kuwait launched a project in 2010 to capture more than 150,000 tonnes of CO_2 annually from Equate, a large petrochemicals company, for food and beverage production. Oman is primarily focused on the R&D of feasible CCUS technology.

Abu Dhabi, as the major oil producing emirate of the United Arab Emirates (UAE), is making major progress on CCUS beyond carbon capture with Masdar's development of a domestic CCUS network. In addition to the completion of a two-year CO_2-EOR pilot project in November 2011 at an onshore field, Masdar is implementing a CO_2-EOR project that brings 800,000 tonnes of carbon annually from the Emirates Steel Industries (ESI) factory to an oil field of the Abu Dhabi National Oil Company (ADNOC).

The slow progress of CCUS development and deployment can be attributed to the poor or unclear value proposition of CCUS in this region. For most GCC countries, oil production is mainly in the primary and secondary production phases; with EOR being gradually introduced to extend the production life of some oil fields. Saudi Arabia, for example, can increase oil production without the use of EOR. When needed, Saudi Aramco uses highly optimised and cost effective water flooding operations for EOR.

BOX 5.4

Current progress of CCUS in the Gulf Cooperation Council – (continued)

On the other hand, Abu Dhabi is interested in promoting CO_2-EOR to replace the traditional practice of gas-EOR in the emirate. By increasing the output of natural gas for domestic consumption, CO_2-EOR may effectively reduce the emirate's dependence on imported natural gas. The incentive for CO_2-permanent storage for most GCC countries is unclear as the capture cost for CO_2 may not be adequately covered by the carbon price supported by the CDM.

The weak and unclear value proposition of CCUS in the GCC also affects the progress of CCUS regulation and policy development. So far, no CCUS specific regulation has been developed in the GCC. Only Abu Dhabi has started evaluating a policy framework for a domestic CCUS industry, and is identifying a roadmap for technology deployment and rollout of commercial scale projects. For the remaining GCC countries, it is believed that the environmental regulations related to carbon capture and transportation can be governed by existing environmental laws. Property rights of CO_2 transport facilities and pore spaces will continue to be regulated by national oil companies. New regulation for permanent storage has to be developed. Meanwhile, the regulation for CO_2-EOR, transboundary CCUS, and incentive design remain challenging for GCC countries, as oil and gas production in the region is governed by implicit rules set by national oil companies; transboundary CCUS may interact with existing transboundary oil and gas agreements; and industrial development tends to be driven predominantly by government initiatives.

In the absence of strong economic incentives, government commitment for CCUS as a climate change mitigation measure is critical to drive CCUS development and deployment. So far, Saudi Arabia and the UAE are the only two countries in the GCC that acknowledge CCS as one of the key greenhouse gas mitigation strategies in their national communications to the UNFCCC. It is expected that the rest of the GCC countries will increase their commitment to CCUS as confidence is gained from pilot projects and with regional collaborations on CCUS R&D and development, as promoted by the UN and the IEA, expand.

Asia Pacific

Governments, regulators and policymakers across the Asia Pacific region continue to show interest in the development of law and regulation for CCS. While the pace of development has reduced in the region over the past 12 months, the Institute's recent regulatory Toolkit exercise with the State of Victoria (Box 5.5) has demonstrated that the Asia Pacific region continues to provide some of the world's most comprehensive CCS-specific regulatory regimes.

Several 'second-generation' regulators in the region have continued to examine their regulatory options for the technology in the past year, with several discrete reports, workshops and conference presentations produced by regulators and policymakers from across the Asia Pacific region.

Australia

Legal and regulatory development in Australia has slowed in the past 12 months, following the completion of overarching framework regimes in some states, including primary and secondary legislation, and significant changes to Federal climate change policy. While proposed legislative developments in the states of New South Wales and Western Australia have not eventuated, there have been notable developments in the states of Queensland and Victoria in the past twelve months. The Victorian Government's recent deployment of the Institute's Regulatory Test Toolkit is discussed in greater detail in Box 5.5 below.

The Queensland Government has commenced a reform of its resource Acts, which will see the eventual replacement of several pieces of resources legislation and the subsequent development of a common, standardised resources Act and accompanying regulations. The Government has instigated this reform because it believes that the present tenure system, which underpins several of the state's key pieces of mining petroleum and energy resource legislation, has become unwieldy and complex. The *Modernising Queensland Resources Acts (MQRA) Program* will continue until 2016-17 and will seek to *'progressively modernise, simplify and harmonise the resources legislation'.*

Queensland's *Greenhouse Gas Storage Act 2009* is one of the five Acts included within the scope of this program, whose provisions will largely be consolidated under the single proposed Act. The Government proposes that the provisions of each of the existing acts will reduce over time, until their ultimate repeal, as elements are transferred over to the common resources Act. This transfer process will be facilitated via three separate Bills, which are to be introduced over the next four years.

The first stage of this reform, the *Mineral and Energy Resources (Common Provisions) Bill 2014,* was introduced to the Queensland Parliament in June 2014. This first Bill seeks to consolidate a number of common provisions found in each of the five Acts and addresses in particular: dealings; land access; and restricted land issues.

BOX 5.5

Assessing regulatory models: the Victorian Toolkit exercise

The Regulatory Test Toolkit ('the Toolkit'), originally launched by the Institute in 2011, is an assessment exercise designed to assist governments and regulators when evaluating their regulatory models for CCS. The process was originally undertaken by the Scottish Government and it has since been successfully deployed in Scotland, Romania, Trinidad and Tobago and Malaysia.

In 2013, the Victorian Government, in collaboration with the Federal Government and the Institute, deployed the Toolkit process for the first time in Australia. The Victorian Department of State Development, Business and Innovation (DSDBI) sought to use the Toolkit to assess whether Victoria's existing regulatory model, including its comprehensive CCS-specific legislation, could accommodate a commercial-scale CCS project. As a part of the process, the project team designed a hypothetical CCS project in Gippsland and assessed it against the requisite Commonwealth and Victorian regulatory models, to develop a mock approvals and permits register of all the necessary permits, approvals and licences.

The Toolkit process culminated in a one-day workshop, held in Melbourne in late 2013, which attracted approximately 40 key Commonwealth and Victorian regulators. Workshop participants examined the approvals and permits register in greater detail, using the hypothetical project as a reference point, with a view to identifying any outstanding issues, gaps or obstacles within the regulatory framework.

A significant message of the Toolkit exercise was that the Victorian legal and regulatory regime was deemed to be generally fit-for-purpose. The process did however outline a number of areas where there were further opportunities to enhance the regulatory model, to accommodate a commercial-scale CCS project in Victoria. Thirteen recommendations, classified according to one of four categories (needs gaps, relationships, refinement of processes and secondary guidance), will be progressed over the forthcoming years.

A *detailed report of the Toolkit exercise in Victoria*, including the (mock) approvals and permit register, key themes and recommendations, was published by the Institute.

Southeast Asia Scoping Study

The Asian Development Bank (ADB), supported by the Institute and the UK Department of Energy and Climate Change (DECC), has published a detailed study examining the potential for CCS in Indonesia, the Philippines, Thailand and Viet Nam. The report, *Prospects for Carbon Capture and Storage in Southeast Asia,* includes a summary chapter that considers the legal and social issues for the technology in these countries. Further information is included in the Indonesia case study in Chapter 6 (CCS in Developing Countries).

While the four countries considered have all adopted domestic climate change policies, the report highlights that none have developed or enacted CCS-specific legislation. Closer examination of their domestic energy and resource legislation did, however, reveal that all four countries have aspects of their regulatory regimes that may be adapted to accommodate CCS activities. Notwithstanding the considerable effort necessary in developing CCS-specific frameworks, it is positive to note that the future development of law and regulation in these countries will not necessarily prove unfamiliar to regulators or require entirely novel approaches.

5.5

PERCEPTIONS SURVEY FINDINGS ON POLICY, LAW AND REGULATION

Policy perspectives

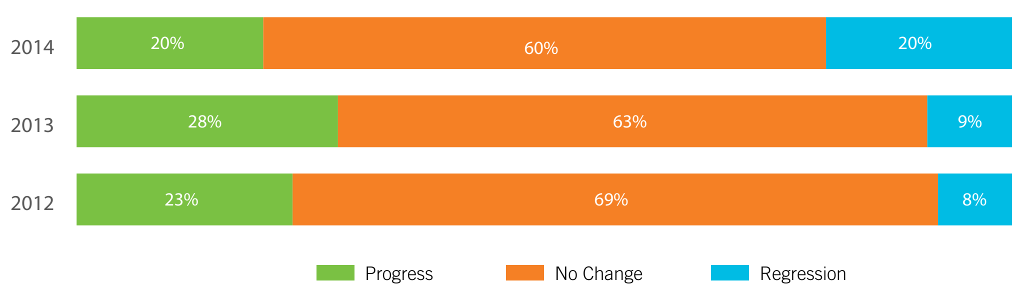
Responses to the Institute's 2014 Perceptions Survey have reaffirmed the perception of CCS project proponents reported in recent Status Reports, that only modest policy progress has been achieved over the annual cycle. Over the past three years, a solid group of around 60-70% of respondents has indicated they had not noticed material changes to their CCS policy environment over the preceding year (Figure 5.1), suggesting the policy development process is viewed as iterative and slow-moving. This is clearly despite the presence of some major policy discussions that have been conducted in various regions.

As noted earlier in this chapter, the next 18 months will be important for determining the quality of international and national support settings for CCS activities, not only in the lead-up to COP 20 and 21 but also within a broader context of the new climate change agreement.

For the first time the number of survey respondents citing progress in the CCS policy environment is matched by the number citing a regression, whilst the majority still cite no change. The respondents pointing to a regression are distributed across all regions, highlighting the need for international policy progress.

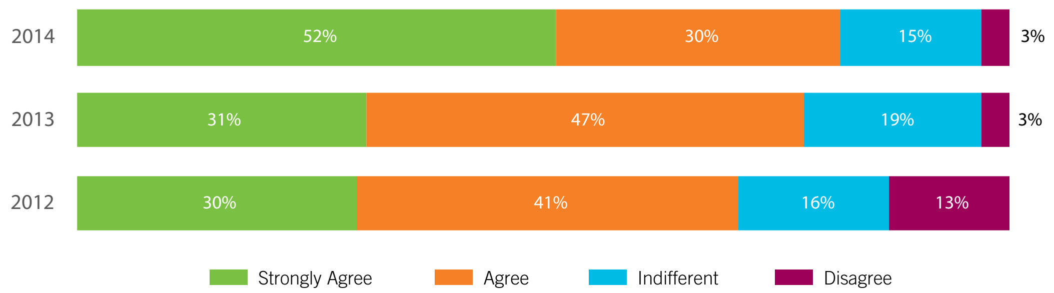
Around half of the survey respondents who cited progress in the CCS policy environment were from the UK. This outcome reflects the significant policy advances made in that country, which were discussed earlier in the chapter.

Figure 5.1 **Have there been material changes to the CCS policy environment over the past 12 months?**



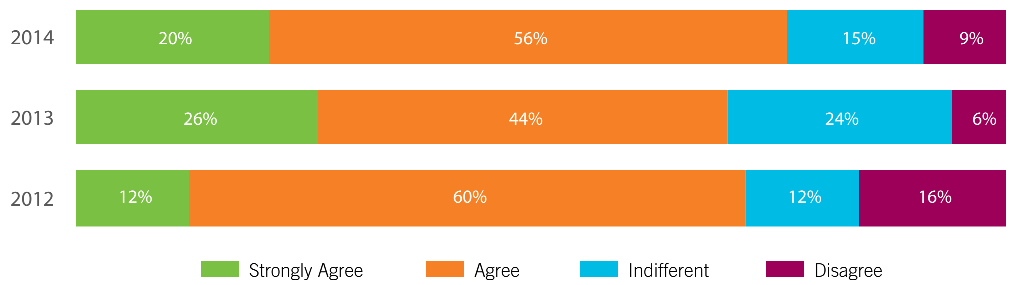
Despite perceiving a slow rate of progress in the global CCS policy environment, a large majority of project proponents remain strong in their belief that CCS will play an increasingly important role in mitigating emissions over the next decade. Similar to the 2012 and 2013 survey results, around 80% of respondents in 2014 are convinced of the growing importance of CCS into the future, indicating a strong commitment to progressing the current pipeline of CCS projects (Figure 5.2).

Figure 5.2 Do you agree that the importance of CCS to mitigate emissions will increase this decade?



More than three-quarters of respondents cited policy uncertainty as a major risk to their project's viability (Figure 5.3), consistent with the findings of the 2012 and 2013 Perceptions Surveys. This perception of policy uncertainty may reflect either the nature of current policy development processes (a fear that governments will announce unexpected policy design attributes), and/or a perceived likelihood of sovereign risk in relation to either the quality of implementation of new policies and/or the rescinding of existing policies.

Figure 5.3 Do you agree that policy uncertainty is a major risk to your project?



Reinforcing the importance of the CCS policy environment to the viability of CCS projects, around two-thirds of survey respondents indicated that existing policy settings substantively contributed to their project's business case, compared with 58% in 2013 (Figure 5.4). On the other side of the ledger, it is a concern that more than 40% of respondents consider current incentives to be inadequate to avoid the economic stranding of their project, broadly consistent with results from previous years (Figure 5.5).

Figure 5.4 Importance of current and new government policy settings – 2013 and 2014

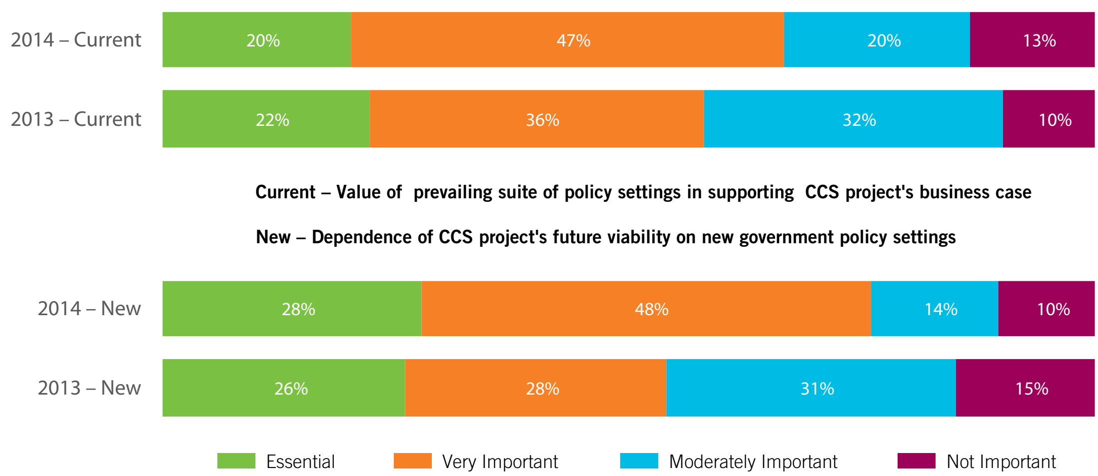
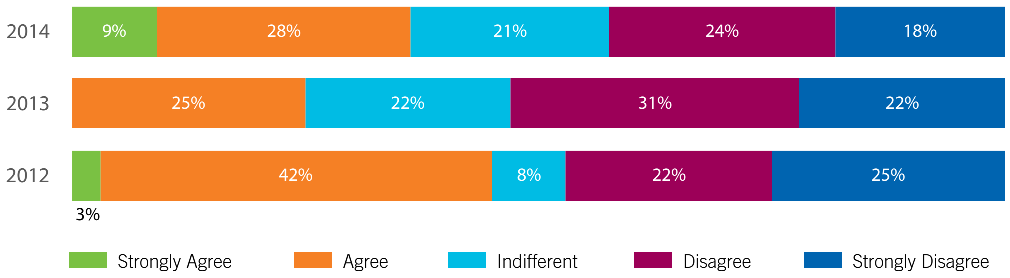


Figure 5.5 **Do you agree that incentives are adequate to avoid commercially stranding your project?**



An overwhelming majority of respondents (76%) indicated that their CCS project's viability is substantively dependent on new policy settings, up significantly from 54% in 2013. The increasing dependence of CCS projects on yet to be revealed and/or implemented policy decisions is especially prevalent in Asia. This outcome is not surprising considering responses to other survey questions, which indicate the need for further work in non-OECD countries to embed CCS into national and regional legal and regulatory frameworks (see 'Legal and regulatory policy perspectives').

Over the past few years CCS project proponents have expressed broadly consistent policy support preferences (Table 5.1)[21].

Table 5.1 **Most important policy enablers**

	MOST IMPORTANT ENABLERS FOR YOUR PROJECT				
	RANK	PREFERENCES (%)			NUMBER OF RESPONSES
		1ST	2ND	3RD	
Access to direct subsidies	1	55%	36%	9%	11
Access to a viable CO_2 storage solution	2	31%	31%	38%	13
Off-take arrangements offering guaranteed prices	2	67%	22%	11%	9
Streamlined and efficient regulatory approvals processes	4	21%	21%	57%	14
Regulated returns on CCS investment/s	4	56%	22%	22%	9
An appropriate carbon price	6	20%	40%	40%	10
Access to indirect subsidies	7	25%	38%	38%	8
Compliance with performance standards obligations	8	40%	60%	0%	5
Being paid a premium price for the off-take through a feed-in tariff	9	20%	40%	40%	5
Selling output into a guaranteed market with tradable certificates	10	25%	50%	25%	4
Access to common user infrastructure	11	0%	25%	75%	4

Access to direct subsidies (ranked 1st in 2013 and 2014), off-take arrangements that offer guaranteed prices (ranked equal 2nd in 2014), and streamlined and efficient regulatory approvals processes (ranked equal 4th in 2014) have been carried over from the 2013 Perceptions Survey as the most highly rated policy enablers for CCS projects.

[21] The 2014 policy enabler rankings in Table 5.1 were determined by applying different weights to: the number of respondents citing an option as most important (1.0 weighting); second most important (0.5 weighting); and third most important (0.25 weighting); and then ordering the options from highest to lowest based on their corresponding weighted sum of responses.

The relative importance of access to a viable CO_2 storage solution (ranked equal 2nd in 2014) and regulated returns on CCS investments (ranked equal 4th) as CCS project enablers has increased over the past 12 months, while an appropriate carbon price and access to indirect subsidies (ranked 6th and 7th respectively) have dropped back to the middle of the pack.

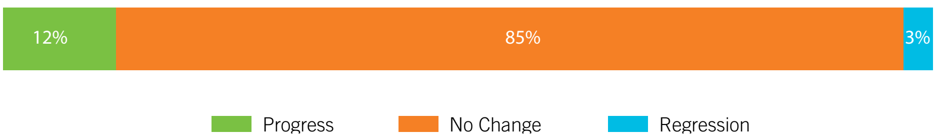
Access to a suitable storage solution has been identified by survey respondents in 2014 as the equal second most important policy enabler for CCS projects. This lends further weight to the argument put forward in Chapter 3 (Large-scale CCS Projects) regarding the importance of early storage characterisation to help accelerate CCS.

In summary, while policy developments to date have been crucial in supporting the business cases for some CCS projects, strong outcomes from upcoming global climate discussions and the translation of these into national and regional policy frameworks is vital for the delivery of a sustainable pipeline of large-scale CCS projects post-2020.

Legal and regulatory perspectives

From a project's perspective, the global legal and regulatory environment remained largely unchanged in the past 12 months (Figure 5.6). This result is particularly marked in the Asia, Americas and Middle East regions where nearly all respondents indicated 'no change' in the regulatory environment. While 'no change' was still the majority response in Europe and Australia, a small number of respondents reported progress in the development of law and regulation (as it impacts their specific circumstances).

Figure 5.6 **Changes to the regulatory environment since 2013**

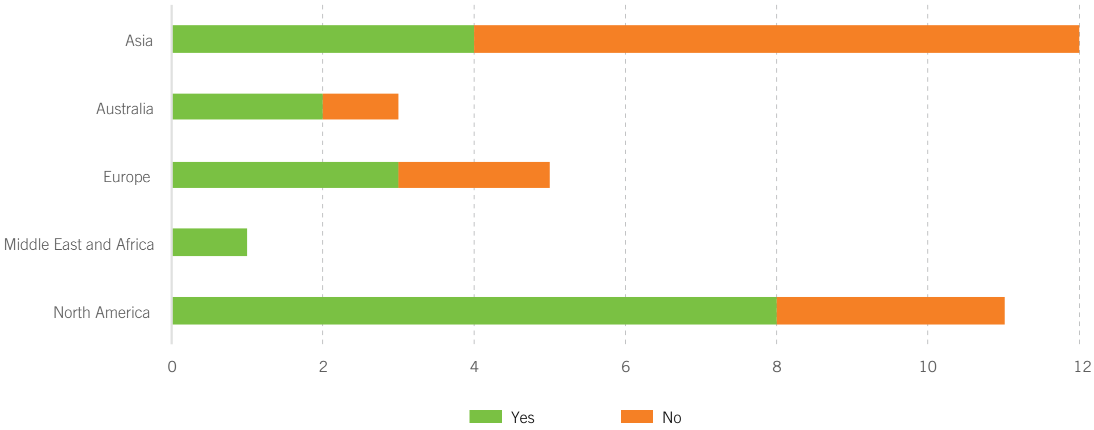


The perception of a largely unchanged regulatory environment has a mixed impact on the ability of projects to proceed through to a final investment decision (Figure 5.7). There is an almost even split between projects who view their regulatory environment as supportive for the purpose of proceeding to a final investment decision and those that do not. This broad observation is consistent with the views expressed in last year's survey, however the 2014 Perceptions Survey suggests that some regional perspectives have altered in the past 12 months.

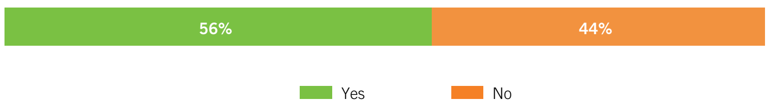
Key observations include:

- Projects where EOR is the main storage type generally indicate they could proceed to a final investment decision under current regulatory regimes. This reaffirms the role of existing legal and regulatory models for supporting the deployment of large-scale CCS projects with an EOR storage option. These projects are centred mainly in the US, the Middle East, with a number of such projects in advanced planning in China.
- In Europe and Australia, where there are well-characterised legal and regulatory regimes for the technology, the majority of respondents expressed a positive view of their regulatory environment. In Europe especially, there has been a change in projects' views, with a higher number of projects now suggesting they would be able to take a final investment decision within the current regulatory environment (compared to the opposite response in the 2013 survey). This may be indicative of increased regulatory activity in some jurisdictions in Europe, although a change in the Perceptions Survey's sample size and composition may also have played a role, with seven European projects either cancelled or put on hold in the last 12 months, nearly all from mainland Europe.
- Responses from Asia indicate that the (non-EOR) projects do not believe they could proceed to a final investment decision under the current legal and regulatory environment. This result is not surprising, considering the nascency of CCS-specific laws and regulation in many parts of the region. While a lack of CCS-specific law and regulation is unlikely to impact those projects with a focus upon EOR, it will be increasingly important to progress the development of legal and regulatory regimes to support those projects considering dedicated geological storage options.

Figure 5.7 **Whether a project can proceed to a final investment decision within the current regulatory requirements**



Number of responses



The annual Perceptions Survey requests projects make an appraisal of a selection of key legal and regulatory principles in their individual jurisdictions. In line with previous years, projects were asked to determine whether each of the principles, identified in the question, had been 'addressed', 'partially addressed' or 'not addressed' in domestic regulatory regimes. The consolidated responses are detailed in Figure 5.8.

Key observations include:

- The 2014 Perceptions Survey (Figure 5.8) again highlights several issues that respondents consider to be largely 'unaddressed' by domestic legal and regulatory regimes: specifically, the following issues have consistently been highlighted by respondents:
  - standards to account for cross-border movement of stored CO_2
  - rules to accommodate CCS projects within market mechanisms, and
  - a range of issues associated with financial security and longer-term liabilities for storage operations.

These issues were consistently emphasised in previous Perceptions Surveys and are common across jurisdictions, suggesting that their resolution remains important for projects globally. Regulators and policymakers, including those that have developed detailed regulatory frameworks, will need to be cognisant that projects continue to regard these issues as 'unaddressed'.

- The 2014 Survey (Figure 5.9) also suggests that, outside of Asia, projects regard many of the remaining items listed, within their domestic regimes, as either entirely 'addressed' or 'partially addressed', including the following:
  - selection and evaluation of a storage site
  - definition of project boundaries
  - identification of property and access rights
  - drafting and implementation of a monitoring plan, and
  - how CCS activities are to be treated under pre-existing planning and permitting regimes.

For a number of these items, the number of projects (outside of Asia) that identified an item as completely 'addressed' significantly outweighs the project respondents that identified the item as 'not addressed'. Notwithstanding that some critical issues for resolution remain common across jurisdictions, this a positive sign of progress in certain parts of the regulatory environment among the early-mover countries in the development and implementation of law and regulation for CCS. The second-generation regulators must now accelerate efforts to lay the legal and regulatory foundations for CCS.

Figure 5.8 **Project appraisals of the domestic regulatory environment – all respondents**

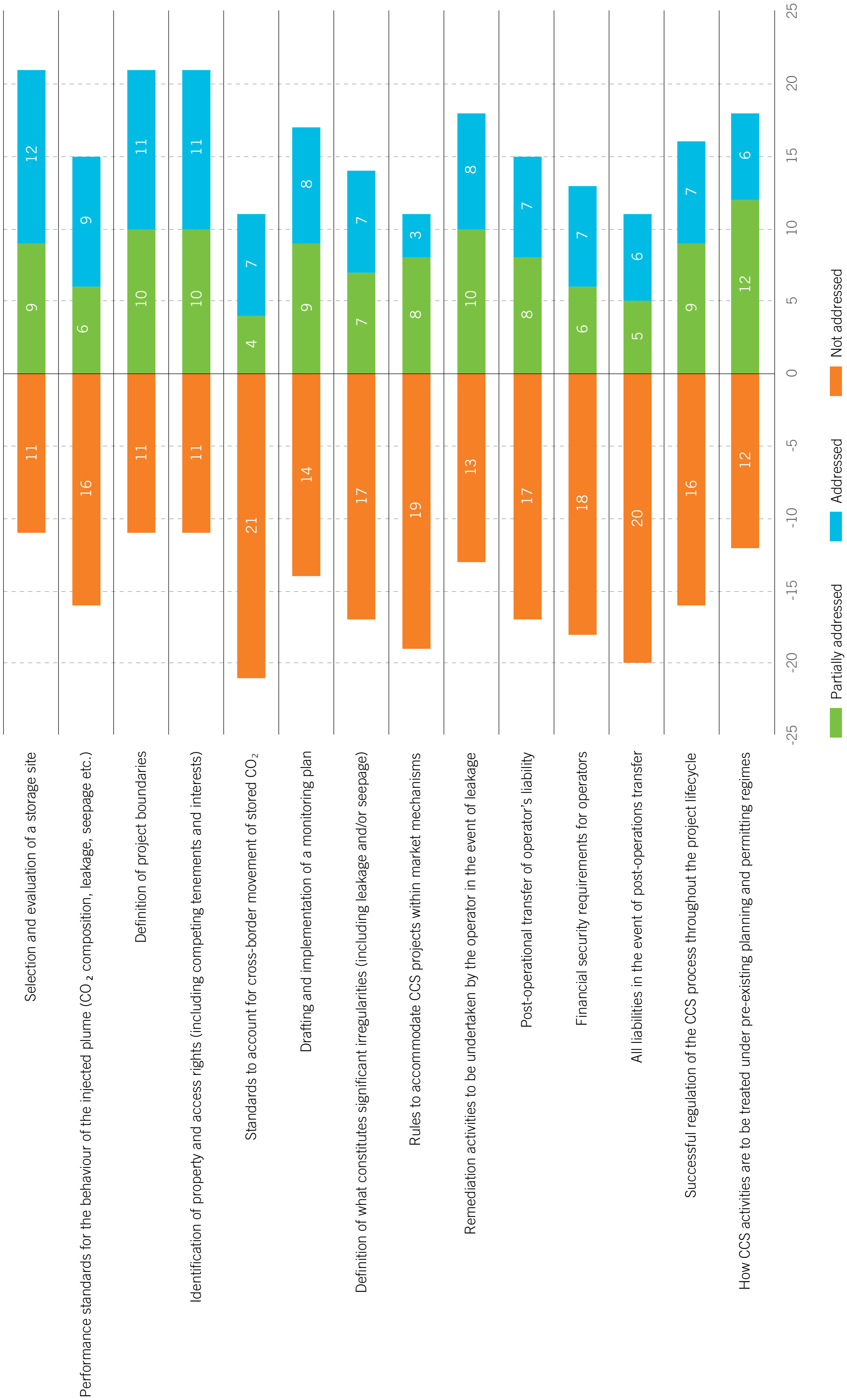
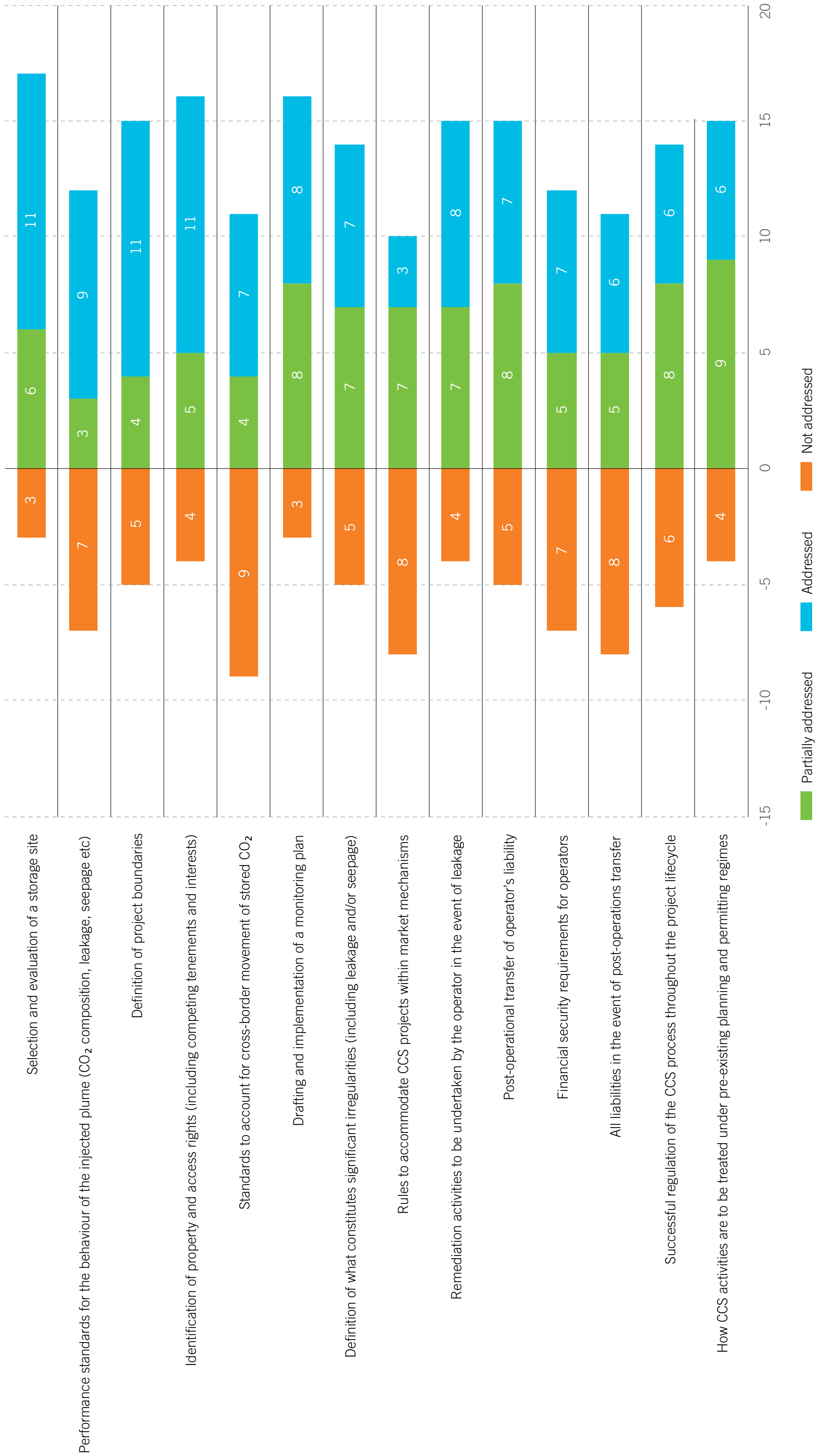


Figure 5.9 **Project appraisals of the domestic regulatory environment – excluding Asian projects**



NOTES

[6]

CCS IN DEVELOPING COUNTRIES

A floating production, storage and offloading (FPSO) installation similar to those utilised by the Petrobras Lula Oil Field CCS Project.

CHAPTER HIGHLIGHTS

- If longer-term climate goals are to be met, the largest deployment of CCS will need to occur in developing countries.

- Three case studies highlight encouraging CCS activity in developing countries at different stages along the CCS Development Lifecycle.

  1. Indonesia is making a promising start; early-mover opportunities have been identified and a high-level CCS Roadmap developed.
  2. Mexico has made good progress on its CCS/CCUS policy development and enabling environment, and is moving towards pilot-scale deployment.
  3. Brazil has enjoyed deployment success with its Petrobras Lula Oil Field CCS Project – the world's first large-scale CCUS offshore project.

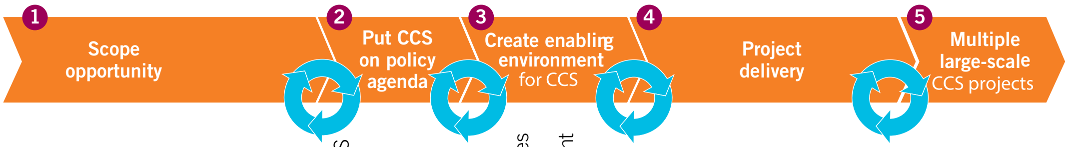
6.1 INTRODUCTION

Developing countries will need to play a critically important role in the longer-term deployment of CCS[1]. The IEA has projected that by 2050, non-OECD countries will need to have captured 70% of the cumulative mass of CO_2 captured and stored between 2015 and 2050 to achieve the emission reductions needed to keep the global temperature increase to within 2ºC[2]. A number of developing countries have engaged in CCS-related activities (Figure 6.1), however much of this activity is at the scoping stage or aimed at developing an enabling environment. Nevertheless, activity has progressed and at least three more developing countries are undertaking CCS-related activities compared to two to three years ago.

[1] For the purposes of this chapter the term 'developing countries' will be used to refer inclusively to all Non-Annex 1 countries under the UNFCCC, with the exception of Korea.

[2] IEA, 2012. *Energy Technology Perspectives 2012: Pathways to a Clean Energy System,* OECD/ IEA, France.

Figure 6.1 **Activity along the CCS Development Lifecycle**[3]



	Identify basic CCS technical potential	Recognise CCS value proposition	Identify key stakeholders	Raise govt and industry awareness of CCS	Stimulate debate	Investigate CCS as a policy option	Build CCS expertise	Establish funding and financial incentives	Develop policy and regulatory environment	Build public engagement expertise	Identify	Engage public	Evaluate	Define	Execute	Operate	Communicate first project success	Sustain interest groups	Create environment for further projects
Algeria	■										■		■	■	■	■	■		
Botswana	■	■	■	■					■										
Brazil	■	■	■	■			■				■	■	■	■	■	■			
Cambodia							■												
China	■	■	■	■		■	■				■		■	■					
Egypt	■		■																
India	■				■														
Indonesia	■	■	■	■		■	■		■		■								
Jordan	■		■	■															
Kenya	■																		
Kosovo	■																		
Lao PDR							■												
Mexico	■	■	■	■	■	■	■		■		■								
Maghreb	■		■																
Malaysia	■		■	■			■		■	■									
Philippines	■		■				■												
South Africa	■	■	■	■	■	■	■		■	■	■	■							
Trinidad and Tobago	■	■	■	■	■	■			■										
Thailand	■	■	■	■			■												
UAE	■	■	■	■		■	■				■	■	■	■	■				
Venezuela		■		■															
Viet Nam	■		■				■												

KEY: ■ Some activity in this space

Despite programs to promote energy efficiency and deploy renewable energy sources, many developing countries will continue to rely on fossil fuels to support their economic growth and electricity generation for decades to come. Many developing countries have significant domestic sources of fossil fuel energy, representing a form of economic and energy security. In order to meet longer-term global climate goals, it is important that developing countries develop strategies consistent with reducing CO_2 emissions at least cost to economic growth. CCS is currently the only technology proven to directly mitigate CO_2 emissions from fossil fuel use at significant scale.

Chapter 3 of this report highlights the status of large-scale CCS projects in China. This chapter focuses on case studies of three other countries that are at different stages along the CCS Development Lifecycle: Indonesia, Mexico and Brazil. These three countries are large emitters of CO_2 – being among the top 20 emitters in the world[4] – and all have substantial fossil energy reserves.

[3] The CCS Development Lifecycle is a conceptual tool developed by the Global CCS Institute to help identify the type of capacity development and pre-investment activities that are relevant for a country, based on their stage of development. It is based on an Institute assessment that draws upon reports, studies and stakeholder engagement. A blue square signifies that some activity has been undertaken in that space; it does not necessarily signify that activity has been concluded in that space.

[4] The World Bank, *World Bank Indicators: CO_2 Emissions (kt)*, accessed September 2014.

The first case study looks at Indonesia which is at the beginning of its CCS journey and is making a promising start. The second case study focuses on Mexico, which is making good progress towards pilot-scale deployment as it capitalises on CCUS policy developments. The final case study is on Brazil which has had CCUS deployment success.

6.2 INDONESIA – A PROMISING START

Indonesia has abundant fossil energy resources (including oil, natural gas and coal) that meet domestic demand and export requirements. Indonesia has approximately 28 billion tonnes of coal reserves, predominantly in Sumatra and Kalimantan (Figure 6.2) and 7.7 billion barrels of oil reserves. The Indonesian Government plans to rapidly expand the domestic use of coal for electricity generation. For the foreseeable future, power generation and industrial use will continue to dominate coal utilisation[5].

Figure 6.2 **Indonesia – locations of Sumatra and Kalimantan**

Policy environment

Indonesia has developed a strategic, multi-year policy and investment program for low-carbon growth, outlined in the *National Action Plan Addressing Climate Change* (2007) and the *Indonesian Climate Change Sectorial Roadmap* (2009). In late 2011, President Susilo Bambang Yudhoyono approved a decree making a commitment to reduce Indonesia's emissions by 26% below unchecked levels by 2020, and by 41% if the country can secure international funding. The 2007 *National Action Plan Addressing Climate Change* specifically recognises CCS as an important mitigation technology for the power, oil and gas and industrial sectors.

[5] Center for Data and Information on Energy and Mineral Resources 2012, *2012 Handbook of energy and economic statistics of Indonesia,* Ministry of Energy and Mineral Resources, Jakarta, viewed 6 October 2014.

The applicability of CCS in Indonesia, given its significant fossil fuel resources and likely storage capacity, was recognised earlier than in many other countries:

- 2005: Sojitz Corporation and Mitsubishi conducted a study on the potential for CCS
- 2007: Total Indonesie investigated CO_2 emissions and the possibility of CO_2 storage in East Kalimantan, and
- 2008: Shell undertook early scoping work into a potential CCS project.

In 2009, an Indonesian CCS Working Group produced a report called *Understanding Carbon Capture and Storage Potential in Indonesia.* This Working Group comprised of LEMIGAS, the British Embassy Jakarta, Kementerian Lingkungan Hidup, Shell International, PT PLN (PERSERO) and the World Energy Council (Komite Nasional Indonesia). The study found that the two regions with the most potential for CCS (linked to EOR potential) were in East Kalimantan and South Sumatra (including the Natuna Sea).

CCS prospects in South Sumatra

In late 2013, the Asian Development Bank (ADB) (supported by the Global CCS Institute) published *Prospects for Carbon Capture and Storage in Southeast Asia*, a report that explores the prospects for CCS in Indonesia, the Philippines, Thailand and Viet Nam. The study identifies major CO_2 sources and storage opportunities within these countries.

The study ranked the major sources of CO_2 emissions in the South Sumatra region based on their suitability for early-mover CCS projects. The highest ranked CO_2 sources were natural gas processing facilities, as they were the most economically viable given CO_2 separation is undertaken as part of their normal operation.

Storage capacity – South Sumatra

The ADB study also looked at potential storage capacity in different geological storage formations – saline reservoirs, oil fields, gas fields and coal bed methane seams. The study indicated that the estimated theoretical storage capacity in South Sumatra is large and there is enough storage capacity to store CO_2 emissions from the identified CO_2 sources in the region for a long time. In addition, other regions in Indonesia are also likely to present storage opportunities.

The storage evaluation revealed that the greatest storage capacity in the region exists in saline reservoirs. However, storage in depleted oil and gas fields, and storage linked to EOR represent more cost effective options in the shorter term. Depleted oil and gas fields also have the most storage data available for assessment.

Indonesia continues to investigate its storage potential and is participating in the Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) CO_2 Storage Mapping Program. The program provides a forum for storage assessment knowledge sharing, and will produce a CO_2 Storage Atlas for the Southeast Asia region. Indonesia is one of the 'case study' countries for this program.

Legal and regulatory

A legal and regulatory analysis was undertaken as part of the ADB study. It was found that while there are no dedicated CCS regulations in Indonesia, like many oil and gas producing countries, aspects of the existing regulatory framework would be applicable or could be adapted to accommodate CCS.

CCS roadmap

The ADB, the Japan International Cooperation Agency (JICA) and Indonesia's Pertamina are collaborating on a CCS feasibility study for a test injection plant in Merbau, South Sumatra.

This activity fits with Indonesia's Roadmap for CCS Pilot Project in Indonesia, 2012-18 (LEMIGAS). In line with good practice, this high-level roadmap is aimed at moving from pilot to demonstration, then commercial-scale projects, passing through a series of 'decision gates'.

Like many countries, a major barrier to CCS deployment in Indonesia is the lack of incentives or legislative requirements to invest in CCS. Nevertheless, this case study has highlighted that Indonesia is creating the right 'enabling environment' for moving forward with a CCS pilot project.

6.3 MEXICO – MAKING GOOD PROGRESS

Mexico is among the most active countries in international climate change discussions, and has an ambitious domestic strategy to manage its own emissions. Mexico is aiming to reduce its emissions by 30% below 'business as usual' by 2020, and by 50% below 2000 levels by 2050.

Policy environment

In April 2012, the Mexican Senate unanimously passed the *General Climate Change Law* which legislates these targets. The law also creates mandatory emissions reporting for the largest sources of greenhouse gas emissions.

The *Special Program on Climate Change* is Mexico's key climate change policy document, outlining the country's adaptation and mitigation strategies. CCUS was recognised as important in the first *2009-12 Special Program on Climate Change.* It has been included more actively in the 2014-18 policy as a part of Mexico's mitigation pathway, through the implementation of pilot projects by their major power utility (Federal Electricity Commission) and national oil and gas company Petróleos Mexicanos (PEMEX) (SEMARNAT, 2014).

In August 2014, the President of Mexico, Enrique Peña-Nieto, promulgated the complete legislative package of the Energy Reform laws, which provides the legal framework that opens up the energy sector to private investment, technology advancement and competition. This reform is expected to help drive technical innovation – also applicable to CCUS development. An important aspect for CCUS within the energy reform is that CCUS has been clearly defined as a clean energy technology. This is the first time CCUS has been given equal status with renewables as a clean energy technology in Mexico.

CCUS Technology Roadmap

The implementation of the pilot projects identified in the *Special Program on Climate Change,* and supporting actions, are outlined in a CCUS-specific policy document – the *CCUS Technology Roadmap in Mexico.* The Roadmap identifies five key stages:

1. incubation
2. public policy
3. planning
4. pilot and demonstration scale projects, including a pilot project in the oil industry, a pilot project in the power generation sector, and a demonstration-scale project, and
5. commercial-scale project (SENER, 2014).

Dr Moisés Dávila, Mexico Ministry of Energy, at an APEC/Global CCS Institute capacity development workshop for university students, geologists and geophysicists and professors, August 2014.

Pilot projects

PEMEX is already undertaking one pilot project using captured CO_2 for EOR. The Federal Electricity Commission is seeking to implement a 2-20 MWe pilot-scale CO_2 capture plant utilising post-combustion technology on a power plant. The World Bank, through a dedicated CCS Trust Fund (funded by the UK Government, the Norwegian Government and the Global CCS Institute), is currently progressing a feasibility study for this project.

Storage

As part of the North American Carbon Atlas Partnership, Mexico has completed the *National Carbon Storage Atlas*. A basin assessment for storing CO_2 in saline reservoirs was undertaken as part of this project. Work is progressing to continue this assessment, particularly around the Burgos and Sabinas Basins in the north-eastern part of the country.

Creating an enabling environment

The World Bank through its CCS Trust Fund is also supporting other 'enabling activities' that feed into the objectives of the *CCUS Technology Roadmap in Mexico.* These include the development of a legal and regulatory and public engagement frameworks.

The legal and regulatory framework development will build on earlier analysis undertaken by the Asia-Pacific Economic Cooperation Energy Working Group (APEC, 2012) through its report on *Permitting Issues Related to Carbon Capture and Storage for Coal-Based Power Plant Projects in Developing APEC Economies.* The next step is a full analysis of what permits and approvals are applicable under Mexico's existing framework.

Mexico has undertaken a number of capacity development activities over the last two to three years to enhance its understanding of CCUS, particularly in the policy and academic sectors. The Mexican Government has worked with organisations such as the Global CCS Institute, APEC and the

IEA to facilitate these capacity development activities. The *CCUS Technology Roadmap in Mexico* continues to recognise the importance of capacity development, including through the development of undergraduate and graduate programs. The Global CCS Institute is pleased to be working with the Mexican Government to facilitate the implementation of these programs. Mexico is making good progress as it works towards CCUS deployment.

6.4 BRAZIL – DEPLOYMENT SUCCESS

Brazil is the largest economy in Latin America and as a result is one of the largest energy consumers in the world. Renewable energy, primarily from hydroelectricity, is an important part of Brazil's primary energy usage. Nevertheless, CO_2 emissions from Brazil's industrial and fuel combustion sectors remain high.

Policy environment

The *2009 National Policy on Climate Change*, established by the Brazilian Federal law 12.187 of 2009 and associated Decree 7.390 of 2010, officially adopts the emission reduction commitments made at COP 15 in Copenhagen in 2009 (Brazil, 2009). This legislation creates a voluntary national greenhouse gas reduction target of between 36.1% and 38.9% of projected emissions by 2020 compared to a 'business as usual' scenario. The main focus of Brazil's climate change policy is on increasing the share of renewable energy, reducing deforestation, and improving energy efficiency. CCS is not a formal part of its mitigation strategy.

CCUS – deployment success

Nevertheless, Brazil has an operational large-scale integrated CCS/CCUS project, which is the only offshore CO_2-EOR project in the world. In June 2013, Brazil's Petrobras and its partners[6] commenced the Lula Oil Field CCS Project, a CO_2 injection project for EOR. The facilities are located approximately 300 kilometres off the coast of Rio de Janeiro.

Oil and gas is being extracted from carbonate reservoirs in the Santos Basin, which lies between 5,000-7,000 metres below sea level. The solution gas contains CO_2 in its composition that varies from 8-15%. In the Lula field, the CO_2 is removed offshore on two floating production, storage and offloading (FPSO) platforms – the Cidade de Angra dos Reis and the Cidade de Paraty[7]. Approximately five million cubic metres of gas can be processed per day on each system. The processed gas, minus the CO_2, is then transported to the Monteiro Lobato Gas Treatment Unit in Caraguatatuba, in São Paulo, via the Lula-Mexilhão gas pipeline.

The captured CO_2 is compressed and re-injected into the producing reservoir for EOR. The sea floor lies 2,100 metres below the FPSO, making this project the deepest CO_2 injection wells currently in operation. It is expected that 0.7 million tonnes of CO_2 will be injected per annum. The produced oil is offloaded into tankers and transported to shore. The CO_2 injected will be monitored.

The Lula Oil Field CCS Project is based on Petrobras' knowledge developed from previous projects. Petrobas has been injecting CO_2 for EOR since 1987. In 2007, Petrobas – in partnership with the French Institute of Petroleum – commenced investigating the behaviour of this injected CO_2 through modelling and testing MMV techniques.

[6] Petrobras' partners in the Lula field development are BG E&P Brasil Ltd., and Petrogal Brasil SA.

[7] A third FPSO – the Cidade de São Paulo – is installed in the Sapinhoã field, another large pre-salt discovery in the Santos Basin (Petrobras is Operator in partnership with Repsol Sinopec Brasil)

By 2020, Petrobras expects to install 20 new floating production systems in the Pre-Salt province (reservoirs in the Santos Basin that are below a very thick salt layer), many of them to include CO_2/gas re-injection for EOR purposes. This activity suggests that Brazil will continue to play an important role in the CCS/CCUS landscape.

CCS in the coal industry

Brazil's coal industry is investing in CCS research to develop its low-emission options. To facilitate this development, the Clean Coal Technology Centre, a part of SATC[8] based in Criciúma, will invest US$6.5 million from 2010-16 in a low-carbon technology centre, including a dedicated CCUS laboratory. The laboratory is able to synthesize sorbents and perform analytical tests at the laboratory and pilot-scale facilities.

Bio-CCS

Exploration of bioenergy and CCS (bio-CCS) continues to be a focus of research in Brazil. The University of Sáo Paulo, through the Brazilian Reference Center on Biomass (CENBIO USP), was a key contributor to the development of a bio-CCS project concept that aspired to access funding under the UNFCCC's Global Environment Facility (GEF). Although the project is currently on hold, CENBIO USP and the Carbon Emission Policy and Regulation Group are continuing to actively investigate the potential for bio-CCS in Brazil (and estimate that the deployment of such technology could contribute up to 5% of the country's emission reductions from energy production).

Capacity development

The Centre of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (CEPAC) is a collaborative effort between Petrobras and the Pontifical Catholic University of Rio Grande do Sul. CEPAC supports Petrobras in CCS research and implementation.

CEPAC is a key CCS capacity development organisation in Brazil, and has hosted a series of workshops on CCS – often supported by international capacity development organisations like the CSLF and the Global CCS Institute. These workshops have focused on developing CCS knowledge within key CCS stakeholders and within the local community.

The Brazilian Coal Association collaborates with the US National Energy Technology Laboratory (NETL) on a CO_2 capture research and development program. A key part of this partnership is the practical training of five Brazilian researchers in areas such as the synthesis of sorbents, process modelling and capture plant design.

Storage assessment

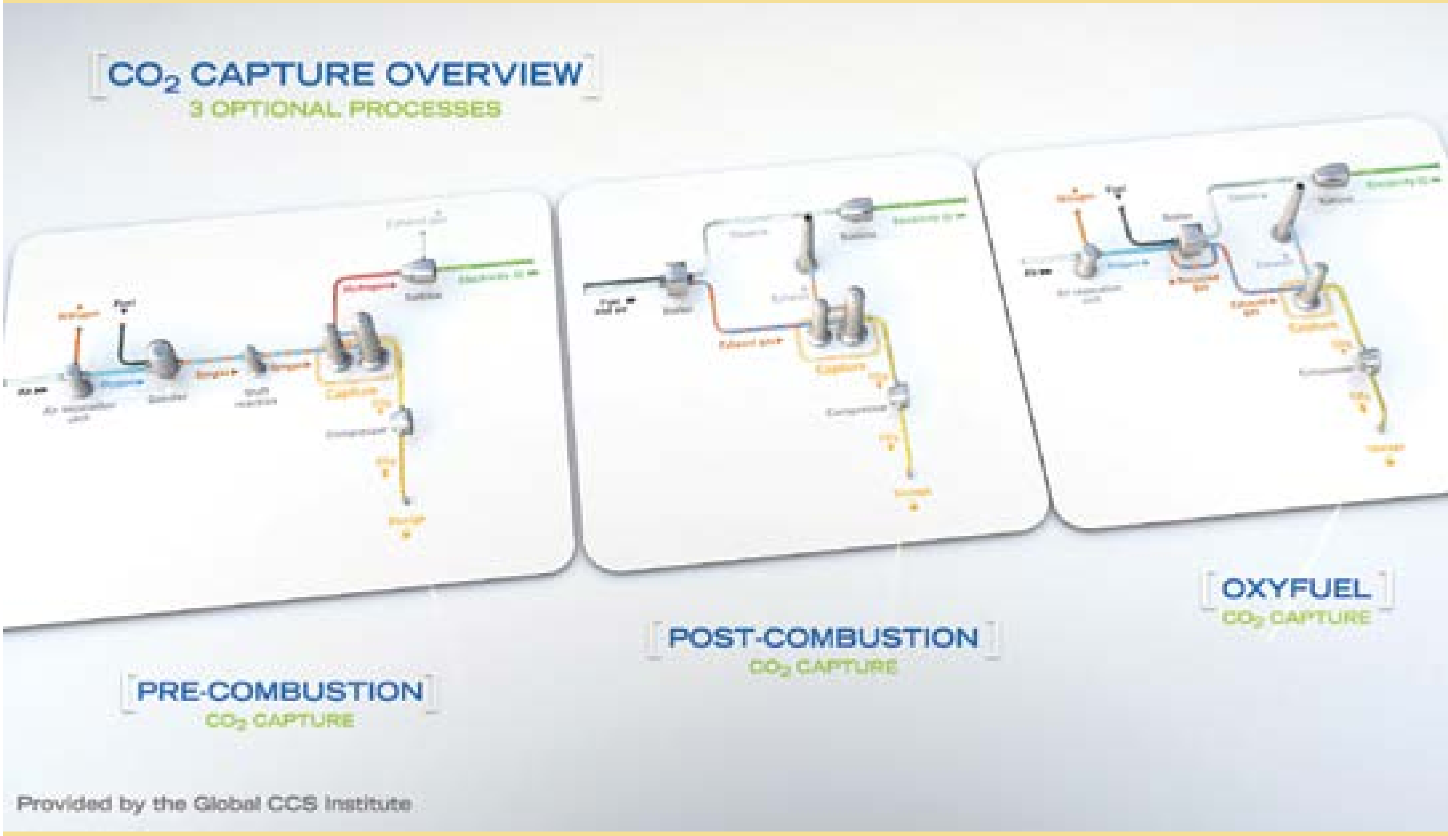
A high-level desktop assessment has been undertaken by CEPAC on the CO_2 storage potential in Brazil, which identifies geological Basins that have good potential for geological storage, both onshore and offshore. The Global CCS Institute is pleased to have supported this work, titled *The Brazilian* CO_2 *Storage Atlas,* which is to be published later in 2014.

[8] SATC is the 'Benevolent Association of the Coal Industry of Santa Catarina', established as an industrial (or technical) school, with primary, secondary, tertiary and research teaching facilities.

NOTES

[7]

CAPTURE



CO_2 CAPTURE OVERVIEW
3 OPTIONAL PROCESSES
PRE-COMBUSTION
CO_2 CAPTURE
POST-COMBUSTION
CO_2 CAPTURE
OXYFUEL
CO_2 CAPTURE
Provided by the Global CCS Institute

CHAPTER HIGHLIGHTS

- Carbon capture technology has progressed significantly, with large-scale CCS power projects moving into operation and construction.
- Cost reduction will continue to be the key focus of technology improvement. CCS proponents have also turned their attention to optimised integration for more cost-effective configurations.
- A portfolio of next generation carbon capture technologies is under development and being tested in pilot-scale facilities. These are being developed globally in several programs with the support of governments, academia and industry.
- The portfolio of R&D capture projects is broad and varied. The most promising technologies have the potential to significantly reduce investment and operating costs in the next 10-20 years.
- International collaboration is key to accelerating the deployment of newer technologies. It is critical that researchers work collaboratively and leverage each other's knowledge resources to achieve better, faster results to produce the future 'game changer' capture technologies that will help accelerate broad CCS deployment.

7.1 INTRODUCTION

The capture element of CCS accounts for the majority of the cost in the CCS chain. In power generation, for example, 70-90% of the overall cost of a large-scale CCS project can be driven by expenses related to the capture and compression process[1]. The current high capital and ongoing operational costs associated with CO_2 capture in new applications (such as power generation) are key targets for improvement looking towards second-generation projects and a stronger business case for CCS/CCUS. This has led to a variety of efforts to reduce costs through:

- successful CCS demonstrations in the power sector and additional industrial applications to gain valuable design, construction and operational experience ('learning by doing')
- continuing R&D effort across a range of capture technologies, higher efficiency power generation cycles and industrial processes, and
- coordinated efforts in knowledge sharing and collaboration along the entire development chain from early laboratory concept to scalable pilot testing and large-scale project demonstrations.

7.2 CARBON CAPTURE TECHNO-ECONOMIC STATUS

A critical mass of projects is essential to acquire the cumulative project experience and lessons learnt for subsequent success in deploying CCS technology. Chapter 3 (Large-scale CCS projects) highlights a potential project portfolio that is expected to provide considerable learnings across a range of capture technologies. Near-term opportunities can be found in two large-scale CCS power

[1] Interagency Task Force on Carbon Capture and Storage 2010, *Report of the Interagency Task Force on Carbon Capture and Storage*, US Department of Energy, Washington, DC, viewed 1 September 2014.

plant projects in North America – the Boundary Dam project in Canada (operational in 2014) and the Kemper County Energy Facility project in the US, which is planned to be operational in 2015. Each of these has gone through a 'learning by doing' process during design and construction, with further experience gathered during the commission, start-up and operational phases. This overall experience can be expected to lead to significant cost reduction and performance improvement applicable to the next 'plant of its kind'. It would be expected that continued improvement and optimisation will be realised as these and other power plants with CCS gain operational experience.

Selecting a first-generation capture technology is usually based on specific project conditions including cost, applicability (including site conditions such as water access), and performance (reliability) of the technology in other applications. In turn, these important first-mover projects can provide the commercial scale demonstration platforms that the next set of demonstrations can benefit from and build upon through this 'learning by doing' process.

An illustrative (and by no means exhaustive) list of various large-scale CCS projects and their selected capture technology is shown below:

Projects in operation in 2014

- Air Products Steam Methane Reformer EOR Project (US): vacuum swing adsorption technology to capture CO_2 from a hydrogen production unit tail gas.
- Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project (Canada): Shell/Cansolv amine-based post-combustion carbon capture technology at an existing coal-fired power plant.

Projects in construction in 2014

- Kemper County Energy Facility (US): new build coal-fired IGCC power plant with pre-combustion carbon capture system using a physical solvent (Selexol).
- Abu Dhabi CCS Project (UAE): amine-based carbon capture technology to capture CO_2 from steam reforming product mixture gases (CO_2, CO, H_2) before sending CO and H_2 to a direct reduced iron process.
- Gorgon Carbon Dioxide Injection Project (Australia): BASF MDEA-based CO_2 separation from natural gas.
- Petra Nova Carbon Capture Project (US): Mitsubishi Heavy Industries' amine-based post-combustion carbon capture technology at an existing coal-fired power plant.

Projects in advanced planning in 2014

- ROAD (Netherlands): Fluor amine-based post-combustion carbon capture technology at a new build coal and biomass-fired plant.
- White Rose CCS Project (UK): oxy-combustion at a new build coal and biomass-fired power plant.
- Peterhead CCS Project (UK): Shell/Cansolv amine-based post-combustion carbon capture technology retrofit at a natural gas combined cycle power station.

The projects listed above clearly demonstrate that carbon capture is an available technology at scale and is, or will soon be, operational in commercial applications for post-combustion, pre-combustion, natural gas processing, oxyfuel, and steel-making processes.

Project examples that highlight the potential knowledge sharing benefits from 'learning by doing' are discussed below.

The Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project

Being a first-of-a-kind (FOAK) project, the experience and lessons learnt from the design, construction and operation of the Boundary Dam project can be applied to further reduce the cost of a similar CCS project at the same site or elsewhere. SaskPower has stated that a capital cost reduction of up to 30% is readily achievable for a twin project,[2] which clearly reinforces the importance of advancing the potential portfolio of projects highlighted in Chapter 3.

From an engineering perspective, Boundary Dam has made numerous innovations and breakthroughs to date on the CO_2 capture design that could come to represent the new state-of-the-art for a post-combustion capture system at a coal-fired station. The following achievements are particularly noteworthy.

- Shell Cansolv reported that the heat requirement of the CO_2 capture unit is around ~2.5 GJ/t CO_2[3]. According to the US DOE, *'plants with CO_2 capture require 24-42 percent more fuel input per megawatt hour'*[4]*,* although the Boundary Dam facility is expected to only require an extra 21% in energy to operate[5].
- The project uses a single system for SO_2 removal and CO_2 separation, which reduces costs by not requiring a separate flue gas desulphurisation (FGD) unit. Heat integration between the two processes minimises steam requirements.
- The amine columns are made of concrete with internal linings, achieving significant saving on raw materials (compared with stainless steel) while maintaining process performance and corrosion tolerance. A rectangular/square design instead of a circular design allows for easier and cheaper on-site construction (among other considerations).
- Prefabrication and modular design saves project time and onsite costs[6]. The prefabricated CO_2 stripper is reported to be one of the largest in the world. The design, fabrication, transportation and installation experience of this large equipment is valuable information to other CCS project developers.
- Developed procedures for commissioning and standard operations by SaskPower, with the contribution of Shell/Cansolv, can be applied to new projects.

The ROAD Project

Although the ROAD project is awaiting a positive final investment decision to progress into construction, the project FEED has been completed, and significant engineering design experiences have been made public[7]. The Institute has worked with the project proponents to produce a series of reports to share this learning experience. Much has been learnt from the evaluation process in terms of the cost-effectiveness and performance of various options, leading to the development of a capture technology selection methodology[8]. This methodology, which defines key selection factors and weighting for project developers, may be applicable to other CCS projects. In addition, the ROAD Integration framework, which aims to integrate the operation of the power station and the capture system, can be readily available to other post-combustion capture projects[9].

[2] Ball, M 2014, *Presentation to University of Kentucky,* viewed 18 September 2014.

[3] Shaw, D 2013, Cansolv at Boundary Dam: Integrated SO_2 and CO_2 Capture for SaskPower – *Presentation at The 7th Annual European Carbon Capture and Storage Conference,* viewed 1 September 2014.

[4] Kemp, J 2012, *REFILE-COLUMN-CO_2 capture cost remains barrier to clean coal: Kemp – Reuters,* 27 November 2012, viewed 1 September 2014.

[5] Monea, M 2013, *Bringing Boundary Dam to the World,* viewed 18 September 2014.

[6] Couturier, G, Di Mello, M 2013, *From Engineering to Procurement to Construction of the Boundary Dam Carbon Capture System, Proceedings of the SaskPower CCS Consortium 2013 Symposium,* viewed 1 September 2014.

[7] Huizeling, E, Van der Weijde, G 2011, *ROAD CCS non-confidential FEED study report,* ROAD-I-Maasvlakte-CCS-Project-C.V., The Netherlands, viewed 1 September 2014.

[8] Van der Weijde, G & Van de Schouw, G 2011, *CO_2 capture technology selection methodology,* viewed 1 September 2014.

[9] Hylkema, H, Read, A, Kombrink, M 2013, *Integration of Capture Plant and Power Plant,* viewed 1 September 2014.

7.3 PROGRESS IN INDUSTRIAL APPLICATIONS

In its 2013 Technology Roadmap for CCS, the IEA stated that *'CCS is not only about electricity generation. Almost half of the CO_2 captured between 2015 and 2050 in the 2DS scenario, is from industrial applications (45%)'.*[10]

The industrial sector encompasses many industries where CO_2 is produced as a by-product of chemical conversion and/or from the combustion of fossil fuels. Industrial sources with high CO_2 concentration gas streams include coal gasification, conversion of coal-to-liquid fuels, and chemical processes making products such as ethanol, ammonia, hydrogen and synthetic methane gas. Carbon capture technologies in some of those industrial applications have been commercially deployed.

Industrial sources with relatively lower CO_2 concentration gas streams include cement production, iron and steel manufacturing, and oil refining, where CCS is particularly important as there is limited potential for substitution of fossil fuels. Implementing CCS in these industries requires the integration of the capture system with an existing, mature process, where the main challenge remains development of customised systems. Therefore, there is a need for more capture pilot testing and demonstration projects in these industrial processes.

Iron and steel

The majority of the CO_2 emitted by the iron and steel sector comes from blast furnaces. The capture technology for this area shows great diversity.

In recent years CO_2 capture concepts for this sector have been investigated and developed by the European Low Impact Steel project (formerly ULCOS). However, many of its R&D activities have been curtailed in light of difficult economic conditions, and currently no pilots or demonstrations are under development.

In Japan, the COURSE 50 Project (see Chapter 4, Notable Projects – Japanese Project Case Studies) aims to develop technologies to enable a 20% reduction in emissions through the application of CCS. Both chemical absorption and physical adsorption technologies are being evaluated.

- **Chemical absorption technology:** Nippon Steel & Sumikin Engineering and the Research Institute of Innovative Technology for the Earth (RITE) are developing ESCAP (Energy Saving CO_2 Absorption Process). This process includes a multi-stage absorbent cooling system to improve absorption kinetics, and integrates the heat released during absorption with the heat required for regeneration[11,12]. A regeneration temperature of 95°C and a regeneration energy of 2.3 GJ/t CO_2 are reported.
- **Physical adsorption technology:** JFE Steel Corporation is evaluating an adsorption-based process (zeolite adsorbent) to capture CO_2 from blast furnaces, and it has constructed a 3 tonne per day facility called the 'Advanced Separation System by Carbon Oxides Adsorption' (ASCOA-3). The system is reported to have achieved a capture energy target of 123 kWh_e/t CO_2 for 33% CO_2 inlet gas[13].

A key project in this sector is the Abu Dhabi CCS Project that is based on a direct reduction iron-making process instead of a blast furnace. The project uses a Steam Methane Reforming (SMR) process to produce H_2 and CO. An amine solvent-based process is used to capture CO_2 from the SMR product gases. The carbon capture process is already embedded in the Direct Reduction Plant. The advantage of this process is that it produces a very pure stream of CO_2 (>98%), so the actual CCS project only involves dehydration and compression of the CO_2 gas. The project is expected to be operational in 2016.

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[10] International Energy Agency 2013, *Technology Roadmap: Carbon Capture and Storage,* viewed 24 September 2014.

[11] Nippon Steel & Sumitomo Metal Corporation 2014, *ESCAP® (Energy Saving CO2 Absorption Process) – Nippon Steel & Sumitomo Metal Corporation Technical Report,* vol. 5, pp. 73-74.

[12] Nippon Steel & Sumitomo Metal Corporation 2013, *Nippon Steel & Sumitomo Metal Corporation Sustainability Report 2013.*

[13] Saima, WH, Mogi, Y, Haraoka, T 2013, *'Development of PSA System for the Recovery of Carbon Dioxide and Carbon Monoxide from Blast Furnace Gas in Steel Works', Energy Procedia,* vol. 37, pp 7152–7159.

Cement

Capture of CO_2 from cement production can be achieved using either post-combustion capture technology or oxy-combustion. The advantage of solvent based post-combustion capture technology is that it can be readily retrofitted to cement kiln flue gases. However, an additional energy source is required in order to reclaim the solvent. A study by the European Cement Research Academy[14] suggests that oxy-combustion may be beneficial for the cement sector, but would require substantial modifications to the cement plant compared to post-combustion capture. More research is needed to better understand the applications of oxy-combustion to a cement plant.

There are currently no large-scale CCS projects in the cement sector, but several pilot-scale tests are being conducted at a cement plant in Brevik, Norway[15]. These tests are aimed at acquiring information on the performance of different post-combustion technologies in different flue gases from cement kilns. Four technologies are to be tested in the first phase, which is expected to run until 2017. Testing under a planned second test phase will depend on the outcomes of current testing. The four technologies (and technology providers) are shown below:

- **Amine technology – Aker Solutions**. An absorption process using an amine solvent would be tested using Aker's mobile test unit (MTU). The CO_2 capture capacity would be approximately 2,000 tonnes per annum.
- **Membrane technology – a consortium led by DNV.GL.** The extent to which this technology will progress will depend on results from a small-scale test unit using gas separation membranes.
- **Solid sorbent technology – RTI International.** The test schedule is the same as that for the membrane technology. A remotely operated bench-scale unit is used to assess sorbent performance and stability.
- **Carbonate looping – Alstom.** Initial pilot testing was started at the University of Stuttgart at a scale of around 200 kWth. Depending on the results of this pilot, a larger version may be tested at Brevik.

An alternative calcium looping process, using an oxy-fired rotary kiln calciner and a fluidised bed carbonator, has been tested in a 1.9 MWth pilot capturing approximately one tonne of CO_2 per hour from the flue gas of the Taiwan Cement Corporation plant. Results will be used to design the next demonstration project, which is expected to be in the range of 10-30 MWth[16].

Oil and gas refining

In the oil and gas refining industry, one large-scale CCS is operational – the Air Products Steam Methane Reformer EOR Project – while two are in construction (the ACTL North West Sturgeon Refinery CO_2 Stream Project and the Quest Project, both in Canada). These are all hydrogen production processes with CO_2 capture.

The feed gas for the Air Products Steam Methane Reformer EOR Project has a relatively high CO_2 concentration that is conducive to the use of vacuum swing adsorption (VSA) capture technology. It is worth noting that VSA suitability for post-combustion capture had been considered limited due to lower feed gas CO_2 concentrations and resulting difficulty of scale up. However, the use of integrated multiple modular VSA units may be an alternative configuration if it appears economically feasible for a particular project. From an operational aspect, the use of solid adsorbents eliminates the added complexity of handling caustic amine solvents.

A large-scale capture demonstration test facility in Norway – the CO_2 Technology Centre Mongstad (TCM) – is located at an industrial complex where it can access both the existing infrastructure and operational knowledge to facilitate technology testing. The demonstration test facility comprises two capture units, one based on an amine solvent and the other on a chilled ammonia capture process. Each of these processes

[14] European Cement Research Academy 2012, *ECRA CCS Project – Report on Phase III,* TR-ECRA-119/2012.

[15] Bjerge, L 2014, *Norcem CO_2 Capture Project – Presentation at The 8th Annual European Carbon Capture and Storage Conference,* viewed 1 September 2014.

[16] Chou, YC 2013, 'Experiments on Calcium Looping Process and 1.9 MWth Pilot Plant Demonstration', *Proceedings of the 2013 Taiwan CCS Forum,* Taipei.

7

CAPTURE

can treat gases from a refinery residue catalytic cracker unit (20,000 tpa CO_2) or from a gas-fired combined heat and power plant (80,000 tpa CO_2). The amine unit is specifically designed to be flexible for testing different solvents. Another facility feature is its availability to accommodate small scale tests of additional technologies. The selection of technologies for small-scale testing is ongoing.

7.4 CARBON CAPTURE COST

The selection and use of a CO_2 capture system must take into account several factors such as emission gas characteristics, technology applicability, economic feasibility, utility availability, water availability and usage, and environmental standards, with a goal of optimising for minimal system cost.

As many cost estimates have been reported around the world, it may be prudent to avoid using an absolute cost number as the only cost index because of differing site and locality sensitivities. The energy penalty also needs to be considered as a key parameter in benchmark comparisons.

The US DOE estimates the current capture cost for the n^{th} plant of CCS deployment for coal-based combustion and gasification systems to be about US$60/t CO_2[17]. For second-generation technologies (defined as those technologies that will be ready for demonstration in the 2020-25 time frame with deployment beginning in 2025) the US DOE has targeted a goal of reducing capture cost to around US$40/t CO_2. Further cost reductions are anticipated from third-generation or 'transformational' technologies, targeted for demonstration in the 2030-35 time frame and initial deployment in 2035[18].

It is unsurprising that the primary focus of R&D for CCS technology continues to emphasise overall system cost reduction. Recent breakthroughs in non-solvent technologies show promise for potential cost reductions (e.g. membrane technology and adsorption technology have been applied to acid gas removal). Where applicable, membrane separation often incurs much smaller capital and operating costs, compared with a typical solvent process, as a result of its operational simplicity[19]. It is recognised that for a membrane system, there is an intrinsic trade-off between the membrane area requirement and energy consumption which is essentially a trade-off between capital and operating cost.

Hybrid technology (membrane + amine) has also been applied in situations where a membrane unit acts as a 'roughing stage' for the initial CO_2 capture. Addition of this stage reduces the footprint of the amine unit, resulting in overall reduction in capital and operational costs[20].

In addition, some reports[21] suggest that a two-step counter-current sweep membrane process combining cryogenic separation may have great potential to capture CO_2 at a cost lower than US$30/t for a post-combustion scenario. A capture cost of US$15/t CO_2 and a regeneration energy of 1.5 GJ/t CO_2 using structured adsorbent technology are reported[22]. Emerging new technologies under development by leading technology suppliers are making solid progress in carbon capture cost reduction. Techno-economic analyses of advanced power cycles with oxygen transport membranes have reported increases in cost of electricity of less than 35% and capture cost of less than US$40/t CO_2[23]. Similar analyses report that amino-silicone solvent technology will also be able to achieve US$40/t CO_2 captured[24]. These and other reported technologies are at various technology readiness levels (TRL), and further development and demonstration are still needed.

[17] The cost is for coal-fired power station and includes capture and compression (2200 psia, 150 bara).

[18] National Energy Technology Laboratory 2013, *Carbon capture: technology program plan,* NETL, Pittsburgh, viewed 1 September 2014.

[19] US EPA, 2008, *Acid Gas Removal Options for Minimizing Methane Emissions - Lessons Learnt from Natural Gas STAR – Presentation at EPA Annual Implementation Workshop,* viewed on 1 September 2014.

[20] Brown, T W G 2009, WG 2009, 'Selecting gas treating technologies', GAS, pp. 13-9.

[21] Merkel, T C, Lin, Q, Wei X, Baker, R 2010, 'Power plant post-combustion carbon dioxide capture: An opportunity for membranes', *Journal of Membrane Science,* vol. 359, no. 1-2, pp. 126-139.

[22] Carbon Capture Journal, *Inventys – CO2 capture for $15 per tonne,* Digital Energy Journal, London.

[23] Kelly, SM 2014, *Praxair's Oxygen Transport Membrane for Oxy-combustion and syngas Applications – 2014 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014;

[24] Wood, B 2014, *Pilot-Scale Silicone Process for Low-cost CO_2 Capture – 2014 NETL CO_2 Capture Technology Meeting.*

7.5

DEVELOPMENT TRENDS IN CO_2 CAPTURE TECHNOLOGIES

CO_2 capture technologies have undergone significant development in the last decade, and today large-scale CCS demonstrations are underway. Industry has gained sufficient experience and confidence to build and operate large-scale capture units. For the next generation of projects, significant cost savings can be realised by:

- optimising the first-generation processes through 'learning by doing', and
- continuing R&D efforts on promising new concepts followed by pilot testing at facility sizes that can provide confidence for technology users to scale up to commercial projects.

Several concepts for capturing CO_2 in industrial processes and power plants are being developed around the world. Also, advancements are being pursued under effective collaborations among governments, academia and industry. For example, the Clean Coal Research Program supported by the US DOE not only funds applied research but also establishes partnerships with industry and laboratories in making available the National Carbon Capture Center (NCCC) for bench-scale and pilot testing. In the Province of Alberta (Canada), The Climate Change and Emissions Management Corporation (CCEMC) receives funds from the government and directs a part of them towards innovative CCS projects.

In Europe, development efforts are supported by the Horizon 2020 Program (former 7th Framework Program), the CLIMIT program in Norway, and funding initiatives from the UK Energy Technology Institute and the UK CCS Research Centre. International collaboration is key in accelerating the commercialisation of capture technologies, not only by bilateral collaborations between countries but also with dedicated international networks like the Test Centre Network that aims to improve global knowledge sharing among various test centres, including the NCCC in the US and TCM in Norway. A network such as this also enables the establishment of accepted global best practices and standards across the industry.

In Australia, CSIRO, CO2CRC and the Peter Cook Centre have a network of facilities for carbon capture development. In China, the CCS Industry Technology Innovation Alliance was established in 2013. It includes the Ministry of Science and Technology (MOST), major oil/gas corporations, power generators, and major R&D organisations and focuses on knowledge/resources sharing and coordination. In Korea, the KCCSA (Korean Carbon Capture and Storage Association) is a focal point for CCS R&D and projects. In Japan, major technology providers have established ad hoc collaborations on carbon capture technology development like the Japanese Knowledge Network

The estimated time to commercialisation of a technology can often be reflected by its Technology Readiness Level (TRL). TRL assessment considers the scale and the conditions under which a certain capture technology has been validated. Typical-first generation technologies that are commercially available and demonstration-ready include: post-combustion amine-based chemical solvent separation; pre-combustion physical solvent separation; and atmospheric pressure oxy-combustion.

Many of the innovative technologies currently in early developmental stages (second- and third-generation) are based on specific physical or chemical mechanisms, the most relevant of which have been included in Table 7.1. Technologies in the table are grouped into four broad TRL categories representative of the development status described in Box 7.1, and consistent with technology scale ranges defined by DOE[25]:

- technology concepts fall within TRL values of 1 to 2
- technologies being tested at the lab/bench-scale are in the TRL range from 2 to 5
- pilot-scale testing covers TRL ranges from 5 to 7, and
- demonstrations and commercial-scale operations fall within TRL ranges from 7 to 9.

[25] National Energy Technology Laboratory 2013, *Carbon capture: technology program plan,* NETL, Pittsburgh, viewed 1 September 2014. Discussions on the usage of TRLs are also included in the Technology and Capture chapters of the 2011 and 2012 editions respectively of the *Global Status of CCS* reports.

The TRL levels assigned in Table 7.1 represent the most advanced systems for each of the listed technology areas. For several of the technology areas, there are specific capture media or processes that are promising but at earlier developmental stages and thus have lower TRLs.

BOX 7.1

TRL categories

	CONCEPT	LAB/BENCH	PILOT	DEMONSTRATION
Test purpose	The idea is demonstrated using theoretical calculations and/or observation of basic principles in laboratory.	The core process components are tested in a lab facility or at bench-scale to demonstrate the working principle.	The main parts are tested in a complete process to conduct performance tests and sensitivity analyses.	The process is implemented at full or reduced scale but is representative of a commercial plant in performance and complexity.
System integration	NA	Testing occurs on single components or integration is limited to main parts of the process.	Main components are integrated to create a complete process. First engineering design takes place.	The process is engineered in the same manner as a commercial project and fully integrated with the flue gas source process.
Test environment	NA	Simulated: Flue gas is artificial, containing only main species relevant for proofing of working principles	Actual: Flue gas may be derived from a new or existing source, conditioned to meet actual characteristics if necessary (e.g. dedicated burner).	Operational: Flue gas is derived from a source representative of the commercial application. The plant operates over the full range of operating conditions.
Correspondence with DOE TRL [26]	1 - 2	2 - 5	5 - 7	7 – 9

Table 7.1 **TRL assessment by capture technology**

TECHNOLOGY	TEST STAGE	TRL
POST-COMBUSTION		
Amine-based solvents	Demo	7-9
Advanced amine-based solvents	Pilot	5-7
Amino-Acid salt solvent	Pilot	5-7
Aqueous Ammonia solvent	Demo	7-9
Precipitating solvents	Lab/Bench	2-5
Two-phase liquid solvents	Lab/Bench	2-5
Catalysed enhanced solvents	Lab/Bench	2-5
Ionic liquids	Lab/Bench	2-5
Temperature or Pressure Swing Adsorption with solid sorbents (TSA/PSA)	Pilot	5-7
Calcium Looping (CaL)	Pilot	5-7
Membranes	Pilot	5-7
Cryogenic CO_2 separation	Lab/Bench	2-5

[26] The four categories are overlapping to account for unavoidable uncertainties of a high-level evaluation.

TECHNOLOGY	TEST STAGE	TRL
PRE-COMBUSTION		
Physical solvents	Demo	7-9
Ionic liquids	Lab/Bench	2-5
Temperature or Pressure Swing Adsorption with solid sorbents (TSA/PSA)	Lab/Bench	2-5
Sorption Enhanced Water Gas Shift (SEWGS)	Pilot	5-7
Sorption Enhanced Reforming (SER)	Pilot	5-7
Water Gas Shift Reactor (WGSR) membranes	Lab/Bench	2-5
Membranes	Pilot	5-7
Cryogenic CO_2 separation	Concept	1-2

OXY-COMBUSTION		
Atmospheric pressure oxy-combustion	Demo	7-9
Ion Transport Membranes (ITM)	Pilot	5-7
Oxygen Transport Membranes (OTM)	Lab/Bench	2-5
Pressurized oxy-combustion	Pilot	5-7
Chemical Looping Combustion (CLC)	Pilot	5-7

Post-combustion

For post-combustion capture, new generation projects are focused on reducing cost through technology development in three general areas: materials, process and equipment[27]. This is true across solvent, sorbent and membrane platforms.

Advanced amine-based solvents in pilot-scale tests have shown considerable performance improvements over standard MEA solvents. Many technology providers have been able to reduce the energy penalty by up to 25%[28]. The typical post-combustion absorption process can be further optimised through process reconfigurations,[29] and/or effective waste heat integration with the power plant[30].

Several promising new solvents or combinations of solvents – like ionic liquids and enzyme enhanced solvents – are progressing through various lab and pilot testing. Worth noting is a biocatalyst-enabled process that has completed more than 1,600 hours of pilot testing at the NCCC[31].

A number of diverse concepts for sorbent-based systems, utilising temperature or pressure swing mechanisms, are also progressing towards piloting. A few small pilot systems up to 1 MWe will be tested at Southern Company's Plant Miller and at the NCCC facility[32,33,34].

[27] Luebke, D 2014, *Transformational Technologies: Approach and Successes – Proceedings of the 2014 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014.

[28] UK CCS Cost Reduction Task Force, 2013, *The Potential for Reducing the Costs of CCS in the UK.*

[29] Le Moullec, Y, Kanniche, M 2011, 'Screening of flowsheet modifications for an efficient monoethanolamine (MEA) based post combustion CO_2 capture', *International Journal of Greenhouse Gas Control,* vol. 5, pp. 727–740.

[30] Wall, T 2014, *Waste Heat Integration with Solvent Process for More Efficient CO_2 Removal from Coal-Fired Flue Gas: 2014 Update – Proceedings of the 2014 NETL CO_2 Capture Technology Meeting*, viewed 19 September 2014.

[31] Black, S 2014, *Field Pilot Results of a Novel Biocatalyst-Enabled Process for CO_2 Capture – Thirteenth Annual Conference on Carbon Capture, Utilization & Storage,* Pittsburgh, viewed 1 September 2014.

[32] Sjostrom, S, Denney, J 2014, *Evaluation of Solid Sorbents as a Retrofit Technology for CO_2 Capture – Proceedings of the 2014 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014.

[33] Krishnan, G (SRI International) 2014, *Pilot-Scale Evaluation of an Advanced Carbon Sorbent-Based Process for Post-Combustion Carbon Capture – Proceedings of the 2014 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014.

[34] Elliott, J 2014, *Sorbent Based Post- Combustion CO_2 Slipstream Testing - Proceedings of the 2014 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014.

Membrane-based capture for post-combustion systems face significant challenges because the CO_2 concentration in flue gas is relatively low, and thus the driving force for membrane separation is small. However, membrane application in multistage or in hybrid and integrated systems shows significant promise and is being actively explored[35]. At the NCCC, a 1 MWe multistage membrane system is undergoing testing[36].

Calcium looping has been tested in small pilots (up to around 2 MWth) and seems ready for further validation at larger scales[37,38]. Cryogenic CO_2 separation has been developed in recent years up to a mobile 50 kWe equivalent unit for real flue gas testing[39].

Pre-combustion

Improvements to first-generation pre-combustion technologies have mainly focused on advancing the performance of physical and chemical absorbing solvents as well as mixtures of the two.

Several new technologies under development include the Ammonium Carbonate-Ammonium Bicarbonate process which is progressing towards pilot testing,[40] and the Sorption Enhanced Reforming (SER) process, combining coal gasification and CO_2 capture into a single system which is undergoing small scale tests in a unit around 200 kWth[41].

Another process, the Sorption Enhanced Water Gas Shift reactor (SEWGS), focuses on integrating the capture process with the Water Gas Shift reaction, which aims to reduce cost by eliminating the number of components and minimising steam consumption in the overall process[42]. A small pilot system has been tested and the technology appears to be ready for validation at larger sizes[43].

In addition, membranes and solids sorbents for pre-combustion are being developed using similar concepts and materials as those applied in post-combustion, but specifically adapted for the high temperatures and treatment gas composition. For example, a mesoporous carbon-based sorbent capture system will be tested on a 0.1 MWe slipstream at the NCCC[44]. Cryogenic CO_2 separation technologies are still at a relatively early stage of development for pre-combustion applications.

Most pre-combustion technologies are applied to solid fuels; although pre-combustion can be applied with natural gas, the higher investment cost to add a methane reformer makes it less attractive compared to coal.

[35] Belaissaoui, B, Favre, E 2013, *Membrane Separation Processes for Post-Combustion Carbon Dioxide Capture: State of the Art and Critical Overview – Oil & Gas Science and Technology – Rev. IFP Energies nouvelles,* viewed 1 September 2014.

[36] Amo,K, H, Z, Huang, I, Kaschemekat, J, Merkel, T, Pande, S, Wei, X, White, S, Seshadri, P, Farzan, H 2014, *Pilot Testing of a Membrane System for Post-Combustion CO_2 Capture – Proceedings of the 2014 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014.

[37] Arias,B, Diego, ME, Abanades, JC, Lorenzo, M, Diaz,L, Martínez,D, Alvarez,J & Sánchez-Biezma, A 2013, *Demonstration of steady state CO_2 capture in a 1.7 MWth calcium looping pilot – International Journal of Greenhouse Gas Control,* vol. 18, pp. 237-245.

[38] Chou, YC 2013, *Experiments on Calcium Looping Process and 1.9 MWth Pilot Plant Demonstration – Proceedings of the 2013 Taiwan CCS Forum,* Industrial Technology Research Institute.

[39] Sustainable Energy Solutions LLC 2014, *Cryogenic Carbon Capture, SES, Utah, United States..*

[40] U.S. DOE/NETL 2013, *Advanced Carbon Dioxide Capture R&D Program: Technology Update. Appendix B.*

[41] Hawthorne, C, Poboss, N, Dieter, H, Gredinger, A, Zieba, M & Scheffknecht, G 2012, *Operation and results of a 200-kWth dual fluidized bed pilot plant gasifier with adsorption-enhanced reforming – Biomass Conversion and Biorefinery,* vol. 2, no. 3, pp. 217-227.

[42] Beavis, R, Forsyth, J, Roberts, E & et al 2013, *A Step-change Sour Shift process for improving the efficiency of IGCC with CCS – Energy Procedia,* vol. 37, pp. 2256– 2264.

[43] Jansen, D, Van Selow, E, Cobden, P & et al 2013, *SEWGS Technology is Now Ready for Scale-up! – Energy Procedia,* vol. 37, pp 2265–2273.

[44] Alptekin, G 2014, *Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System – Proceedings of the 2014 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014.

Oxy-combustion

A complete oxy-combustion system has been retrofitted and operated on at a 30 MWe scale in the Callide pilot project in Australia. China Huazhong University of Science and Technology planned to commission a 35 MWth pilot plant in Hubei Province in 2014. Larger-scale oxy-combustion demonstrations are in the advanced planning stages and include the FutureGen 2.0 Project in the US and the White Rose CCS Project in the UK.

Oxy-combustion involves a number of additional components and changes to the plant configuration relative to air-fired boiler plants, and therefore, requires additional process integration and optimisation considerations. Advanced oxy-combustion focusses on:

- reducing the cost and power duty of the Air Separation Unit (ASU) or oxygen generation unit
- reducing the amount of CO_2 recycle, and
- optimising the CO_2 Purification Unit (CPU).

These advancements represent potential cost reductions in large-scale projects to be deployed in the next 5-10 years.

Transport membranes for oxygen separation offer the potential for further cost reductions when compared to cryogenic separation but are at an early development stage. Pressurised oxy-combustion has been tested at small scale for coal and waste fuels and shows a number of advantages, including higher performance efficiency, compactness of equipment and reduction in CO_2 compression power relative to conventional atmospheric pressure boilers[45]. Chemical Looping Combustion (CLC) is quite revolutionary as it encompasses a total redesign of the steam boiler, with the potential for significant advantages for future power plants. Several small-scale units of up to 140 kWth have been tested[46], and Alstom Power Group has recently conducted over 40 hours of auto-thermal operation using a 3 MWth limestone chemical looping combustion system[47].

CO_2 compression

As CO_2 compression accounts for a significant part of the energy required in a CO_2 capture system, efforts are focused on reducing the cost and parasitic energy associated with the compressor. For example, most existing industrial CO_2 compressors are built in a single-shaft, multistage, intercooled configuration. New state-of-the-art compressor designs use an integrally geared configuration that has higher efficiency[48]. One innovative concept being tested is compression based on the principle of supersonic shock waves such as the Ramgen/Dresser Rand design, which has the advantages of higher compression ratios, improved performance, and reduced size. This approach offers the potential to reduce capital and operating costs[49].

Flexible capture systems

One increasingly important feature of capture systems is designing for flexibility in power plants with CCS. With renewables increasing in prevalence in the energy market, their associated intermittency challenge can be met by several low-carbon energy options. Fossil power plants with CCS systems can meet the need by designing systems capable of adapting to load changes.

[45] Hong, J, Field, R, Gazzino, M & Ghoniem, AF 2010, *Operating pressure dependence of the pressurized oxy-fuel combustion power cycle – Energy,* vol. 35, no.12, pp 5391–5399.

[46] Boot-Handford, MW, Abanades, JC, Anthony, EJ 2014, *Carbon Capture and Storage Update – Energy & Environmental Science,* vol. 7, no.1, pp. 130-189.

[47] Chiu, J 2014, *Alstom's Chemical Looping Technology Program Update – Proceedings of the 2014 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014.

[48] Beaty PJ, Eisele, K, Maceyka, TD & Schwarz, C, 2000, *Integrally Geared API 617 Process Gas Compressors – Proceedings of the 29th Turbo machinery Symposium,* pp. 239 -246.

[49] Koopman, A 2013, *Ramgen Supersonic Shock Wave Ramgen Supersonic Shock Wave Compression Technology – Proceedings of the 2013 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014.

7 CAPTURE

The effect of incorporating a flexible capture system into a power production unit would depend on the generation technology. An option considered for post-combustion solvent-based capture is designing a system to include buffer storage for the lean and rich solvents to maintain steady operations of the CO_2 transport system while load variations are experienced on the plant side[50]. A recent quantitative study has indicated the potential for such systems to reduce operating costs[51], albeit with trade-offs against the introduction of greater complexity and higher capital costs. IGCC plants in general are best run in constant operation as the gasifier is better operated at optimal loads. Therefore they may not be the most suitable option when flexibility is an important requirement.

For oxy-combustion, rapid load variations may require rapid responses of the ASU and the CPU. The ASU itself can be used as a buffer system by producing extra oxygen during low electricity demand and storing it to be reused during higher demand periods. These are interesting concepts that may warrant further investigation as advances are made in future generation capture systems.

Simulation tools development

In addition to actual physical testing, simulation tools have been developed to support and guide the advancement of carbon capture and storage. The National Energy Technology Laboratory (NETL) of the US DOE established a Carbon Capture Simulation Initiative (CCSI) to promote the development of advanced simulation tools for the capture industry. Such simulators could help CCS project proponents to better identify uncertainty, analyse risks and facilitate decision-making[52]. Process System Enterprise's gCCS[53] is an example of a modelling tool recently developed for simulating the whole CCS chain in steady and dynamic mode.

Hybrid capture technologies

Different combinations of separation technologies may be applied to carbon capture. Solvent absorption, sorbent adsorption, membrane, cryogenic and other separation technologies all have their strengths and weaknesses. Some are more effective for high concentration CO_2, while some are better at handling low concentration CO_2. Therefore, depending on the application, a properly integrated and optimised hybrid capture system may prove to be more energy efficient and lower cost than a homogeneous unit. The US DOE included this option in its announced funding of carbon capture innovations in November 2013, which include several hybrid technology development projects[54].

For post-combustion carbon capture, hybrid concepts being investigated include the incorporation of membranes. Among the many solvent-based configurations, there is one that uses a membrane as a pre-treatment stage to enrich the CO_2 in the flue gas, resulting in reduced flue gas flow volume. Due to the higher CO_2 concentration and the reduced flow volume, the downstream solvent unit would have a much smaller footprint and lower energy penalty. However, specific configurations need to be optimised taking into account the characteristics of the site. Engineering and economic trade-offs need to be made between the cost of adding a membrane unit and savings from a smaller solvent system[55,56,57].

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[50] Chalmers, H, Gibbins, J, 2007, *Initial evaluation of the impact of post-combustion capture of carbon dioxide on supercritical pulverised coal power plant part load performance – Fuel,* vol. 86, no. 4, pp. 2109-2113.

[51] Arce, A, Dowell, NM, Shah, N, Vega, LF 2012, *Flexible operation of solvent regeneration systems for CO_2 capture processes using advanced control techniques: Towards operational cost minimisation – International Journal of Greenhouse Gas Control,* vol. 11, pp. 236-250.

[52] National Energy Technology Laboratory 2014, *Carbon Capture Simulation Initiative,* NETL, Pittsburgh, viewed 1 September 2014.

[53] Global CCS Institute 2013, *The Global Status of CCS: 2013,* Melbourne, Australia.

[54] US DOE 2014, *Energy Department Investments in Innovative Carbon Capture Projects,* viewed 1 September 2014.

[55] National Energy Technology Laboratory 2014, *Bench-Scale Development of a Hybrid Membrane-Absorption CO_2 Capture Process,* viewed 1 September 2014.

[56] Okabe, K, Nakamura, M, Mano, H, Teramoto, M, & Yamada, K 2006, *CO_2 separation by membrane/absorption hybrid method - Studies in Surface Science and Catalysis,* vol. 159, pp. 409-412.

[57] Li, X, Remias, JE, Neatthery, JK & Liu, K 2011, *NF/RO faujasite zeolite membrane-ammonia absorption solvent hybrid system for potential post-combustion CO_2 capture application - Journal of Membrane Science,* vol. 366, pp. 220-228.

Another (membrane + solvent) hybrid system example is using a membrane unit to reject water in the rich solvent before it is sent to the stripper for regeneration. This configuration could reduce the significant energy penalty associated with the latent heat of vaporisation of water in solvent regeneration[58].

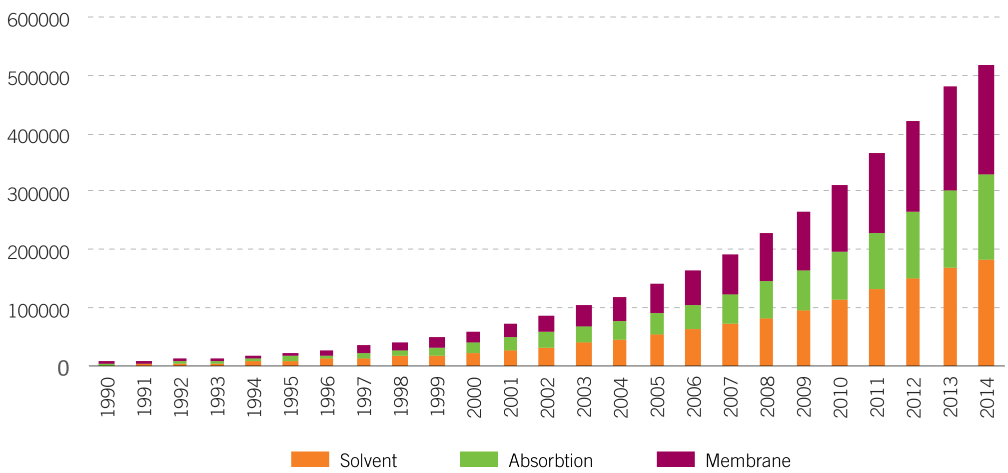
Another alternative hybrid combination is a membrane unit with a cryogenic unit. The combination could be (ambient membrane + cryogenic) or (cryogenic + sub-ambient membrane). Both concepts are being tested at different scales. The ambient membrane hybrid utilises air as a sweep gas to provide driving force while the effluent CO_2 is recycled back to the boiler[59]. The sub-ambient membrane hybrid utilises the high CO_2/N_2 selectivity of a membrane unit at low temperatures[60].

There are also reports about a hybrid system that would include adsorption, cryogenic and membrane units[61]. Such combinations may result in a reduction in capture energy penalty, but a higher equipment cost would be reasonably expected.

What do the statistics tell us?

Since 1990, considerable research has gone into carbon capture technology development globally. A high level measure of the global research effort to date may be taken from the cumulative number of publications and patents[62]. The data clearly show that carbon capture technology R&D has grown significantly since 1990 (Figure 7.1). Publications during the period 2006-10 increased to more than double the number of publications during the period 2001-05, which in turn was almost double the number for the preceding five-year period. The data also reflect the evolution of carbon capture technology research during the last two decades. Solvent technology was the main focus initially relative to sorbent and membrane technologies. Starting in 2000, the global focus of R&D began to shift toward adsorption and membranes for carbon capture. Since 2008, publications in membrane technology have exceeded publications in solvent technology, which may partially reflect increased R&D efforts focused on synthesising new materials for membrane processes. Hybrid technologies, based on a combination of more than one technology, have also gained momentum in the last few years.

Figure 7.1 Carbon capture – cumulative publications by different capture technologies



[58] Li, X, Remias, JE, Liu, K 2010, *A Solvent/Membrane Hybrid Post-combustion CO_2 Capture Process for Existing Coal-Fired Power Plants - Proceedings of 2010 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014.

[59] Amo,K, He, Z, Huang, I, Kaschemekat, J, Merkel, T, Pande, S, Wei, X, White, S, Seshadri, P & Farzan, H 2014, *Pilot Testing of a Membrane System for Post-Combustion CO_2 Capture – Proceedings of the 2014 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014.

[60] Chaubey,T, Kulkarni,S, Hasse, D, Augustine, A & Ma,J 2014, *CO_2 Capture by Cold Membrane Operation with actual Coal-Fired Power Plant Flue Gas - Proceedings of the 2014 NETL CO_2 Capture Technology Meeting,* Pittsburgh, viewed 1 September 2014.

[61] Yuen Fong, JCL, Anderson, C, Hoadley, A 2013, *Optimization of a Hybrid CO_2 Purification Process,* CHEMECA 2013, viewed 1 September 2014.

[62] A variety of different search terms were used in Google Scholar to find the total number of capture-related publications and patents for a particular year.

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The trend identified is similar to one identified in a study published in 2013,[63] which found that the total number of capture related patents filed has been rising steadily, with the US, China and Japan the top three countries for granting carbon capture patents. This study found that the carbon capture technology development portfolio is well balanced – similar numbers of patents have been filed for solvents, sorbents and membranes. A sharp increase in patent filings has been observed since 2005. Another study published in 2011 found that publications in membrane-based carbon capture technology development have been growing since 1991, with rapid growth since 2005[64]. Studies also confirmed that R&D experiences have a positive impact on innovation and commercialisation[65]. Academia is the primary source of publications in general, but corporations are the driving force for patent applications in the area of carbon capture[66].

7.6 INTERNATIONAL KNOWLEDGE SHARING AND COLLABORATION IS VITAL

Although much has been invested in advancing capture technology development over the past decades, it is likely that more could have been achieved faster through broader coordination, collaboration and knowledge sharing. A welcome trend is that there now appears to be a noticeable cultural shift among many technology developers and researchers who recognise the value of cooperation and leveraging resources.

The establishment of the International Test Centre Network, the various regional/national CCS alliances, the China-US and the China-UK joint projects, Carbon Sequestration Leadership Forum (CSLF), and Australia-China Joint Coordination Group on Clean Coal Technology are examples of collaborative mechanisms that help maintain the global momentum in developing advanced capture technologies. Collaboration, cooperation, and coordination in R&D also have the potential to achieve hybridisation and synthesis of innovative ideas and concepts to advance the development of capture technologies at a faster pace and with lower overall development cost.

[63] Li, B, Duan, Y, Leubke, D, Morreale, B 2013, *Advances in CO_2 Capture technology: A patent review – Applied Energy,* vol. 102, pp. 1439-47.

[64] Sun, C, Zheng, X 2011, *Progress of separation of carbon dioxide from gas mixture by Gas separation membrane technology - China Science Paper Online,* 2011.

[65] Van Prooijen,I, *Knowledge creation and commercialisation: the role of R&D experience and R&D network position,* Master Thesis (Utrecht University), November 2013.

[66] Rijnsoever, FJV, Prooijen, IV, Alphen, KV 2014, *Using Organizational Learning to assess micro-incentives of the Triple Helix – The DRUID Society Conference 2014,* DRUID Society, Copenhagen, viewed 1 September 2014.

NOTES

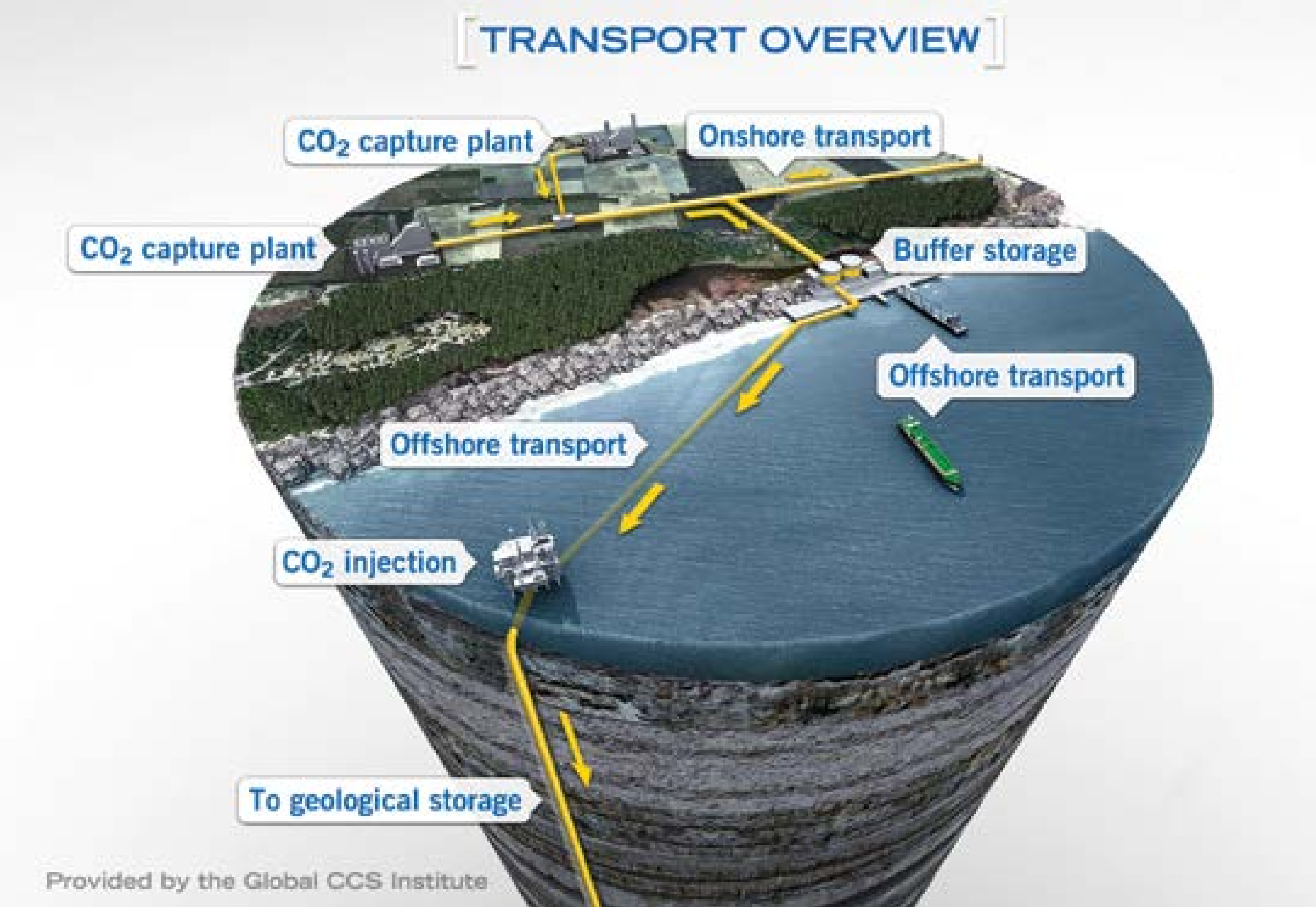
7

CAPTURE

[8]

TRANSPORT

This chapter has been prepared in cooperation with the Energy Pipelines CRC.



CHAPTER HIGHLIGHTS

- The technology for CO_2 pipelines is well established and CO_2 transportation infrastructure continues to be commissioned and built.
- CO_2 pipelines and ships pose no higher risk than is already managed for transporting natural gas and oil.
- International standards are being developed to supplement existing national and international standards and codes.
- Fine-tuning research activities are focussed on designing for variations in CO_2 composition and dispersion modelling.
- Large-scale transport of CO_2 by ship is promising and studies into this are an important part of ongoing R&D efforts.
- The CO_2 transportation infrastructure to be built in the coming 30-40 years (consistent with the IEA's least-cost pathway to halve energy-related CO_2 emissions by 2050) is estimated to be approximately 100 times larger than currently exists.
- Incentives are needed that encourage the efficient design and development of transportation infrastructure through shared hub opportunities that connect multiple CO_2 sources and sinks.

8.1 CO_2 TRANSPORTATION TECHNOLOGY IS WELL ESTABLISHED

Transport of CO_2 by pipelines, trucks, trains, and ships is already a reality, occurring daily in many parts of the world. Pipelines are – and are likely to continue to be – the most common method of transporting the large quantities of CO_2 involved in CCS projects.

In the US alone there are around 6,500 km of onshore CO_2 pipelines, representing over 50 different pipelines, transporting roughly 68 Mtpa of mainly naturally sourced CO_2 for EOR purposes. These pipelines have been operated with an excellent safety record since the first pipelines were laid in the early 1970s. The longest CO_2 pipeline built in the US is the Cortez pipeline at a length of 800 km and with a capacity of over 20 Mtpa. The only offshore CO_2 pipeline in operation is associated with the Snøhvit CO_2 Storage Project in Norway. The pipeline is 153 km long and has been operational since 2008.

Ship transportation can be an alternative option in a number of regions of the world, especially where onshore and near-shore storage locations are not available. Shipment of CO_2 already takes place on a small scale in Europe, where six ships transport food-quality CO_2 from large point sources to coastal distribution terminals. Larger-scale shipment of CO_2, with capacities in the range of 10,000 - 40,000 m^3, is likely to have much in common with the shipment of liquefied petroleum gas (LPG), an area which has developed into a worldwide industry in recent decades.

Transport of smaller volumes of CO_2 has been undertaken by truck and rail for industrial and food grade CO_2 for over 40 years. However, the cost of transportation by truck or train is relatively high per tonne of CO_2 compared to pipelines, so it is unlikely that truck and rail transport will have a significant role in CCS deployment, except for small pilot projects.

8.2

CO_2 TRANSPORTATION – STATUS AND NEW DEVELOPMENTS

Expanding CO_2 pipeline networks in the United States

In the US, the majority of the existing CO_2 pipeline infrastructure was built in the 1980s and 1990s to connect natural CO_2 sources in Colorado (McElmo Dome and Doe Canyon) and New Mexico (Bravo Dome) to the Permian Basin, where the CO_2 is used for EOR. Subsequent development of natural CO_2 supplies at Jackson Dome, Mississippi, and the capture of large amounts of CO_2 at the Shute Creek natural gas processing plant in Wyoming, provided the foundations for the second round of CO_2 pipeline infrastructure growth at the turn of the century in the Gulf Coast and the Rocky Mountain areas[1].

More recently, a series of new large-volume CO_2 pipelines have been commissioned in the Rocky Mountain, Gulf Coast, and Mid-continent areas to allow for new, mainly industrial, sources of CO_2 to be developed and utilised for EOR. Main pipelines that have started operations in recent years include the Green pipeline in the Gulf Coast (2011) and the Greencore pipeline in the Rockies (2013), both owned and operated by Denbury Resources, as well as the Coffeyville to Burbank CO_2 pipeline in Kansas (2013), owned by Chapparal Energy.

Appendix C provides a listing of all major CO_2 pipelines in the US.

According to the US DOE's Office of Fossil Energy, incremental oil production from CO_2-EOR operations is expected to increase significantly from 282,000 barrels per day in 2012 to 615,000 barrels per day in 2020. This growth relies heavily on CO_2 captured from large-scale industrial sources (due to limits on accessible, affordable supplies of naturally occurring CO_2) and the expansion of existing CO_2 transport infrastructure[2].

The majority of large-scale CCS projects in the US either utilise or are planning to utilise existing CO_2 pipeline networks (Table 8.1). Nevertheless, there are still a number of CO_2-EOR projects in Texas, Mississippi, Kansas, Oklahoma and California that utilise or are planning to utilise dedicated CO_2 pipelines (as is also the case for the two projects in Illinois using deep saline aquifers for storage). The FutureGen Alliance, for example, in early 2014 published its proposed pipeline route from the Meredosia Energy Center to a geologic storage area in eastern Morgan County. The proposed 45 km route crosses mostly rural and sparsely populated agricultural lands. Significant effort has been placed on public consultation with landowners who live along the pipeline route[3].

Table 8.1 Pipeline routes and large-scale CCS projects in the US*

CO_2-EOR REGION (STATE)	PROJECT NAME	PROJECT LIFECYCLE STAGE	CAPTURE CAPACITY (CO_2 MTPA)	TRANSPORT LENGTH (KM)**	MAIN PIPELINE NAME	OPERATOR
Permian Basin (Texas, New Mexico)	Val Verde Natural Gas Plants	Operate	1.3	356	Canyon Reef Carriers	Kinder Morgan
	Texas Clean Energy Project	Define	2.7	Not specified	Multiple, incl. Central Basin	Kinder Morgan
	Century Plant	Operate	8.4	>255	Multiple, incl. Bravo, Sheep Mountain, ESTE	Kinder Morgan, Oxy Permian

[1] Kuuskraa, V., Wallace, M., 2014. *CO_2-EOR set for growth as new CO_2 supplies emerge,* Oil and Gas Journal, volume 112, issue-4.

[2] DiPietro, P., 2014. *Near-Term Projections of CO_2 Utilization for Enhanced Oil Recovery,* US DOE/NETL-2014/1648.

[3] FutureGen Alliance (2013). FutureGen 2.0: Frequently Asked Questions—Pipeline website: http://www.futuregenalliance.org/wp-content/uploads/2013/12/FutureGen-FAQ-Pipeline-Dec-2013.pdf

CO_2-EOR REGION (STATE)	PROJECT NAME	PROJECT LIFECYCLE STAGE	CAPTURE CAPACITY (CO_2 MTPA)	TRANSPORT LENGTH (KM)**	MAIN PIPELINE NAME	OPERATOR
Gulf Coast (Mississippi, Texas)	Air Products SMR EOR Project	Operate	1.0	158	Green	Denbury
	Indiana Gasification	Evaluate	5.5	>700	Delta	Denbury
	Mississippi Clean Energy Project	Evaluate	4.0	Not specified	Free State	Denbury
Rocky Mountain (Wyoming, Montana)	Lost Cabin Gas Plant	Operate	0.9	374	Greencore	Denbury
	Shute Creek Gas Processing Facility	Operate	7.0	>400	Multiple, incl. Powder River Basin	Anadarko, ExxonMobil
	Medicine Bow CTL Facility	Define	2.5	Not specified	Greencore	Denbury
	Quintana South Heart Project	Evaluate	2.1	Not specified	Greencore	Denbury
	Riley Ridge Gas Plant	Evaluate	2.5	Not specified	Greencore	Denbury
Dedicated lines (State)						
Texas	Petra Nova Carbon Capture Project	Execute	1.4	132	Not specified	TCV
Mississippi	Kemper County Energy Facility	Execute	3.0	98	Plant gate -Heidelberg	Mississippi Power
Kansas	Coffeyville Gasification Plant	Operate	1.0	110	Coffeyville-Burbank	Chaparral Energy
Oklahoma	Enid Fertilizer CO_2-EOR Project	Operate	0.7	225	Enid-Purdy	Merit Energy
Illinois	Illinois Industrial CCS Project	Execute	1.0	1.6	Not specified	ADM
Illinois	FutureGen 2.0 Project	Define	1.1	45	Not specified	FutureGen Alliance
California	Hydrogen Energy California Project	Define	2.7	5	Not specified	SCS Energy

** Overview of large-scale CCS projects in the US that use or plan to use existing CO_2-EOR pipeline infrastructure (main CO_2 lines) in the Permian Basin, Rocky Mountain and Gulf Coast regions and CCS projects that use or plan to develop 'dedicated lines' between the capture facility and the CO_2 injection site.*

*** Transport length covers both the distance between the CO_2 capture facility and the intersection with the main line plus the estimated distance the CO_2 is transported through the main before it reaches the injection facility.*

**** The Sargas Texas Point Comfort Project has not been included in this table as key CO_2 pipeline information is not specified.*

CO_2 pipelines under construction in Canada

In Canada, procurement of equipment for the 240 km Alberta Carbon Trunk Line (ACTL) has begun. At full capacity, the ACTL will be able to compress and transport up to 14.6 Mtpa of CO_2. The initial supply of CO_2 will come from the Agrium Fertilizer Plant and the North West Sturgeon Refinery for use in EOR at a mature oil field in Central Alberta.

Also in Alberta, pipeline construction for the Quest project started in the latter part of 2013. The project sought landowner input to determine the final route of its dedicated 64 km pipeline that will transport CO_2 from the Scotford Upgrader to the injection location north of the facility.

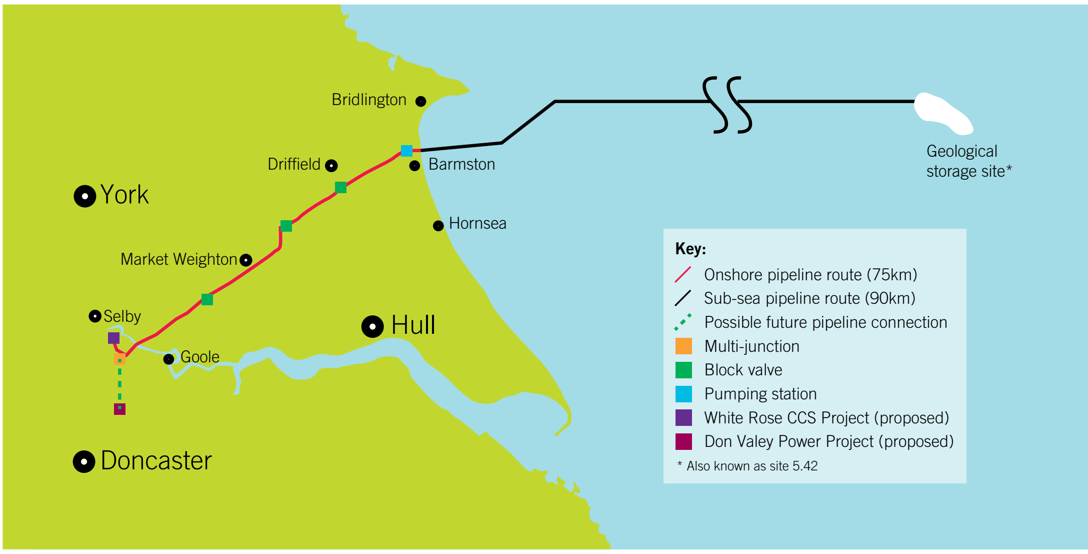
In the neighbouring province of Saskatchewan, Cenovus has completed its 66 km Rafferty pipeline that will transport CO_2 from SaskPower's Boundary Dam project near Estevan to the Weyburn oil unit. The CO_2 from Boundary Dam will supplement Cenovus' current CO_2 supply of around 3 Mtpa from the Great Plains coal gasification (synfuel) plant in Beulah, North Dakota (US), which utilises a dedicated 329 km CO_2 pipeline that crosses the border between the US and Canada.

Offshore pipelines planned for Europe

The last CO_2 pipeline constructed in Europe was in 2008 as part of the Snøhvit CO_2 Storage Project (Norway). This offshore pipeline covers some 153 km linking LNG facilities near Hammerfest in northern Norway to the Snøhvit field under the Barents Sea. At present, four new offshore CO_2 pipelines are being proposed in Europe, three of which are in the UK.

In March 2014, National Grid Carbon completed a fourth series of public consultation for the design and route of their common-user pipeline (Figure 8.1). The pipeline consists of a 75 km onshore section and 90 km subsea section. The White Rose CCS Project at Drax and the Don Valley Power Project near Stainforth would connect into this line through a multi-junction to be constructed close by the proposed power plants. The proposed 'Yorkshire and Humber CCS Cross Country Pipeline' would be built with significant excess capacity to allow other industrial sources of CO_2 to be connected at a later stage[4].

Figure 8.1 Proposed route for Yorkshire and Humber CCS Cross Country Pipeline in the UK



Co-financed by the European Union's European Energy Programme for Recovery.

Source: National Grid Carbon, 2014, *Yorkshire and Humber CCS Project.*

[4] NGC (National Grid Carbon), 2014. *Yorkshire and Humber CCS Project.*

National Grid Carbon is also involved in the Captain Clean Energy Project for which it is proposing to reuse an existing underground high pressure natural gas transmission pipeline (the 'Feeder 10 Pipeline') to supply CO_2 from a new IGCC power plant, to be constructed at the port of Grangemouth in central Scotland, to a new compression station close to the St. Fergus Terminal in the north east of the country. From there, the compressed CO_2 would be transported via an existing (decommissioned) natural gas transmission pipeline, which would be redesigned to supply CO_2 to an offshore saline formation below a depleted gas field in the North Sea off Scotland.

The Peterhead CCS Project proposes to transport the CO_2 captured at the Peterhead power station 100 km offshore to the depleted Goldeneye gas reservoir. A short, new dedicated section of pipeline, approximately 20 km, would be built to connect the Peterhead power station directly to the existing Goldeneye pipeline, which runs from the St Fergus Terminal to the Goldeneye platform.

On mainland Europe, the ROAD project in the Netherlands has already obtained a permit for its 25 km pipeline. The proposed ROAD pipeline system starts at the discharge of the CO_2 compressor located at the Maasvlakte Power Plant 3 (MPP3) site. The captured CO_2 would initially be transported 5 km over land where it crosses Rotterdam's Yangtze Harbour and the Maasgeul waterway. From the coast, the pipeline would run one metre below the seabed of the North Sea, transporting the captured CO_2 to depleted gas reservoirs located approximately 20 km off the coast of Rotterdam[5].

Located within the Maasvlakte section of the Port of Rotterdam's industrial area, the ROAD Project could act as a stepping stone for the realisation of the Rotterdam CO_2 collection network. Such a CO_2 transport infrastructure may be important for the port to maintain competitiveness and attract new investments[6].

New CO_2 pipelines in the Middle East

In Abu Dhabi, a 45 km pipeline will transport CO_2 from the Emirates Steel Plant to the Rumaitha oil field, where the CO_2 will be used for EOR. In the Kingdom of Saudi Arabia, a 70 km pipeline will transport CO_2 from the Hawiyah NGL (natural gas liquids) Plant to the injection site in the Uthmaniyah production unit of the giant Ghawar oil field.

Planned pipelines in Asia

No large CO_2 pipelines have been constructed in Asia to date. The most advanced CCS projects in China are EOR related projects, with two projects looking to deliver CO_2 to the Shengli oil field.

1. The first of these two projects plans to initially transport 0.35 Mtpa of CO_2 from the Sinopec Qilu petrochemical facility in Zibo city (Shandong Province) to the Chunliang/Zhenglizhuang production units of the Shengli oil field. This 75 km pipeline would be designed to allow for a planned increase in throughput to 0.5 Mtpa.
2. The other project involves an 80 km pipeline which would transport CO_2 captured from the Sinopec Shengli power plant to the Xianhe and Chunliang production units of the Shengli oil field.

The Yanchang Integrated CCS Demonstration Project in the Shaanxi Province, which includes two coal-to-chemicals plants, is examining the construction of pipeline infrastructure from the gasification facilities to the Jingbian and Wuqi production units of the Yanchang oil field in the Ordos Basin in central China. Until the pipeline is commissioned, smaller volumes of CO_2 are being transported by truck to the Jingbian producing unit (but this is not economical at larger volumes).

Another project that could be commissioning a new pipeline (of around 35 km) is the PetroChina Jilin Oil Field EOR Project (Phase 2), located in Jilin Province.

[5] ROAD, 2013. *Flow assurance & control philosophy: Special report for the Global Carbon Capture and Storage Institute.*

[6] Rotterdam Climate Initiative (RCI), 2013. *Transport and storage economics of CCS networks in The Netherlands, prepared for the Global CCS Institute.*

A small number of projects in Asia are evaluating transportation of CO_2 to offshore storage locations by ship, including the two Korea CCS projects being studied by the Korean Electric Power Corporation. Chiyoda Corporation of Japan, in partnership with the University of Tokyo, is progressing an R&D study into CO_2 transportation by ship. The study looks at using shuttle-ships with an individual capacity of 3,000 tonnes to transport CO_2 to offshore storage facilities over distances ranging from 200 km to 1,600 km. The study found that CO_2 shipping is technically feasible and the economic feasibility depends on many variables, including locations of the CO_2 source and storage options and alternate transportation methods to service such options[7].

CO_2 transport network developments in Australia

With the Gorgon Carbon Dioxide Injection Project, Australia hosts one of the largest CCS projects in the world in terms of volume of CO_2 captured and stored. However, the transportation distance from the capture facilities to the injection site is very short (7 km) and therefore the planned CO_2 network projects in Victoria and Western Australia are more interesting from a transport perspective.

The CarbonNet Project is investigating the potential for establishing a large-scale CCS network, bringing together multiple CO_2 capture projects in Victoria's Latrobe Valley, transporting CO_2 via a common-use pipeline and injecting it deep into an offshore underground storage formation in the State's Gippsland region. A number of pipeline network designs have been developed for this project.

The South West Hub in Western Australia has conducted engineering studies for the transportation infrastructure required to transport up to 2.5 Mtpa of CO_2 from the proposed Perdaman Chemicals and Fertiliser plant near Collie, via an 80 km pipeline to the proposed storage location near Harvey. The pipeline network could be extended to Kwinana to collect CO_2 from possible new industrial developments and/or retrofits in the area.

Both the CarbonNet and the South West Hub projects are supported by the efforts of Geoscience Australia, through the National CO_2 Infrastructure Project, to create a national, web browser-based pipeline corridor and infrastructure assessment tool for the transport of CO_2. Amongst other things, the tool will enable projects and regulators to analyse potential CO_2 transport networks and source to sink matching by identifying logistical hurdles and best (practical) routes[8].

8.3 BROADENING THE CO_2 TRANSPORT INFRASTRUCTURE

While capture and storage characterisation costs are given much prominence, costs of scaling up transportation infrastructure to enable large-scale deployment of CCS are not insignificant. The estimated CO_2 transportation infrastructure to be built in the coming 30-40 years (consistent with the IEA's least-cost pathway to halve energy-related CO_2 emissions by 2050) is roughly 100 times larger than currently exists.

The costs of CO_2 transportation differ from project to project due to factors such as pipeline length, volumes of CO_2 and the corresponding pipe diameters, cost of labour, and economic life of the infrastructure. Nevertheless, one way to significantly reduce the cost of CCS is to realise economies of scale by sharing a single CO_2 transportation and storage infrastructure system among several operators of separate CO_2 generating plants.

In this sense, it is important to think about CO_2 transport infrastructure through a regional lens (as opposed to point-to-point systems). The development of main CO_2 lines and distribution systems have

[7] Chiyoda, 2013. *Preliminary feasibility study on CO_2 carrier for ship-based CCS: Storage site identification beyond the Japanese continental shelf,* prepared for the Global CCS Institute.

[8] http://www.ga.gov.au/about/what-we-do/projects/energy/co2-infrastructure-project.

proven to be successful in the US in terms of its ability to connect multiple industrial sources of CO_2 to a large number of mature oil fields.

Outside the US, a number of shared CO_2 transportation networks are either in construction or proposed, including Alberta Heartland (Canada), Rotterdam (Netherlands), CarbonNet and South West Hub (Australia), Yorkshire/Humber (UK) and Masdar (Abu Dhabi). These regions share a number of similarities:

- viable 'anchor' projects
- high density of CO_2 emissions
- common policy and regulatory frameworks, and
- high potential of accessible storage volumes.

Given the scale of additional CO_2 transportation infrastructure potentially required in the future, experience is needed outside the US in the planning, designing and implementation of large-scale CO_2 transport networks connecting multiple CO_2 sources and sinks. Governments can play a role here by providing incentives for projects to invest in CCS pipeline network solutions that have the capacity to accommodate future projects with large CO_2 volumes.

8.4 INTERNATIONAL CODES AND STANDARDS FOR CO_2 PIPELINES

The transport of CO_2 by pipeline has been practiced for multiple decades. These pipelines have been operated with an excellent safety record applying internationally adopted standards and codes of practice such as:

- *American Society of Mechanical Engineers* – ASME B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids (2006)
- *Canadian Standards Association* – CSA Z662 Oil and Gas Pipeline Systems (2011)
- *Australian Standards* – AS 2885: Pipelines – Gas and Liquid Petroleum (2012)
- *British Standards/European Norms* – BS EN 14161: Petroleum and natural gas industries – Pipeline transportation systems (2003)
- *British Standards* – BS PD 8010:2004 Code of practice for pipelines
- *International Standard* – ISO 13623 – Petroleum and Gas Industries: Pipeline Transportation Systems (2009)
- *Det Norske Veritas* – DNV OS-F101 – Submarine Pipeline Systems (2007)
- *Det Norske Veritas* – DNV-RP J 202 – Design and Operation of CO_2 Pipelines (2010)

In the US, the US Federal Code of Regulations (Title 149) – Transportation of Hazardous Liquids by Pipeline and the associated ASME standards B31.4 and B31.8 are the main codes which address the transportation of liquids and gases by pipeline respectively. However, these codes have been mainly applied for pipeline systems transporting naturally occurring CO_2 through sparsely populated areas for use in EOR operations. Unlike the recently updated Canadian (CSA Z662) and Australian (AS 2885) standards, the US codes do not specifically address CO_2 transport as part of CCS systems.

A number of European standards are applicable to pipelines transporting CO_2 (Institute of Petroleum code IP6, BS EN 14161, BS PD 8010 and DNV OS-F101), but none of these address anthropogenic CO_2 transported under high pressure as a dense phase fluid[9] or reference CO_2 transport in the context

[9] The term 'dense phase' is a collective term for CO_2 when it is in either the supercritical or liquid states. For most CCS projects economics will drive the need to transport CO_2 in its dense phase since gaseous phase transmission would require larger diameter pipelines for the same mass flow rate.

of CCS. This omission is not an oversight by the standards organisations but merely a reflection of the fact that to date CO_2 has not been transported onshore in this phase in Europe. Hence, standards organisations in Europe are reviewing existing standards in light of planned large-scale CCS projects. In doing so, these standards bodies, as well as those in other parts of the world, keep a close watch on what is happening in relation to the development of an international standard for CO_2 transport.

ISO Standard for CO_2 pipelines

The establishment of an international standard has the potential to harmonise and guide both regulators and operators alike, and improve design, construction, and operation of CO_2 pipelines. In May 2011, the Standards Council of Canada (SCC) submitted a proposal to the ISO to develop internationally agreed standards for CCS. The ISO subsequently agreed to pursue a program of work (ISO/TC 265) that covers the full lifecycle of a CCS system, including CO_2 transportation. Chapter 5 (Policy, legal and regulatory developments) contains an overview of the ISO/TC 265 structure and process.

The working group on CO_2 transport (ISO/TC 265, WG2 'Transportation') is convened by Germany and includes CO_2 transport experts from Australia, the US, Italy, the UK, Spain, France, Norway and Japan. It is one of six working groups convened under ISO/TC 265. The working group on CO_2 transport met for the first time in June 2013 and agreed to develop an international standard that provides requirements and recommendations for the transportation of CO_2 by pipelines.

It was also agreed not to duplicate information that is already covered in existing standards for general transport of fluids in pipelines, such as 'ISO 13623 – Petroleum and Gas Industries: Pipeline Transportation Systems'. It was noted that the majority of the design principles and operating philosophies captured in existing pipeline standards also apply to CO_2 pipelines. Hence, this international standard on pipeline transportation systems is not a standalone document, but is written to be a supplement to other existing pipeline standards.

Over the past year the ISO/TC 265 WG2 has developed a Working Draft of the new international standard on pipeline transportation systems using the industry-based Recommended Practice (DNV-RP J 202 "Design and Operation of CO_2 Pipelines"[10]) as a basis. The new standard intends to consider issues like:

- composition and quality of the CO_2 stream transported by the pipeline system
- thermodynamic behavior of the CO_2 stream in the pipeline system
- specific design issues like wall thickness, corrosion protection, valve placement, and
- health, safety and environmental issues specific to CO_2 transport in the context of CCS.

The next steps in the ISO Standard development process include a review of the Working Draft by all members of the ISO/TC 265 (including members of the other five working groups). After agreement on the contents of this so called 'Committee Draft', a Draft International Standard is prepared and translated for comment by all ISO member bodies. Once these comments have been incorporated, a Final Draft International Standard is distributed to ISO members for voting. It will take a minimum of two years to get the current Working Draft of the International Standard for CO_2 pipeline transport to a Final Draft. Once finalised, this new international standard might become mandatory if adopted by a government and/or becomes part of business contracts.

[10] DNV-RP J 202 is a result of the first phase of a Joint Industry Project 'CO_2 PipeTrans-phase 1' aimed at updating the DNV-OS-F101 code for offshore transportation of CO_2.

8.5 ADVANCING CO_2 TRANSPORT TECHNOLOGY

Current CO_2 pipeline infrastructure has an excellent safety and performance record that results from accumulated experience, proven design methodologies and established codes and regulation. Nevertheless, efforts to build on this knowledge base and increase know-how on pipeline integrity and management in support of large-scale CCS projects, and to provide input into relevant pipeline standards, are ongoing across the globe.

A detailed overview of the major collaborative CO_2 transport R&D programs is provided in Appendix D. A number of these R&D initiatives have been completed in 2014. Key R&D areas covered in these programs included:

- system dynamics and operating regimes
- CO_2 stream composition, and
- dispersion modelling.

System dynamics and operating regimes

In terms of system dynamics, a CO_2 pipeline has different operating modes to consider at both ends. The CO_2 injection facility may require the CO_2 to be delivered in a constant flow, whereas the CO_2 capture unit at the power station may at times operate on a cyclic (intermittent) basis. The requirements of the storage formation, such as flow, pressure and temperature, set the downstream conditions. The emitter, on the other hand, provides another set of upstream conditions in terms of flow rates, ramp-rates, temperature, pressure and composition[11]. These conditions from both the storage and capture facilities need to be taken into account (and optimised) in the design of CO_2 transport infrastructure; in particular when considering CO_2 transport networks connecting multiple CO_2 sources and sinks.

In 2013, the Global CCS Institute commissioned a study to gain insight into the operating systems for the CO_2 stream of an integrated CCS project in steady state, shutdown and start-up conditions. The Flow Assurance Study (FAS) conducted for the ROAD project and described in this study has shown that filling a reservoir of (very) low pressure to an end pressure of 300 bar is possible, but one has to study the behaviour of the CO_2 stream in all its thermo-dynamic aspects within the parameters set by the physical configuration of the CCS system[12].

CO_2 stream composition

In pipeline design it is important to account for the impact of impurities or by-products (such as methane, water, nitrogen and hydrogen) on the physical properties of the CO_2 stream, particularly those properties that affect flow assurance, corrosion, and fracture control. Because of the susceptibility of most pipelines to corrosion due to the presence of carbonic acid, one of the most critical factors to control is the water content of the CO_2 stream entering the pipeline (as CO_2 reacts with water to form carbonic acid). In addition, the presence of other additional 'acid gases' such as hydrogen sulphide (H_2S), and nitrogen and sulphur oxide (NOx and SOx) compounds needs to be considered in the design as they arise from the capture process[13].

The composition of the CO_2 mixture may also impact the decompression behaviour of the CO_2 in the event of a pipeline leak (e.g. as the result of corrosion or mechanical damage). This is important as the characteristics of dense phase CO_2 during decompression can encourage the transition from

[11] Watt, J., 2010. *Lessons from the US: experience in carbon dioxide pipelines,* The Australian Pipeliner, October 2010.

[12] ROAD, *ibid.*

[13] Mohitpour, M., Seevan, P., Botros, K., Rothwell, B., Ennis, C., 2012. *Pipeline transportation of carbon dioxide containing impurities,* ASME Press, New York, US.

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leak to break and the onset of running fracture propagation[14]. This phenomenon is not new and current CO_2 pipelines are provisioned against long fracture propagation via regularly spaced crack arrestors and/or using steel pipes with very high toughness. However, a better understanding of the decompression behaviour of such impurity carrying CO_2 mixtures is beneficial as it may result in better fracture arrest design tools.

Dispersion modelling

The consequences and hazards of a CO_2 release are different from a natural gas pipeline. Existing work concerning the failure of gas pipelines suggests that impacts from CO_2 pipeline accidents may be less severe than with natural gas pipelines[15]. Nevertheless, data about the controlled release and dispersion of large amounts of CO_2 is limited. Therefore, the full-scale CO_2 release tests that are part of several active R&D programs will provide valuable data, which will help validate and improve existing CO_2 release and dispersion models. Accurate modelling at an early stage for the purposes of safety cases and route definition is key to efficient, practical and safe design of CO_2 pipelines.

8.6 OUTLOOK

Transport of CO_2 by various means is a reality, occurring daily in many parts of the world. New infrastructure for the transportation of CO_2 continues to be commissioned and built. Nevertheless, the scale of investment in CO_2 transportation infrastructure required to support large-scale deployment of CCS will be considerable. In order to realise such investments and facilitate the development of new CO_2 transportation infrastructure, there are some key areas that require continuing attention, including:

1. global sharing of pipeline design, construction, and operation experience through industry best practice guidelines and international standards
2. further R&D and demonstration of large-scale CO_2 shipping concepts, and
3. incentives that encourage the efficient design and development of transportation infrastructure through shared hub opportunities that connect multiple CO_2 sources and sinks.

[14] Spinelli, C.M., Demofonti, G., 2011. *Technical challenges facing the transport of anthropogenic CO_2 by pipeline for carbon capture and storage purposes,* 6th Pipeline Technology Conference, 2011.

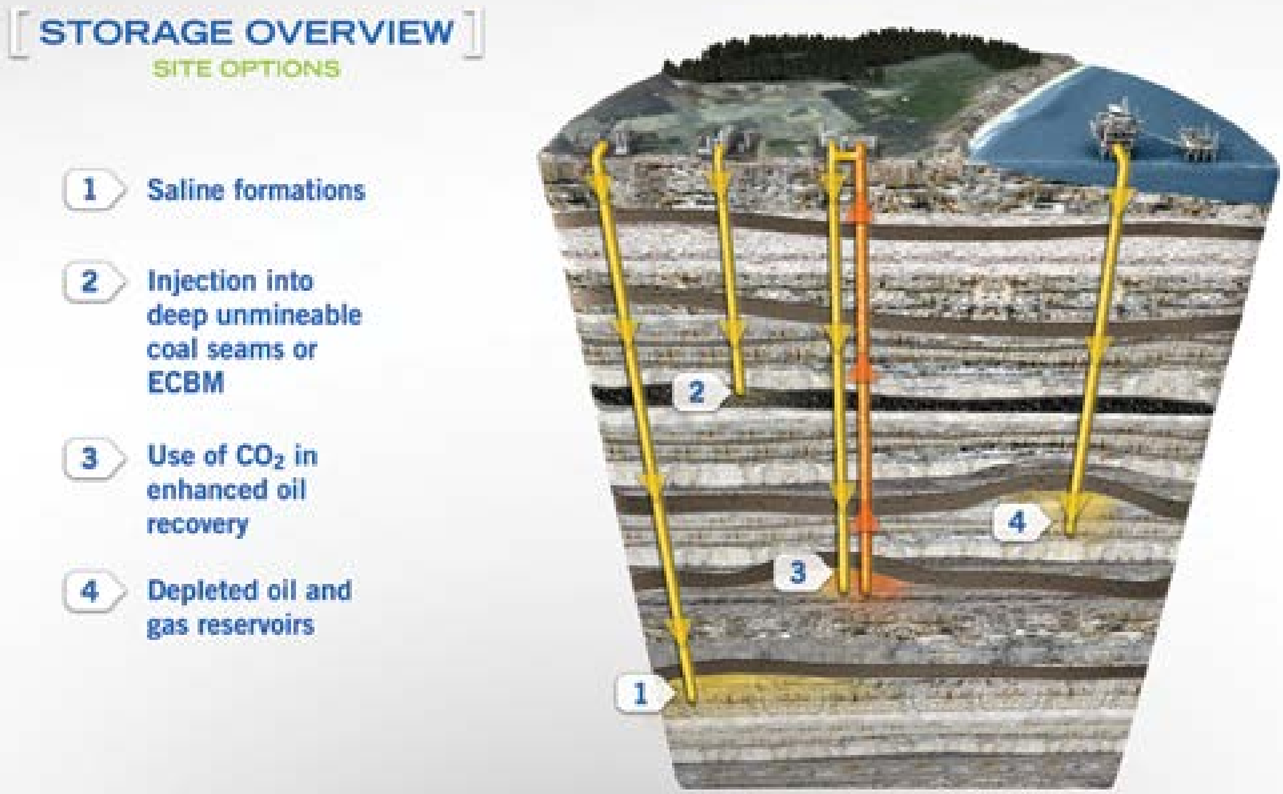
[15] McGillivray, A., Wilday, J., 2009. *Comparison of risks from carbon dioxide and natural gas pipelines,* Health and Safety Laboratory, UK.

NOTES

[9]

STORAGE

This chapter has been prepared in cooperation with DNV GL



CHAPTER HIGHLIGHTS

- There are no technical barriers preventing the implementation of commercial CO_2 geological storage as part of the global deployment of CCS.
- Secure geological storage sites can be selected, characterised, operated and completed (closed) based on well-established risk management principles gained from decades of relevant industry experience.
- A variety of existing monitoring technologies have been successfully deployed at pilot and commercial-scale projects, demonstrating our ability to measure, monitor and verify CO_2 injected into the subsurface.
- Operational experience from commercial-scale projects, and learnings from R&D programs, have informed a range of best practice guidance documents that are currently being integrated into international standards for CO_2 geological storage.
- Current R&D activities continue to improve our ability to monitor and quantify the CO_2 injected into the subsurface

9.1 DEVELOPMENT OF SECURE GEOLOGICAL STORAGE RESOURCES

Established CO_2 storage risk management practices employed by industry today can allow secure and reliable full-scale deployment of CCS. Industrial operators have made major strides over the past 20 years to decrease costs of CO_2 capture and minimise risks, actual and perceived, associated with CO_2 storage.

Today, over 150 sites are injecting CO_2 underground, either for enhanced oil recovery (EOR) or explicitly for the purpose of CO_2 storage. EOR represents the majority of these sites and began over 40 years ago in the US. The first dedicated geological CO_2 storage project started in 1996 near the Sleipner offshore gas field in Norway. The underground storage of natural gas for seasonal and strategic reserve also has several similarities to CO_2 storage and has a long track record that can inform risk management of CO_2 storage sites.

CO_2 storage projects worldwide are benefiting from the extensive experience from operations in oil and gas exploration by implementing best practices in management of risk and uncertainty. This chapter illustrates the sound risk management processes established for CO_2 storage.

The primary risk management approach for CO_2 storage is to minimise the possibility of future leakage by selecting sites with the most suitable geological characteristics and to maintain sufficient integrity for all wellbores in contact with the storage formation.

The monitoring system is an integral part of the risk management plan and is applicable at:

- the site selection phase by defining baseline condition
- the operations phase by taking measurements during injection, interpreting signals and forward modelling based on observations, and
- the closure phase when the site is monitored to ensure the CO_2 remains underground.

The CCS community, consisting of industry, academia, research organisations and investors, has come together in many different forums to develop best practice guidance documents based on CO_2 injection activities. The lessons learnt from pilot, demonstration and large-scale injection are well documented and publically available for stakeholders. Investment by government and research organisations in R&D has led to better understanding of storage mechanisms, CO_2 plume behaviour and migration pathways. Application of CCS technology at demonstration sites has improved well design, plume/reservoir modelling capabilities, and monitoring techniques to effectively track the injected CO_2.

Moreover, collaborative programs such as the US DOE/NETL Regional Carbon Sequestration Partnerships and the EU CCS Demonstration Projects Network foster knowledge sharing and enable projects to learn from improved CO_2 injection practices to accelerate deployment around the globe.

This chapter examines how to take advantage of this experience in order to commercialise storage activity without compromising the secure and reliable track record that has been established to date. To this end:

- Section 9.2 introduces the principles of risk management and describes how they may be applied to underground storage of CO_2.
- Section 9.3 illustrates how monitoring of a CO_2 site is an integral part of risk management over the entire lifecycle of a CO_2 storage project from site selection to operations to post-injection stages. Existing project examples are used to demonstrate the wide array of monitoring technology that has been successfully implemented around the world.
- Section 9.4 provides an overview of best practice guidance documents for secure and sustainable CO_2 injection and storage, highlighting key similarities and differences.
- Finally, section 9.5 describes a number of CO_2 storage projects from around the world that illustrate how the risk management principles described in the preceding sections have been applied during the various lifecycle stages.

9.2 RISK MANAGEMENT PRINCIPLES

The headline risks for CO_2 storage may be summarised by the following two questions.

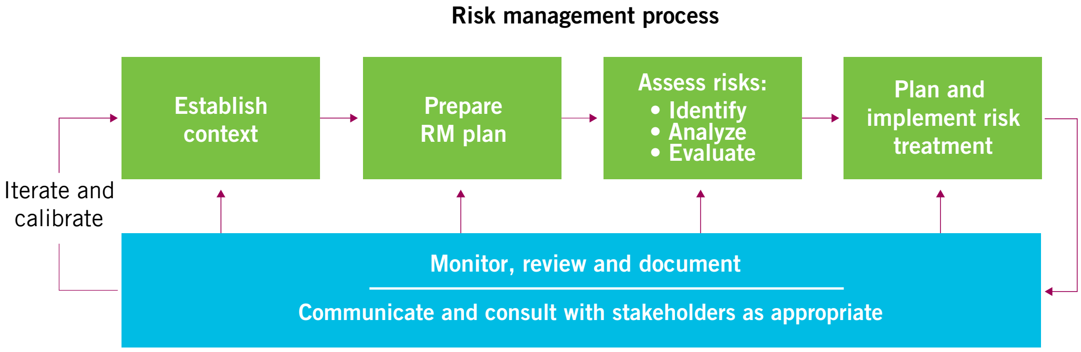
1. *Where does the CO_2 go when injected underground?*
2. *What ensures that the injected CO_2 remains securely stored?*

These two questions will be addressed in this section under the headings of storage capacity and integrity respectively, representing two key requirements for a CO_2 storage site that should be addressed by risk management.

Risk management is a long established practice across a wide variety of industrial sectors that helps society seize new opportunities without taking undue risks. For CO_2 storage projects, the risk management process starts early during the site screening phase and is relevant throughout the project lifecycle.

Best practice within the risk management field has been summarised by the International Organization for Standardization (ISO) document ISO-31000, which represents a starting point for applying risk management principles to CO_2 storage. Figure 9.1 illustrates a risk management work-flow that has been adapted for CO_2 storage by the Canadian Standards Authority from the ISO-31000 standard.

Figure 9.1 Schematic of risk management process for CO_2 geological storage projects from the Canadian Standards Association (CSA) standard (Z741-12)



The first step in Figure 9.1 is to establish the context for the opportunities and risks to be managed in a CO_2 storage project. Unwanted consequences are arranged into categories that typically include human safety, environmental impact, groundwater protection, economic loss and organisational reputation. Benefits include the reduction of CO_2 emissions, but may also include economic incentives or local environmental benefits as well.

The second step in Figure 9.1 is to prepare a Risk Management Plan for the CO_2 storage project in question that describes how this generic work-flow will be applied in practice. This document should include a description of the organisational procedures and practices to be used in managing risk, the schedule for performing risk assessments and a description of what distinguishes an acceptable risk from an unacceptable risk.

The third step is risk assessment. This includes three distinct activities that are scoped and defined in the Risk Management Plan.

1. Risk identification seeks to acknowledge stakeholders' concerns without prior judgement and identifies all types of threat or uncertainty irrespective of their perceived likelihood or magnitude.
2. Risk analysis is the science-based analysis of these risks to determine their probability or frequency of occurrence and an estimate of their potential impact. The timescales of interest for CO_2 storage sites span everything from days, weeks and months up to hundreds or even thousands of years.
3. The final step is to measure or evaluate the risks that have been identified against acceptance criteria that have been agreed with, for example, local populations, national regulators, insurance companies and investors.

Once a CO_2 storage site comes into operation, the site operator and the regulatory authorities will follow the progress of the site in a similar manner to an oil field. This could include, but is not limited to, monitoring of well pressure and flow rates, or geophysical surveys to observe how the reservoir is responding. Such monitoring results are then compared with predictions made in advance. These activities are represented by the lowermost box in Figure 9.1 and almost always generate new knowledge and a better understanding of a reservoir in operation. Such learnings should be used to calibrate expectations towards a CO_2 storage site and incorporated into the next iteration of the risk management cycle.

Storage capacity – where does the CO_2 go when injected underground?

CO_2 is stored in the same kind of porous rock that oil or gas flow out of when a well is drilled into a reservoir. The amount of fluid that a rock can hold varies with rock type and depth below the surface of the earth; the pore spaces within a rock that contain fluids are normally too small to be visible to the naked eye, but exist between individual sand grains or within microscopic cracks. In order for CO_2 or any fluid to flow through a particular strata of rock the pore spaces need to be interlinked, making the rock permeable as well as porous. Rocks that exhibit these dual properties of porosity and permeability are suitable for storing or extracting fluids and are known as reservoirs.

At the depth of a typical storage reservoir, CO_2 has a density similar to light oil, which means large amounts of CO_2 will occupy a fraction of the space in reservoirs deep underground compared to their gaseous volume on the surface.

The movement of injected CO_2 is controlled by a number of reservoir characteristics, including the dip of the reservoir, the spatial variation of porosity and permeability, and in response to engineered aspects such as the number and orientation of the injection wells and injection rates.

Accurate predictive modelling of CO_2 injection can be undertaken based on characterisation data, experience from CO_2 injection projects and established knowledge from hydrogeology and reservoir engineering. Monitoring data collected during injection can then be used to calibrate and refine models and to demonstrate confidence in the long-term performance and integrity of storage.

Storage integrity – what ensures that the injected CO_2 remains securely stored?

An analogy can again be drawn to hydrocarbons, whereby the same kind of rocks that keep oil and gas underground can be expected to trap CO_2 over geological timescales. These are called cap rocks or seals, which lie over reservoir rocks and keep buoyant fluids in place by virtue of very low permeability characteristics. Carbon dioxide is trapped naturally in this manner in a large number of gas fields, sometimes as a minor associated gas or sometimes as the principal component.

Naturally-occurring CO_2 reservoirs trapped below cap rocks have been used as the primary source of CO_2 for EOR in the US, providing up to 45 Mtpa[1]. These fields, along with industrial analogues such as acid gas injection and natural gas storage fields, have been extensively studied to learn more about the natural storage integrity that they exhibit.

De-risking investment in CCS

The risk management workflow shown in Figure 9.1 is similar to the risk management workflow used to de-risk investments in the upstream oil and gas sector. Risk assessment is performed prior to each investment milestone in a project in order to measure the degree of confidence that the project developer has in forecast costs and performance.

The same principles have been applied to large-scale CCS storage projects such as those described in Section 9.5. Regardless of whether a project is at the design phase, approaching a final investment decision or nearing completion, no new investment is undertaken until the risk management process is able to document that the project objectives will be met with a degree of certainty appropriate to the level of investment, and in a secure and environmentally responsible manner.

9.3 MONITORING OF CO_2 STORAGE SITES

Monitoring is a key component of the risk management process for a CO_2 storage site, as can be seen from the lowermost box in Figure 9.1. Monitoring enables a project operator to measure the progress of the CO_2 injection program and provides reassurance to stakeholders that the project is developing as expected.

Certain parameters will be important to monitor for all CO_2 storage projects, such as the rate at which CO_2 is flowing into the reservoir and at what pressure. Other parameters are selected on a case-by-case basis to best represent the interests of the project operator or other stakeholders. For example,

[1] Advanced Resources International, 2010. *Optimization of CO_2 Storage in CO_2 Enhanced Oil Recovery Projects,* Prepared for Department of Energy and Climate Change, UK.

the Sleipner CO_2 Storage Project in Norway has updated the geophysical map of CO_2 in the reservoir a number of times over the years using 3D seismic surveys. The frequency of repeat seismic surveys for other projects may be more limited during the project lifetime and, in some cases, 3D seismic may not be amongst the monitoring techniques employed.

The physical parameters that a project will measure, monitor and verify will depend on the monitoring objectives for that project. By way of example, monitoring objectives can include:

- documenting the quantity of CO_2 injected into a given reservoir
- demonstrating that CO_2 flows into a reservoir as expected
- early indication of CO_2 migration to other parts of the reservoir
- early indication of CO_2 migration to other rock strata or the surface, and
- measurement of flow parameters that may be used to update geological models.

Measurement, monitoring and verification (MMV)

A monitoring system designed for a site-specific geological profile is a tool used to judge the effectiveness of CO_2 injection and to trigger responses to unexpected events as required.

Through experience gained from real projects such as those described in section 9.5, the significance of integrating storage characterisation, monitoring design, regular evaluation and frequent performance reviews to actively monitor the site and manage responses to irregularities is well understood by both operators and regulators.

A key learning from R&D and current large-scale CCS projects is that a monitoring plan is site specific and it is therefore difficult to provide a standard template for monitoring activities. However, several standards and guidance documents on CO_2 storage provide a comprehensive methodology to ensure that the MMV plans for different projects, by different developers, have a consistent and recognisable structure, based on similar scope and objectives.

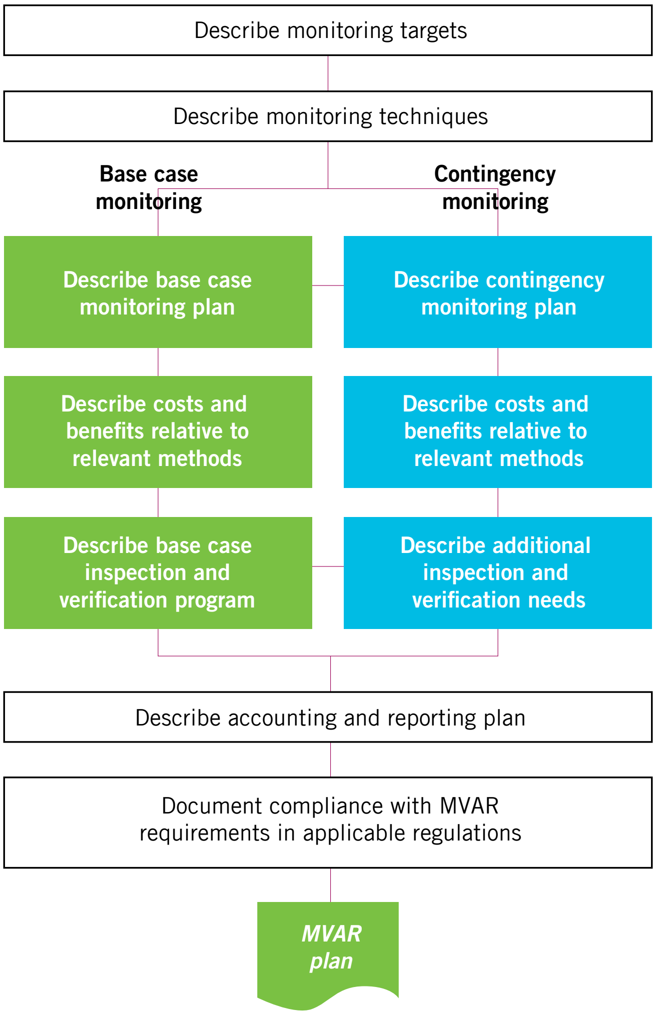
In terms of MMV planning, the current best practice guidance documents recommend a risk-based, fit-for-purpose approach. The MMV plan should describe how the progress towards the performance targets will be measured and how other monitoring objectives will be met.

The MMV plan should include a comprehensive baseline monitoring plan, to understand the background conditions at the site within the atmosphere, biosphere, hydrosphere and geosphere:

- the operator should identify the key monitoring tasks during injection and post-injection
- identify monitoring technologies that would link to each monitoring task, and
- the MMV plan differentiates between a base case monitoring program and a contingency monitoring program.

Figure 9.2 summarises the workflow adopted by most CO_2 storage sites today:

Figure 9.2 Work flow for preparation of the MVAR (Monitoring, Verification, Accounting and Reporting) plan from the CO_2QUALSTORE guideline



A base case monitoring program is designed with the assumption that the site will perform as expected. However, a contingency monitoring plan consists of possible corrective measures in case of anomalies in site performance. A contingency monitoring plan will consist of:

- additional monitoring that may be required in the event that the CO_2 plume is not behaving as predicted, and
- additional monitoring activities and potential remediation options in the event of an unexpected leak of CO_2 or other reservoir fluids.

Performance targets

Monitoring objectives are measured using performance targets, providing a set of assessment criteria by which the project can be evaluated. These can be set in terms of injectivity, containment, service reliability or other parameters that assess storage performance.

Key performance indicators are used to track the efficiency of the CO_2 storage Risk Management Plan or, more precisely, are based on the ability to monitor the behaviour of CO_2 in the subsurface and identify any anomalies from predicted behaviour. Monitoring also provides assurance that the CO_2 is not leaking from the storage site.

Performance targets allow the operator to bring focus to the essential aspects of a project to develop a cost-effective monitoring plan, tailored to the unique characteristics of each site.

A site operator will generally align performance targets with current regulations and involve regulators, insurers, the public and other stakeholders. Regulators are increasingly using key performance targets as an instrument to reach consensus on conditions for granting relevant permits. This can include operational requirements to demonstrate safe operations and project development, and site closure requirements in accordance with previously agreed performance targets.

Performance targets should be specific, measurable and time bound. Examples of key performance targets for MMV include:

- achieving a minimum duration/coverage of baseline characterisation data before the injection phase
- verifying injected CO_2 and affected fluids are adequately contained in the storage complex during injection and post-injection phases
- continuing surveillance of the hydrosphere, biosphere and atmosphere, sufficient to demonstrate storage integrity through the absence of any significant impacts to the environment from project activities, and
- verifying that actual storage performance conforms to predicted storage performance within an acceptable range of uncertainty.

Monitoring technologies in practice

Investment in research on monitoring technologies and their application in planned or operational projects has helped build confidence in the ability to monitor CO_2 behaviour in the reservoir and demonstrate storage integrity. Many of the technologies currently deployed are standard monitoring techniques used in oil and gas field exploration and development. Table 9.1 below illustrates how projects have deployed different technologies to meet their monitoring targets.

Investment in research programs, demonstration and pilot projects have contributed to rapid advancements in effective monitoring techniques for CO_2 storage. The IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project in Canada, for example, is one of largest projects to measure, monitor and verify CO_2 injection, providing a field laboratory for testing and practical implementation of CO_2 monitoring techniques. Learnings from various demonstration and pilot projects are widely available in best practice guidance documents, for example, the US DOE/NETL *Best Practice Manual on MMV of CO_2 stored in deep geologic formations*.

Several ongoing research programs are focusing on improved ability to quantify injected CO_2 using, for example, chemical and isotopic data. The EU funded ECO_2 project on sub-sea CO_2 storage is testing novel techniques to detect and quantify fluxes of formation fluids, including CO_2 from storage sites, and develop appropriate and effective monitoring strategies. The project is conducting field work at natural CO_2 seeps that serve as analogues for potential CO_2 leaks from storage sites and comparing it with models and laboratory experiments.

The Quantifying and Monitoring potential Ecosystem impact of Geological Carbon Storage (QICS) project, funded by the Natural Environmental Research Council of the UK, has also led to improved understanding of the nature and probability of unexpected leakage and is testing methods of monitoring for leakages offshore.

Table 9.1 Examples of monitoring technologies and their application

Examples of Monitoring technologies and their typical application	Monitor CO_2 in reservoir	Storage Integrity	Monitor surface conditions	Demonstrated at commercial scale	Demonstrated at pilot/R&D scale	Example project where the technology has been applied
Time-lapse (4D) seismic	✓	✓	-	✓	✓	Sleipner, Norway
Satellite measurement of ground surface (InSAR)	✓	✓	-	✓	✓	In Salah, Algeria
Microseismic	✓	✓	-	✓	✓	Weyburn, Canada
Pressure in injection well	✓	✓	-	✓	✓	Snøhvit, Norway
Geochemical soil analysis	-	-	✓	✓	✓	Weyburn, Canada
Chemical tracers	✓	✓	✓	✓	✓	In Salah, Algeria
Cross-hole Electrical Resistance Tomography	✓	✓	-	-	✓	Ketzin, Germany
Downhole pressure and temperature	✓	✓	-	-	✓	Aquistore, Canada
Surface gravimetry	✓	-	-	-	✓	Sleipner, Norway
Downhole fluid chemistry	✓	✓	-	-	✓	Otway, Australia
Vertical seismic profiling	✓	✓	-	-	✓	Decatur, US

Appendix E provides greater detail on how the various monitoring technologies are deployed.

9.4

STANDARDS AND BEST PRACTICE GUIDELINES FOR CO_2 STORAGE

Best practice guidelines

Since 2007 there have been numerous publications released covering the best practices, guidelines and standards for CO_2 storage. These documents assist with the introduction of new technologies by providing guidance to manage risks, design and costs. They help to:

- bridge the gap between regulatory development and technology advancement at a time when public expectations around secure storage are high
- harmonise the various methodologies being applied worldwide, and
- capture the results and share knowledge and experience from industrial and research projects.

These documents range from very topic-specific manuals to those covering the entire CCS chain. There is a wide range in the level of detail that is covered, with some offering concept overviews, some offering highly detailed discussions and others providing the technical operations, calculations and geologic parameters that went into real-world projects. Together, these various publications provide a comprehensive database of best practices necessary for CO_2 storage. A comprehensive *review of the then existing best practice manuals for storage and regulation* was prepared for the Institute by the CO2CRC in 2011 and is found at *http://www.globalccsinstitute.com/publications/review-existing-best-practice-manuals-carbon-dioxide-storage-and-regulation.*

A summary of some key guidelines is shown in Table 9.2. One key feature of all these guidelines is that the risk management principles described in section 9.2 provide a basis for developing secure and reliable storage sites. For example, all the documents listed in Table 9.2 describe a site specific, risk-based approach to designing a CO_2 storage monitoring plan.

Table 9.2 **Comparison of Guidance Documents**

Existing Standards and Guidance documents	Audience	Overview of existing monitoring technology	Guidance on selecting/ evaluating monitoring techniques	Guidance for verification of MMV plan	Lists performance criteria	Guidance on development and execution of MMV plan	Regulatory monitoring requirement
NETL BPM Monitoring, Verification and Accounting of CO_2 Stored in Deep Geologic formations (2012 update)	Technical	✓	✓	-	-	Detailed	For US
DNV GL Recommended Practice on CO_2 Storage (DNV- RP-J-203)	Technical	-	✓	✓	✓	Detailed	Generic
CSA Z741-12 Geological Storage of Carbon Dioxide	Technical	-	✓	✓	✓	Detailed	Generic
European Union Directive 2009/31/EC Guidance Documents	Technical and non-technical	✓	✓	-	✓	Detailed	For EU member states
Regulatory Framework Assessment, Alberta, Canada	Technical and non-technical	-	-	-	✓	Basic	For Canada

Standards under development

Best practice guidelines represent the first stage of standardisation within a new industry and this is also the case for CCS. The second stage is to compile best practices into formal standards and this process was initiated for CCS through the ISO/TC 265 in 2012, as described in Chapter 5 (Policy, Legal and Regulatory Developments).

The aim of international standardisation is to facilitate exchange of goods and services through the elimination of technical barriers to trade. For CCS, there are many aspects that are internationally diverse and touch on all aspects of current and future demand, therefore ISO standards for CCS technology will help to provide a common basis for commercial and business transactions.

Six working groups have been established to draft standards covering capture, transportation, storage, quantification and verification, EOR, and cross-cutting issues. The CCS standard developed by the Canadian Standards Association (CSA) Z741-12 will be the seed document for the new international standard for CO_2 storage.

9.5 OPERATIONAL EXPERIENCE

The project examples described in this section illustrate effective risk management for CO_2 site development and operations. Although all the required technologies are already available 'off-the-shelf' to develop a large number of secure CO_2 geological storage sites, the communities of geosciences and subsurface engineering are still producing considerable innovations to both improve overall solutions and to widen the range of suitable storage sites.

These case studies, along with focused research in the area of CO_2 storage and monitoring, weave a narrative of both practical problem-solving at real injection sites and a more ambitious vision of CCS providing the desired reductions in CO_2 emissions. A continuous decrease in risks and costs is expected as seen for other carbon management technologies.

Sleipner CO_2 Storage Project

The Sleipner CO_2 storage site has been in operation since 1996 to permanently store reservoir CO_2 separated from natural gas production at the Sleipner platform in the central North Sea (Norwegian sector). The CO_2 is re-injected into the Utsira sandstone formation that lies at a depth of approximately 900m, and above the Sleipner gas field.

The operation has been heavily monitored from the outset to maximise scientific learning from the project in addition to verifying CO_2 containment and storage reservoir performance. Injection takes place through a single well and has been proceeding at a rate of approximately one million tonnes of CO_2 per annum, yielding a total stored mass of 15 million tonnes in 2014.

The principal monitoring tool at Sleipner has been repeated seismic surveys, which show the CO_2 dispersing through multiple internal layers within the Utsira sandstone formation and being trapped by the thick overlying shale and mudstones. Recent monitoring results have confirmed that the distribution of CO_2 in the Utsira sandstone matches prior predictions.

Weyburn-Midale

Anthropogenic CO_2 sourced from a gasification plant in North Dakota has been used for CO_2-EOR operations in the Weyburn oil field of southern Saskatchewan, Canada since 2000, and in the neighbouring Midale oilfield since 2005. Well in excess of 25 million tonnes of CO_2 is now stored in these oilfields as a result of CO_2-EOR operations. Weyburn is also to receive additional CO_2 supplies from the Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project.

The large-scale injection of CO_2 at Weyburn provided the basis for the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project (WMP), which yielded over a decade of detailed research under the management of the Petroleum Technology Research Centre (PTRC). Storage research included geological characterisation, predictive modelling, geochemical and geophysical monitoring, wellbore integrity and risk assessment.

Highlights of the research program included the successful demonstration of 3D surface seismic surveys as an effective monitoring tool to track CO_2 distribution within the storage reservoir, and the use of extensive geochemical monitoring to demonstrate the integrity of the CO_2-EOR operations. The project also established strong outreach links with the local community and other stakeholders. The WMP culminated in the publication of a Best Practices Manual in 2012 and provided the basis for a public outreach publication, *'What Happens When CO_2 is Stored Underground?'*, produced by the PTRC for the Institute in 2014 (see also Chapter 10, Public Engagement).

Snøhvit CO_2 Storage Project

The Snøhvit project began in 2008 and injects about 700 thousand tonnes of CO_2 annually in a deep geological layer of porous sandstone called the Tubåen formation. An expansive monitoring plan was developed for the site to study CO_2 behaviour in the reservoir. The injection well is subject to seismic surveys and continuous pressure monitoring. Three repeated seismic surveys have been carried out.

Soon after the start of injection, monitoring identified maximum pressure limits were being reached earlier than expected. Mitigating actions were enacted over a two-year period including[2]:

[2] Hansen, O. R., 2013. *The history of injection and storing 1 MT CO_2 in the Fluvial Tubåen Formation,* Energy Procedia 37, 3565-3573.

- injection of small volumes of solvents to dissolve suspected clogging deposits of salt and other materials in the formation near the injection wellbore; and
- re-perforation in a slightly shallower zone.

The long-term solution was to drill a new CO_2 injection well in a different formation (Stø formation) in the reservoir, a few kilometres from the original injection wellbore. This experience illustrates some of the risk management flexibility that lies in the technical concept of CO_2 storage in saline aquifers and a need in the Risk Management Plan to include a contingency scenario for additional wells in case the reservoir is not performing as expected.

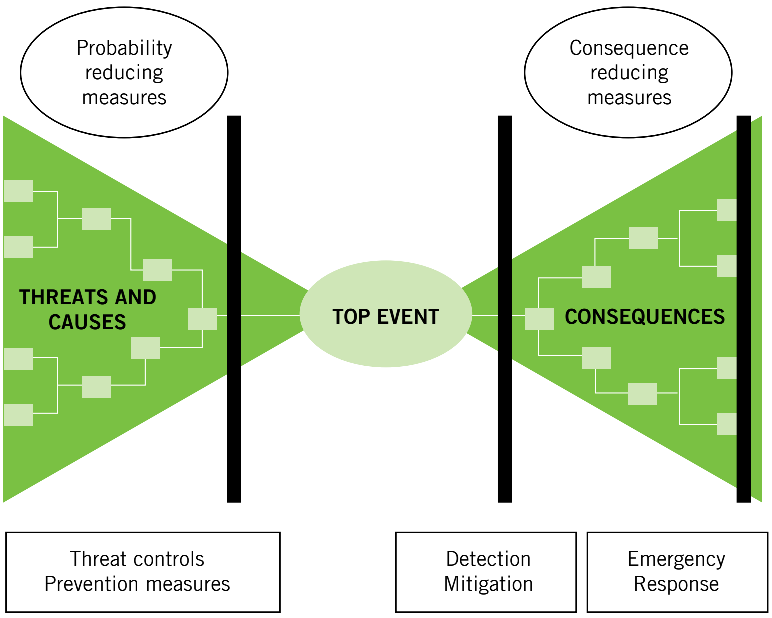
By early 2013, a total of nearly two million tonnes of CO_2 had been stored in Snøhvit.

Quest

The Quest Project in Canada has developed a fully integrated risk management process as part of its storage development plan. The plan takes into consideration all the necessary decision gates for the project lifecycle. The holistic risk management plan includes the perceived risks in the eyes of the public, financial risks and technical and safety risks related to a CO_2 storage site.

The Quest team held extensive risk assessment workshops with relevant experts to identify and manage risks. Figure 9.3 shows an example of a risk management tool applied by Quest to manage the risks. The fully integrated risk management plan has allowed early identification of gaps and sufficient time to manage risks before the regulatory submissions. The organised and structured approach allowed for transparency that has been tremendously effective in stakeholder communication.

Figure 9.3 Bow-Tie methodology is an example of a tool used by the Quest team to manage storage risks*



Courtesy DNV GL

**The Bow-Tie allows for the visualisation of the threats and causes that may lead to an unwanted event and its consequences. It shows the risk reducing measures applied as controls on one side and as mitigation on the other side.*

In 2011 the Quest storage development plan underwent an expert panel review over a two-week period with CCS experts from academia and research institutions. The summary of the review sessions was included in regulatory submissions.

The risk management process for Quest is well documented on the project website along with future monitoring plans, engineering studies and stakeholder engagement material[3]. The procedures that have been followed and the way in which they have been made publicly available set a benchmark for transparency in CCS project development.

[3] See for example, Shell, 2010. *Quest CCS Project: Volume 1: Project Description,* Appendix A, MMV plan.

Aquistore

SaskPower owns a dedicated storage site adjacent to the Boundary Dam power station – the Aquistore project, which will provide a 'buffer' facility to EOR sales, thus giving SaskPower operational flexibility.

Storage at Aquistore will be in Basal Cambrian sands at over 3 km depth. The storage reservoir is overlain by a series of low permeability 'caprocks', including shales and salts, and there are no legacy wellbores in the area that penetrate down to these depths. Initial risk assessments therefore showed Aquistore to be an extremely secure option for geological storage, a finding subsequently confirmed by the drilling of injection and monitoring wells and baseline geophysical surveys. These site investigations also confirmed that Aquistore meets SaskPower operational requirements for storage capacity and injectivity.

As Canada's first deep saline aquifer storage site, Aquistore will also be operated as an R&D project managed by the PTRC. With the financial support of governments and industry and through a series of international collaborations, Aquistore will employ a host of cutting-edge monitoring technologies, including a permanent surface seismic array and downhole instrumentation, to monitor CO_2 plume development within the reservoir and ensure the local environment remains protected.

Gorgon Carbon Dioxide Injection Project

At Barrow Island, offshore Western Australia, the Gorgon Project partners are completing construction of the CO_2 Injection Project that will have the highest injection rates and largest planned total storage of any project to date.

The CO_2 that will be separated from the natural gas stream on Barrow Island is destined to be injected into the Dupuy Formation, approximately 2.3 km immediately below the island. As with other CO_2 storage reservoirs, this formation was selected as the best candidate from a shortlist of options in the surrounding area. Seismic monitoring of the CO_2 storage operation is planned and it is understood that these results will be used both to verify the security of the injection operation and test the predictions of reservoir performance made during design of the multiple well injection scheme. The number of injection wells that a given project requires is normally a function of the rate at which CO_2 needs to be stored and the nature of the geological formation into which it should be injected.

Peer review of the CO_2 storage plans in the Gorgon Project has been ongoing since 2003 in conjunction with the project receiving regulatory approval. The Department of Mines and Petroleum in Western Australia has undertaken a total of five rounds of formal technical reviews and due diligence in order to satisfy themselves that CO_2 storage will progress in a secure and reliable manner, in accordance with regulatory requirements.

The CO2CRC Otway Project

Worldwide R&D and pilot projects contribute to the advancement of CCS through the acceleration of technical knowledge and scientific improvements, with MMV technologies in particular progressing well. It is important to test MMV technologies as these are critical in detecting CO_2 movement and reducing uncertainty around migration and trapping mechanisms.

The CO2CRC Otway Project, located in south-western Victoria, is one of the world's most prominent research projects, with over 65,000 tonnes of CO_2 injected since 2003. Over the lifetime of this project, MMV was a major focus with a wide range of methods employed, adapted and assessed. The selection of monitoring technologies was based on a risk assessment, as well as regulatory requirements, and measured through key performance indicators.

The MMV program was designed to assess all significant risks (where possible) and four key zones were subsequently targeted, including injected CO_2 in the reservoir, overlying aquifers, the soil profile and the atmosphere. Key risk elements that could have affected these four zones were wellbore or fault leakage. Several technologies were employed to evaluate these risks, including repeated seismic surveying directly above the seal, regular groundwater sampling in overlying aquifers, regular soil gas sampling and atmospheric composition measurements. None of these techniques detected the presence of injected CO_2 above the storage reservoir.

Another important learning from the Otway site addressed local sensitivities and the practicality of each monitoring technique. For example, land access and the large physical footprint of repeated 3D seismic surveys made the process logistically challenging and expensive, with obvious impacts on landholders. Thus the development of unobtrusive, permanently-installed downhole seismic sensors was seen as an important development in the MMV program and assisted the surface seismic surveys in assessing the integrity of the seal.

The development, implementation and learnings from the Otway Project have addressed issues relevant to any CCS project, including managing risks, addressing the requirements of regulators and reducing community concerns through a wide variety of monitoring technologies.

The CarbonNet Project

The time and effort required to characterise and qualify a candidate site in a way that meets regulatory and permitting requirements poses a significant threat to many CO_2 storage projects. The storage site permitting process is becoming more standardised and predictable in more jurisdictions. The schedule risks for the entire CCS project development can be high, especially if a candidate storage site is rejected near the end of the permitting process while design of the capture and transport infrastructure progresses in parallel. Schedule risk can be mitigated by national and regional geological surveys and by pre-qualifying the most promising candidate storage sites.

The Department of State Development, Business and Innovation in Victoria (Australia) is testing this site pre-qualification strategy through its CarbonNet Project. A long list of subsurface structures was evaluated for CO_2 storage feasibility and the most promising candidates were selected in 2013. The site selection process was completed according to a recognised, open-source recommended practice, which was subject to a review process involving international experts and scientific peers. Based on this short list of candidates, the CarbonNet team may choose to focus on one candidate for further appraisal and characterisation on a path to certification of storage site qualification. Pre-qualifying sites is an important process in the evaluation of a CO_2 storage site through the de-risking of the site selection process and by utilising best practice procedures to identify and manage potential risks.

[10]

PUBLIC ENGAGEMENT

Students from Boddam Primary School, Aberdeenshire demonstrate carbon capture at a CO2degrees Education workshop.

CHAPTER HIGHLIGHTS

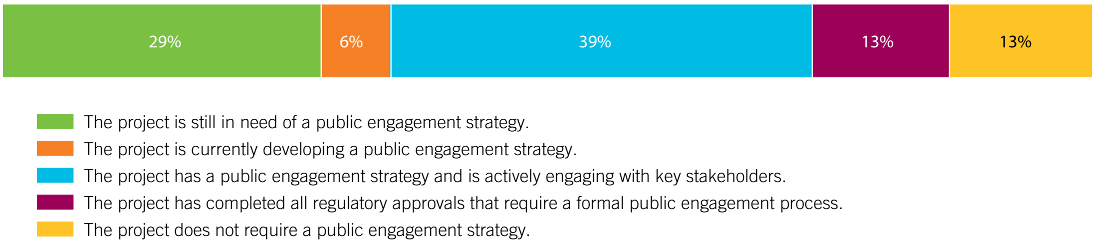
- The importance of extensive public engagement is well established with projects in the OECD economies. This is encouraging but results from the 2014 Perceptions Survey reinforce research findings that further effort is required to improve access to lessons learnt and best practice in non-OECD economies.
- Project case studies and comments from leading voices in the CCS and climate change community highlight the value of collaborating with others. Emphasis is placed on engaging outside the regular CCS community, as well as learning from communication and outreach experts in related fields such as climate science communication.
- Key milestones in the development of CCS are being reached in 2014-2015. These provide excellent opportunities to publicly showcase internationally significant projects and support education and outreach activities. A number of innovative education and outreach initiatives are taking place across the globe, focusing attention on how CCS can help tackle climate change.

10.1 PUBLIC ENGAGEMENT IS CRITICAL FOR PROJECT DEPLOYMENT

Advanced projects lead the way in public engagement

The Institute's 2014 Perceptions Survey highlights the importance of taking a strategic approach to public engagement on CCS. The majority of project respondents confirmed that they had completed, or were currently implementing, a public engagement strategy as part of their project development. The most advanced CCS projects have shown they are fully committed to public engagement and long-term outreach activity, not just with their local stakeholders, but also on the international stage.

Figure 10.1 Status of public engagement strategy development



A soon-to-be-published report on establishing Canada's Aquistore Project – the CO_2 storage research program attached to the newly operational Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project – devotes an entire chapter to cataloguing the project's extensive communication and outreach activities:

“Communication is critical to any CCS project. Even where CCS awareness is high, many CCS projects – successful and failed – have received negative attention. Strategic outreach and engagement is necessary for ensuring CCS projects have support.”

Petroleum Technology Research Centre (PTRC), 2014.
***Aquistore – CO_2 Storage at the World's First Integrated CCS Project,* Pg. 113.**

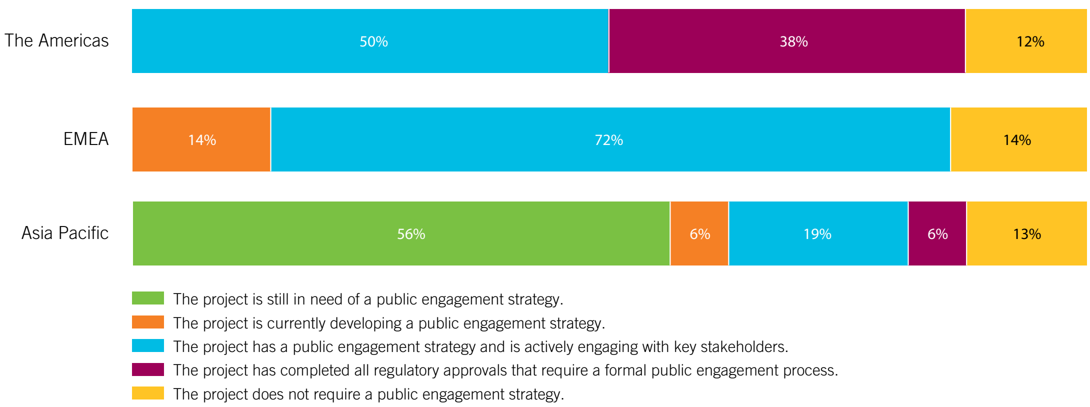
A critical barrier for public acceptance of CCS is that until now it has not been deployed at large scale in power generation. There are now three large-scale CCS projects in the power sector that have taken a positive final investment decision, with the Boundary Dam project now in operation (and the other two planned to follow in 2015 and 2016). There are a number of other large-scale CCS projects that will enter operation in 2015-16 that will add considerably to our stock of knowledge on the geological storage of CO_2.

These projects (and the ones that will follow) will be vital in establishing a positive perception of CCS as an important part of an effective and efficient CO_2 emissions reduction portfolio. These developments will provide opportunities for extensive public engagement programs. Leveraging these milestones in CCS deployment is critical to creating awareness and building enthusiasm to empower communication efforts, not just around CCS technology, but also on climate change and low-carbon energy more generally.

Tailoring best practice for less advanced projects in non-OECD economies

The first-mover projects that have progressed to the most advanced stages of the project lifecycle since the beginning of this decade lie exclusively in the Americas and EMEA regions. Most of the large-scale CCS projects in the early stages of project development are in the Asia Pacific region, for example, China's growth in CCS projects has been a fairly recent trend. While approximately one-third of the projects in the Asia Pacific region are either engaged with stakeholders or developing a public engagement strategy, a substantial number are yet to develop such a strategy.

Figure 10.2 Status of public engagement strategy development by region



This makes those projects that are adopting best practice approaches important and instructive case studies for others in the region. For example, from the early stages of project design, Japan's 'notable project' in Tomakomai, covered in detail in Chapter 4 (Notable projects – Japanese case studies), has implemented a comprehensive public engagement approach:

“ Japan CCS Co., Ltd. consider the public acceptance of our CCS Demonstration Project at Tomakomai City, Hokkaido, a major factor of project success. Through events such as CCS forums, media interviews, panel exhibitions, operational site visits and kid’s science rooms, we actively explain CCS technology and provide progress reports and future project plans to the local government and various interested stakeholders and citizens. These activities are all carried out with the support of the local government, Tomakomai City. We have found that improving our community’s understanding of CCS, helps improve confidence in the technology and the progress of our project. ”

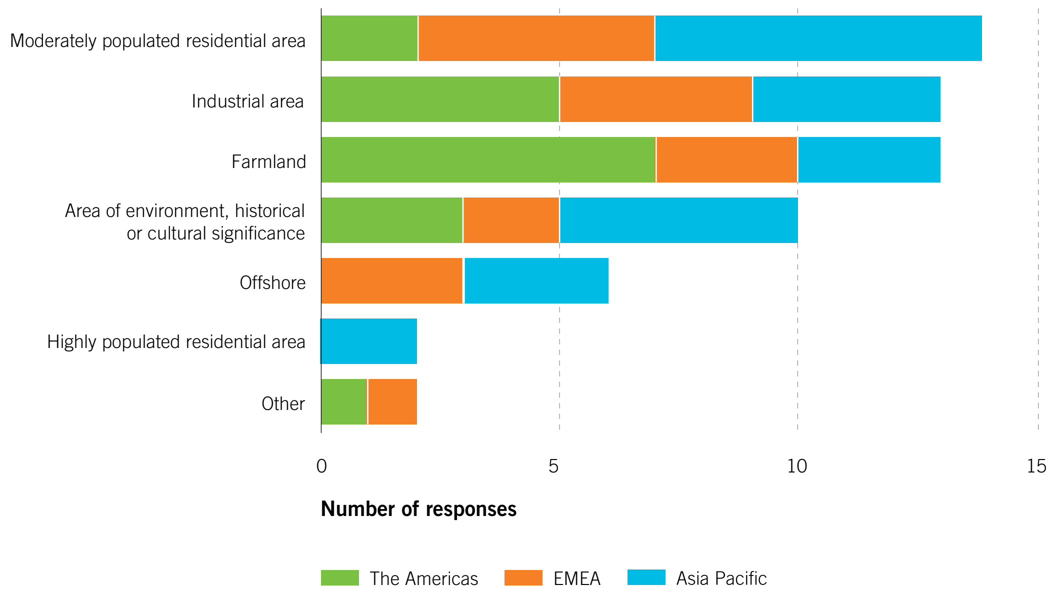
Yutaka Tanaka, Tomakomai Project, Japan

The Guangdong CCUS Centre, China (case study in Box 10.1 below) is also committed to bringing public engagement best practice and social research learnings to Guangdong’s first large-scale CCS project.

Sharing research is important. Ashworth *et al’s* (2013) recent synthesis of the body of CCS social research highlighted that the majority of research carried out to date has focused on the developed world, shedding very little light on the role of CCS within developing countries. While this is not surprising given the areas of the world where CCS is most developed, it does raise issues over the applicability of existing research and best practice to those developing nations that are now actively pursuing power and industrial CCS projects as a part of their energy mix.

These results underline the importance of improving access to the learning and experiences of CCS developers and researchers in the developed world, in order to understand any difference in needs between developed and developing regions and allow projects in developing countries to benefit from lessons learnt (as described in the existing literature).

Figure 10.3 **Type of community in which CCS projects are taking place by geographic region (respondents could select more than one type of community)**



Research shows that the more highly populated the community, the more important it is that the appropriate diligence is undertaken at the earliest stages of project planning to understand the needs and concerns of impacted communities (Bradbury, 2012; Brunsting et al., 2012a; Global CCS Institute, 2013; Wade and Greenburg, 2011).

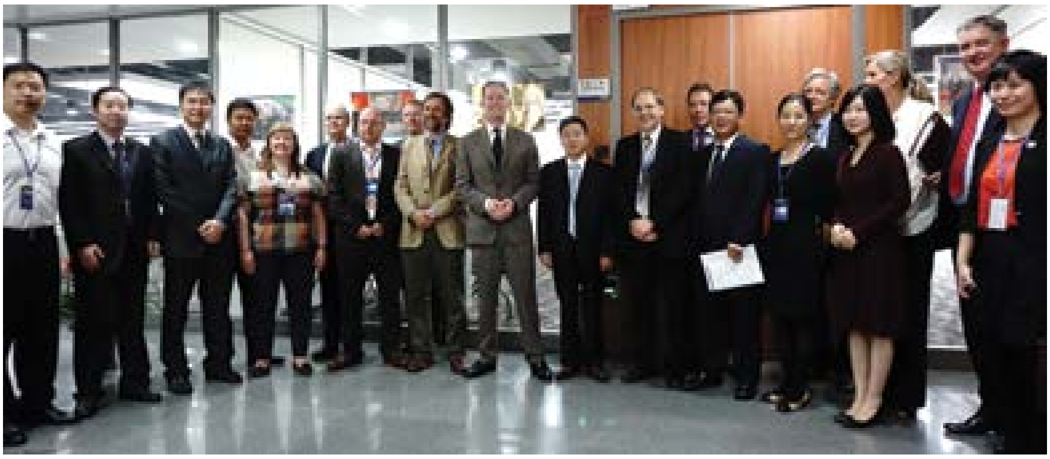
10

PUBLIC ENGAGEMENT

To date, the majority of CCS project case studies that have been analysed to determine public engagement best practice have been in low/moderately populated farming or industrial areas. This emerging collection of projects in populated residential areas is an important area for international collaborative research.

BOX 10.1

UK-China (Guangdong) CCUS Centre



On 15 May 2014, the UK-China (Guangdong) CCUS Centre Office welcomed the UK Minister for Energy and Climate Change, Mr Gregory Barker, the British Consulate General, advisers and members of the Centre to meet with Guangzhou Officials.

Early CCS projects have documented significant gains in the development of CCS public engagement best practice. A key development in 2014 is the focus that the UK-China (Guangdong) CCUS Centre has placed on the importance of including a public engagement strategy as part of its development plan. It is the intent of the Centre to make this body of work available to other CCS/CCUS projects in China.

The UK-China (Guangdong) CCUS Centre was established with support from China's National Development and Reform Commission, the Guangdong Development and Reform Commission, the UK Foreign and Commonwealth Office, the UK Department of Energy and Climate Change and the Scottish Government. The Centre is a non-profit organisation which aims to boost industrial development and academic cooperation in CCUS and other near-zero emission technologies to mitigate greenhouse gas emissions to combat climate change.

The China Resources Power (Haifeng) Integrated Carbon Capture and Sequestration Demonstration Project is the first CCUS demonstration project endorsed by the Guangdong Provincial Government. The project aims to capture 1 Mtpa of CO_2 from the Haifeng Power Plant, then transport the CO_2 to China National Offshore Oil Corporation's Huizhou Refinery to mix with CO_2 from high concentration sources. The mixed CO_2 stream would be transported to an offshore CO_2 storage site in the Pearl River Delta Basin. In August 2014, the China Resources Power Haifeng Project appointed the Guangdong CCUS Centre to develop a CO_2 capture testing unit at Unit 1 of their ultra-supercritical coal-fired power units to compare different technologies.

The Haifeng Power Plant is located in Xiaomo Town (population 13,000) in the Haifeng County (population 746,000). Xiaomo Town is located on the west end of Shanwei City, on the east coast of Guangdong Province. The town covers an area of 34.45 km^2, including 17 villages. Of the 13,000 population, 50% are farmers and 27% are fishermen. The town also accommodates approximately 1,000 Hong Kong, Taiwan, Macau and overseas Chinese people.

As the largest company in Haifeng, China Resources Power has established and maintained close links with the local public in Xiaomo Town. For example, it has helped improve roads in

BOX 10.1

UK-China (Guangdong) CCUS Centre (continued)

Xiaomo Town, donated stationery for local schools, helped improve local school facilities, as well as set up financial grants to support local residents' children to study at university.

In China, to build a successful coal-fired power plant, authorities require an environmental impact assessment (EIA). The EIA includes four public consultations as well as a public hearing. These projects also require another public consultation process through the Municipal Department of Land and Resources for land usage. In addition to the formal process, the project acknowledges the need for more informal engagement with the public to ensure they fully understand project objectives, thereby reducing the risk of public opposition.

A key goal of the Centre is to promote best practice public engagement and to involve the local community in their work as appropriate. To facilitate this work, the Centre is working with a leading Chinese science journalist, Ms Yaming Lin, from the Nanfang Media Group, international engagement specialists, and other locals to develop a communication and engagement strategy for all aspects of the project.

Using the Institute's *Communication and Engagement Toolkit* (2011) as a guide, one of the Centre's first activities has been to conduct a baseline survey of the general public's views across the Guangdong region. The survey focused on the environment, climate change and energy technologies, in particular CCUS. The survey was completed by 2,410 participants in August 2014.

When asked to rate the top five issues they deemed to be very important, the environment ranked first (54%), followed by education (45%), drinking water supply (41%), house purchase and rental cost (37%) and employment (34%). When asked if they had heard of CCUS, 34% responded positively. When asked if they would support the concept of a CCUS project, 59% said they would support such a project with 11% showing strong support. Furthermore, more than 50% said they would be interested in attending a workshop to learn more about CCUS.

The Centre Secretary, Dr Xi Liang, confirmed the important role for public engagement within this project:

> **"The UK-China CCUS Centre has benefitted greatly from the knowledge and experiences of early CCS projects and research, we know that engaging local communities around the project will help reduce the risks involved with public acceptance of the project and will benefit our local communities if they can make the most of having an innovative project located close to them. The baseline survey work is an important goal for gaining an understanding of the communities we are dealing with and will provide us with valuable information to measure our project against as it proceeds."**

In addition to the baseline survey, the Centre hopes to run a workshop with communication experts to review the communication strategy and will also aim to conduct a number of interviews with influential stakeholders from across the region to understand their perceptions of the project. There are a number of other communication activities planned, and tracking the impact of these on the public's attitudes will provide interesting lessons to enhance ongoing work.

Engaging stakeholders to manage risk

Enhancing stakeholder involvement in project decision making is a concept frequently cited in CCS social research as an opportunity to build trusting relationships and improve engagement with influential project stakeholders (Jammes et al., 2013; Bradbury, 2012; Ishii and Langhelle, 2011).

Reports from CCS projects that have involved stakeholders in final design decisions have also been positive. Both the Quest project in Alberta, Canada and National Grid's Yorkshire and Humber CCS Cross Country Pipeline project in the UK, discuss the benefit of stakeholder involvement in the siting of their pipeline corridors (Global CCS Institute, 2012).

However, at a more basic level, projects have also found involving stakeholders in the creation of the communication and engagement strategy for the detailed design stage of a project an empowering process that can help form strong stakeholder relationships for other parts of project development (Bradbury, 2012; Prangnell, 2013). The sensitivity around a final investment decision makes this a particularly critical stage to manage and be in regular contact with influential stakeholders (in order to stay aware of external influences that could impact project development).

In his 2014 paper, *Effective risk communication and CCS: The road to success,* Professor Ragnar Loftstedt examines CCS in the context of the well-established catalogue of risk communication theory. Loftstedt highlights Baruch Fischhoff's 1995 summary of the seven stage evolution of risk communication as an analogy for the development in CCS communication and engagement – highlighting the potential cost and time saving benefits of considering lessons from wider research.

The Evolution of Risk Communication (Fischhoff 1995, p. 137 as quoted in Loftstedt, 2014):

- "All we have to do is get the numbers right
- All we have to do is to tell them the numbers
- All we have to do is to explain what we mean by the numbers
- All we have to do is show them that they've accepted similar risks in the past
- All we have to do is show them that it's a good deal for them
- All we have to do is treat them nice
- All we have to do is make them partners
- All of the above"

This mature 'all of the above' attitude to stakeholder engagement is increasingly evident in some of the more advanced CCS projects, with projects investing substantial time and resources to ensure that stakeholder engagement is effectively managed.

> **"On the Peterhead CCS Project, we recognised from the start the importance of genuine and meaningful engagement with the local community and we have been working hard to build trusting and respectful relationships. While we are convinced of the value and significance of CCS, we cannot assume that communities will feel similarly assured, so our job is to go out and talk to people, to share information with them as the project progresses, to listen, to ask for their views, to address their concerns and to demonstrate how the project can bring benefits to their area."**
>
> **Bill Spence, Business Opportunity Manager, Peterhead CCS Project, Shell**

Predicting stakeholder reactions

The importance of gaining a comprehensive understanding of the social context for potential CCS developments as early as possible in the project planning process is consistently recognised in all of the CCS social research and best practice guidance emerging from early-mover projects (Ashworth, 2011; Bradbury, 2012; Brunsting et al., 2012b; Global CCS Institute, 2013; Kombrink, 2012; Prangnell, 2013; Wade and Greenberg, 2011).

Social research, and difficult project experiences like those witnessed with the Jänschwalde Project in Germany (Prangnell, 2013), also highlight the need for governments and low-carbon energy projects to be in alignment, and for governments to communicate more (and at the earliest stages of development) about their energy choices and the role for CCS within the future energy mix (Ashworth et al., 2013).

However, for areas that are new to CCS technology and at the early stages of considering the potential for this technology to play a part in their future energy mix, trying to gauge possible public reactions to the technology can be particularly challenging (Hammond and Shackley, 2010).

Various methods have been employed by researchers to try and create an 'informed' collection of stakeholders to then analyse reactions to a potential CCS siting (Ashworth et al., 2012; de Best-Waldhober et al., 2012; Japanese Knowledge Network, 2013). In 2014, the BASTOR2 Project – a research program supported by the Swedish Energy Agency, the Global CCS Institute and a host of Swedish industrial partners looking at the potential for CO_2 storage in the Baltic Sea – reported useful results from a slightly different approach.

BOX 10.2

BASTOR2: Social considerations of Baltic CO_2 storage

In Sweden, CCS is included as a priority area within the energy and climate policy framework and was recently included in the process document for developing a 2050 Roadmap for reaching zero net emissions. However, there is currently no existing CCS infrastructure, with low awareness and understanding of CCS amongst all stakeholder groups, and the technology is rarely mentioned in the media or in political discussions. This lack of visibility makes it difficult to gain a constructive understanding of likely public reaction to a CO_2 storage project in the Baltic region, as acceptance studies are fairly dependent on subjects being questioned from an educated start point (Stigson et al., 2014).

Instead of dealing in CCS hypotheticals, the BASTOR2 Project decided to analyse three large energy projects that have been planned or undertaken in the Baltic Sea. None of the projects involved CCS, however all were relatively recent projects, dealing with the geographic area in question (including activities on the seabed) and dealing with similar stakeholders to a potential CO_2 storage project:

- **SwePol Link** – A 230 km electricity transmission link between Sweden and Poland.
- **Nord Stream** – A natural gas pipeline laid across the seabed of the Baltic Sea from Russia to Germany.
- **OPAB – Oil Prospecting** – Subsidiary of a privately owned exploration company seeking governmental permission for exploratory drilling in the largest undrilled prospect in the Baltic Sea.

Each of the case study projects underwent literature and media studies as well as stakeholder interviews with those involved in, or impacted by, the project. The case studies considered two key questions.

1. Which stakeholder groups opposed or supported these projects?
2. What were the key arguments within the different stakeholder groups?

BOX 10.2

BASTOR2: Social considerations of Baltic CO_2 storage (continued)

Dr Peter Stigson, lead author of the report, confirmed the valuable learning that was derived from studying the challenges faced by these three projects:

> **"By analysing these three real energy initiatives in the Baltic region and relating their positive and negative experiences to a future Baltic CO_2 storage context, we aimed to ground our research in reality. The views by the industry interviewees really resonated with those of the BASTOR2 industry representatives. The study helped to concretise sometimes 'fluffy' social concepts such as risk and benefit perceptions. It also provided answers into what that nature of proactive actions could be. The method also provided results that could help define stakeholders' sense of place and values through very practical, tangible examples. I think this work has shown that a great deal can be learned from both positive and negative past experiences in projects and industries that are embedded in similar contexts as a CCS infrastructure."**

10.2 COLLABORATION IS A KEY SUCCESS FACTOR

There is a consistent trend emerging from the last three years of Perceptions Survey data with regards to the effectiveness ratings that projects assign to different methods of engagement. This year, the engagement methods ranked most effective by projects were face-to-face meetings, site visits, formal consultation events and education programs. Less direct forms of communication such as media, internet sites, leaflets, and commissioned research were still cited as important tools by the majority of respondents, but there is clear recognition of the value of personal interaction with stakeholders.

These results are consistent with the findings of the 2013 synthesis of CCS social research results. Ashworth *et al.* (2013) cite research conducted by Torvanger and Meadowcroft (2011), which found that on the whole, public perceptions of CCS are not fixed and are open to influence, and that the public learns experientially and through relationships. They also highlight research on trust from the University of Leiden in the Netherlands (Terwell et al., 2011):

> **"Building relationships has been identified as key to conditions of trust. A lack of relationship may result in an absence of trust in developers by the public, which may result in an inability by the developers to fully comprehend the publics' views."**

Ashworth et al., 2013. *Synthesis of CCS social research: Reflections and current state of play in 2013,* pg. 20.

Based on these findings, the synthesis report recommends the following best practice approach:

> **"Project developers need to engage in meaningful dialogue with stakeholders and the public well in advance of project plans being finalised, making use of trusted advocates within different stakeholder groups."**

Ashworth et al., 2013. *Synthesis of CCS social research: Reflections and current state of play in 2013*, pg. 23.

In *The Global Status of CCS: 2013* report we reported on projects who had established collaborative relationships with representatives from the environmental NGO community. This year, a number of projects have reported positive experiences from working in close collaboration with local councils in order to integrate CCS projects and research programs into the heart of community activities.

An example of this is the creative program of community initiatives developed to raise awareness and understanding of the pilot CO_2 injection and storage project in Hontomin, Northern Spain, and in Cubillos del Sil, where the project's CO_2 capture and transportation facilities are located.

BOX 10.3

Community collaboration – CIUDEN

CIUDEN (Spain's Public Research and Innovation Foundation), working in close collaboration with Hontomin Council, has managed to achieve what many in mainland Europe had hailed impossible – establishing an environment of widespread community support for an onshore CO_2 storage program at its Hontomin CO_2 injection pilot in Northern Spain.

Daniel Fernandez-Poulussen, geologist and Community Relationship Manager for the Hontomin CO_2 Storage Program explains:

> **"We really believe in the importance of building and maintaining the trust of the local community who will be living near our CO_2 storage project. Having the opportunity to partner with the Local Council in Hontomin has been an excellent experience. We have been able to raise awareness and understanding not just of the Hontomin facility and the innovative research that will go on there, but also to engage local people on the topic of CO_2, climate change, energy and local geology!**
>
> **Through Hontomin Council, we have been able to integrate fun learning opportunities into most of the local festivals and community events. We have held children's workshops on cooking with CO_2, adult workshops on 'Geology and Wine' and 'Wine and CO_2', local tours and scavenger hunts based on 'The Magic Rocks of Hontomin' and activity and information booths at religious festivals and the Hontomin Blood Sausage Festival to name just a few!**

BOX 10.3

Community collaboration – CIUDEN (continued)

Initial community concerns over what we meant by onshore storage of CO_2 have largely been dealt with through this completely transparent and inclusive public engagement strategy. The continuous support of Hontomin Council has made an incredible difference to the impact of our outreach activities. In fact, the engagement program at Hontomin has been deemed such a success that we are now working with the Council Representatives of Cubillos del Sil – the village where CIUDEN has CO_2 capture and transport facilities. ”

Families from the village of Cubillos del Sil and other members of the public enjoy a guided tour from CIUDEN staff as part of their 'Origin of Coal' activity. Visitors to the Energy Museum (Ene. Museo) are taken to an outcrop containing fossilised trees (from the Carboniferous Age), then visit a local garden center 'Ciuden vivero' that is cultivating a species of Fern to be planted at Ene.Museo that is similar to those present in the forests where coal was created millions of years ago.

Collaboration to develop engagement tools

Collaborating with trusted groups is important, not just at a community or project stakeholder level, but also within the wider communication of CCS. In *The Global Status of CCS: 2013* we provided a preview of a project with the working title 'Creating Core Messages' that aimed to use the 12 years of CO_2 monitoring data from the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project to help provide simple but research-backed answers to some of the most commonly asked questions about what happens to CO_2 when it is stored underground.

The initial question and answer style resource underwent extensive community testing in the Weyburn-Midale area, followed by reviews from engagement specialists from across industry, academia and ENGO groups. The resulting document abandoned its working title for the simpler *'What happens when CO_2 is stored underground?'* (PTRC, 2014). Author, Norm Sacuta (PTRC), believes that the resource benefitted substantially from the extensive collaboration and constructive feedback from the wide variety of stakeholders consulted:

> **"The resource is simple and easy to use, but it is based on verified data from seismic imaging, core sampling and soil gas analysis. We knew the basic information was good, but working in collaboration with such a wide range of reviewers outside of the standard, informed CCS space, meant we were really challenged on the complexity and presentation of the material. The result was a restructured resource, presented in everyday language."**

The resource provides CCS projects around the world with an informative and transparent tool with which to communicate effectively on CCS.

Learning lessons from climate communication

Collaborating outside of the CCS community is important not only to establish CCS as a critical part of the global response to climate change in the minds of the public, but also, to provide additional support and resources to those communicating about CCS.

Communicating about CCS in the context of energy and climate change has been a key point within best practice presentations for many years now (Ashworth *et al.*, 2010; van Alphen *et al.,* 2007; Shackley *et al.,* 2005). However, too often this guidance has simply resulted in average temperature graphs being added to already overly-technical CCS factsheets, rather than a comprehensive attempt to collaborate with those communicating in the wider energy and climate change space.

In a recent *Climate Change Adaptation Community of Practice* webinar (July 2014), Cara Pike, the Executive Director of the Climate Access Network, strongly advised those trying to communicate about climate solutions to avoid overwhelming people with new and largely negative information that is always focused on the future. Pike emphasised the importance of:

- Exploring trends rather than arguing about science, and discussing current, regional impacts that set the impacts of climate change in a personal context.
- Focusing on innovation and the benefits of climate solutions, such as improved and more sustainable infrastructure.
- Amplifying stories of positive and rewarding leadership, rather than focusing on the negative consequences of inaction.

- Encouraging early use of communication mediums such as art and storytelling to gain attention and engage people in discussion before entering into the science and economics of climate solutions.

Applying this method to CCS communication could help to support the *'values based communication'* activity that Prangnell, in his review of five large-scale CCS demonstrations, singles out as, *'…the basis of all the successful engagement work being carried out by the projects'* (Prangnell, 2013, pg. 6).

10.3 LEVERAGING PROJECT SUCCESS TO IMPROVE EDUCATION AND UNDERSTANDING

Initial public perceptions of CCS tend to focus on risks and uncertainties, especially risks associated with CO_2 storage. This is a common theme arising from international social research data (Ashworth *et al.,* 2012), as is the difficulty in being able to grasp or compare the scale of these projects without seeing them under construction or in operation. With a significant number of key CCS project milestones being reached in 2014-15, an opportunity has emerged to publicly and collectively leverage these successes and actively promote CCS at a local, national and international level.

Rhonda Smysniuk, Director of International Relations & Consortium for the Boundary Dam project, made a commitment not only to support international knowledge sharing and promotion of CCS through the Boundary Dam launch, but also to support local teachers to create a low-carbon education initiative in celebration of their local CCS project:

> **"The tagline of our International CCS Symposium was 'The Future is Here' and we believe that. We have been working with the Regina Catholic School Division and a team of international experts for over nine months to establish the 'SaskPower CCS Challenge' and fully integrate it to the Saskatchewan education curriculum. Following the launch workshop that we hosted in the Regina Science Centre, hundreds of young students have now taken up the challenge to learn more about CCS and low-carbon energy and share their learning internationally."**

Grade 7 students from Regina Catholic School Division taking part in CO_2 experiments demonstrated by international students.

10 PUBLIC ENGAGEMENT

The Boundary Dam education workshop was a truly international affair that saw students from Norway, the US, Spain, Japan, the UK and Australia all getting involved to field-test and film experiments and activity demonstrations as part of the Institute's CO2degrees education program. These demonstrations were then used at the workshop to engage the Canadian students to learn more about CO_2, energy and CCS.

Piloting CCS educational workshops in Japan

Throughout 2014, the Research Institute of Innovative Technology for the Earth (RITE) in Japan has also been developing CCS education and outreach opportunities, by translating and adapting the Institute's 'Introduction to CCS' education resource and workshop materials to suit the Japanese education systems. Throughout the summer, RITE ran a series of successful pilot workshops in educational settings in Kyoto and Osaka. The workshops were held in after-school programs at schools and science centres and featured lectures on CCS and climate change, games and hands-on experiments.

The workshop experiences will be used to help shape the final Japanese resource. The final resource is being created by RITE and will include reviews from science education specialists.

Japanese elementary students from Kyoto and Osaka learning more about CO_2 and CO_2 storage while participating in environmental education workshops during their summer vacation.

10

PUBLIC ENGAGEMENT

APPENDIX A: RECONCILIATION WITH 2013 STATUS REPORT

The table below provides a reconciliation of large-scale CCS projects with those presented in the *Global Status of CCS: 2013* report.

COUNTRY	PROJECT NAME	CAPTURE CAPACITY (MTPA)	COMMENTS
Newly identified Projects			
China	China Resources Power (Haifeng) Integrated Carbon Capture and Sequestration Demonstration Project	1.0	Coal-fired power generation at a new build power plant in Haifeng County, Guangdong Province, with associated CO_2 separation and injection into offshore, deep saline geological formations (though EOR options are also being considered). Project currently in the 'Identify' stage.
US	Sargas Texas Point Comfort Project	0.8	New build natural gas power generation with associated CO_2 separation and injection for onshore EOR. Project currently in the 'Define' stage.
Projects removed from listing			
Australia	Surat Basin CCS Project	1.0	This project is considered cancelled following advice that the project proponents are evaluating options of lesser scale.
China	Lianyungang IGCC with CCS Project	0.8-1.0	This project is considered cancelled following advice that the project has not progressed since its inception three years ago.
France	Low Impact Steel Project	0.6-0.8	This project is considered cancelled following advice that it will no longer be pursued as an active large-scale project (though will continue as a research project).
Italy	Porto Tolle	0.8-1.0	This project is considered cancelled due to delays in project delivery after the decision of the Italian State Council to annul the environmental permit for the Porto Tolle power plant and difficulties in achieving closure for the financial structure of the project.
Norway	Industrikraft Möre AS Norway	1.4-1.6	This project is considered on-hold following recent materials from the project proponents indicating that the project is on-hold.
	Full-scale CO_2 Capture Mongstad (CCM)	1.0-1.2	This project is considered cancelled following the announcement by the Norwegian Government in September 2013 that the project had been cancelled. Subsequently, the Government reiterated its support for CCS as an important technology in the efforts being made to reduce carbon emissions from industry and from power production.
Romania	Getica CCS Demonstration Project	1.4-1.6	This project is considered on-hold as the project sponsors seek funding to enable the work to progress towards the capture FEED and storage appraisal phases.
Spain	OXYCFB 300 Compostilla Project	1.0-1.2	This project is considered cancelled. The project completed the work that it had committed to carry out under the terms of its EEPR grant by October 2013 and subsequently took a decision not to proceed to full scale demonstration.
UAE	Emirates Aluminium CCS Project	2.0	This project is considered on-hold as the project proponents consider future CCS opportunities in Abu Dhabi.

COUNTRY	LSIP	CAPTURE CAPACITY (MTPA)	COMMENTS
UK	Teesside Low Carbon	2.0-3.0	This project is considered cancelled as Progressive Energy has indicated that the project will not proceed further in its current form.
US	Kentucky NewGas	5.0	This project is considered cancelled after Peabody Energy officially advised the Commonwealth of Kentucky in 2013 it had ceased further development work on the project.
	Lake Charles CCS Project	4.5	This project is considered cancelled. Leucadia National Corporation announced that it had decided not to proceed with further development of the greater Lake Charles project. It reached this conclusion based on "final estimates of the likely ultimate cost of completion of the project".
Project progress			
Canada	Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project	1.0	Moved from Execute to Operate
China	Yanchang Integrated Carbon Capture and Storage Demonstration Project	0.46	Moved from Evaluate to Define
Korea	Korea-CCS 2	1.0	Moved from Identify to Evaluate
UAE	Abu Dhabi CCS Project	0.8	Moved from Define to Execute
UK	White Rose CCS Project	2.0	Moved from Evaluate to Define
	Peterhead CCS Project	1.0	Moved from Evaluate to Define
US	Petra Nova Carbon Capture Project	1.4	Moved from Define to Execute
Renaming - substantive amendments only			
Australia	South West Hub	2.5	Formerly South West CO_2 Geosequestration Hub
China	Sinopec Qilu Petrochemical CCS Project	0.5	Formerly Sinopec Shengli Dongying CCS Project
	Yanchang Integrated Carbon Capture and Storage Demonstration Project	0.46	Formerly Yanchang Jingbian CCS Project (Phase 2)
UAE	Abu Dhabi CCS Project	0.8	Formerly Emirates Steel Industries (ESI) CCS Project
US	Kemper County Energy Facility	3.0	Formerly Kemper County IGCC Project
	Petra Nova Carbon Capture Project	1.4	Formerly NRG Energy Parish CCS Project

APPENDIX B: 2014 LARGE-SCALE CCS PROJECTS LISTING

The table overleaf presents the detailed list of the large-scale integrated CCS projects (LSIPs) included in the analysis for *The Global Status of CCS: 2014 report.* The 2014 LSIP number correlates with the world map of LSIPs (Figure 3.9) and regional maps (Figures 3.16, 3.17 and 3.18) presented in Chapter 3 (Large-Scale CCS Projects) of this report.

LSIP NO. 2014	PROJECT LIFECYCLE STAGE	PROJECT NAME	YEAR OF OPERATION	LOCATION	INDUSTRY	CAPTURE TYPE	CAPTURE CAPACITY (MTPA)	TRANSPORT TYPE	PRIMARY STORAGE OPTION	LSIP NO. 2013
1	Operate	In Salah CO_2 Storage	2004	Wilaya de Ouargla, Algeria	Natural gas processing	Pre-combustion capture (natural gas processing)	0 (injection suspended)	Pipeline, 14 km	Dedicated geological storage, onshore deep saline formations	1
2	Operate	Val Verde Natural Gas Plants	1972	Texas, United States	Natural gas processing	Pre-combustion capture (natural gas processing)	1.3	Pipeline, 356 km	Enhanced oil recovery	2
3	Operate	Enid Fertilizer CO_2-EOR Project	1982	Oklahoma, United States	Fertiliser production	Industrial separation	0.7	Pipeline, 225 km	Enhanced oil recovery	3
4	Operate	Shute Creek Gas Processing Facility	1986	Wyoming, United States	Natural gas processing	Pre-combustion capture (natural gas processing)	7.0	Multiple pipelines, maximum of 460 km	Enhanced oil recovery	4
5	Operate	Sleipner CO_2 Storage Project	1996	North Sea, Norway	Natural gas processing	Pre-combustion capture (natural gas processing)	0.9	No transport required (i.e. direct injection)	Dedicated geological storage, offshore deep saline formations	5
6	Operate	Great Plains Synfuel Plant and Weyburn-Midale Project	2000	Saskatchewan, Canada	Synthetic natural gas	Pre-combustion capture (gasification)	3.0	Pipeline, 329 km	Enhanced oil recovery	6
7	Operate	Snøhvit CO_2 Storage Project	2008	Barents Sea, Norway	Natural gas processing	Pre-combustion capture (natural gas processing)	0.7	Pipeline, 153 km	Dedicated geological storage, offshore deep saline formations	7
8	Operate	Century Plant	2010	Texas, United States	Natural gas processing	Pre-combustion capture (natural gas processing)	8.4	Pipeline, >255 km	Enhanced oil recovery	8
9	Operate	Air Products Steam Methane Reformer EOR Project	2013	Texas, United States	Hydrogen production	Industrial separation	1.0	Pipeline, 158 km	Enhanced oil recovery	9
10	Operate	Coffeyville Gasification Plant	2013	Kansas, United States	Fertiliser production	Industrial separation	1.0	Pipeline, 110 km	Enhanced oil recovery	11
11	Operate	Lost Cabin Gas Plant	2013	Wyoming, United States	Natural gas processing	Pre-combustion capture (natural gas processing)	0.9	Pipeline, 374 km	Enhanced oil recovery	12

LSIP NO. 2014	PROJECT LIFECYCLE STAGE	PROJECT NAME	YEAR OF OPERATION	LOCATION	INDUSTRY	CAPTURE TYPE	CAPTURE CAPACITY (MTPA)	TRANSPORT TYPE	PRIMARY STORAGE OPTION	LSIP NO. 2013
12	Operate	Petrobras Lula Oil Field CCS Project	2013	Santos Basin, Brazil	Natural gas processing	Pre-combustion capture (natural gas processing)	0.7	No transport required (i.e. direct injection)	Enhanced oil recovery	10
13	Operate	Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project	2014	Saskatchewan, Canada	Power generation	Post-combustion capture	1.0	Pipeline, 66 km	Enhanced oil recovery	13
14	Execute	Kemper County Energy Facility (formerly Kemper County IGCC Project)	2015	Mississippi, United States	Power generation	Pre-combustion capture (gasification)	3.0	Pipeline, 98 km	Enhanced oil recovery	14
15	Execute	Quest	2015	Alberta, Canada	Hydrogen production	Industrial separation	1.08	Pipeline, 64 km	Dedicated geological storage, onshore deep saline formations	18
16	Execute	Illinois Industrial Carbon Capture and Storage Project	2015	Illinois, United States	Chemical production	Industrial separation	1.0	Pipeline, 1.6 km	Dedicated geological storage, onshore deep saline formations	15
17	Execute	Uthmaniyah CO_2-EOR Demonstration Project	2015	Eastern Province, Kindom of Saudi Arabia	Natural gas processing	Pre-combustion capture (natural gas processing)	0.8	Pipeline, 70 km	Enhanced oil recovery	16
18	Execute	Alberta Carbon Trunk Line ("ACTL") with Agrium CO_2 Stream	2015	Alberta, Canada	Fertiliser production	Industrial separation	0.3-0.6	Pipeline, 240 km	Enhanced oil recovery	19
19	Execute	Gorgon Carbon Dioxide Injection Project	2016	Western Australia, Australia	Natural gas processing	Pre-combustion capture (natural gas processing)	3.4-4.0	Pipeline, 7 km	Dedicated geological storage, onshore deep saline formations	17
20	Execute	Petra Nova Carbon Capture Project (formerly NRG Energy Parish CCS Project)	2016	Texas, United States	Power generation	Post-combustion capture	1.4	Pipeline, 132 km	Enhanced oil recovery	26
21	Execute	Abu Dhabi CCS Project (formerly Emirates Steel Industries (ESI) CCS Project)	2016	Abu Dhabi, United Arab Emirates	Iron and steel production	Industrial separation	0.8	Pipeline, 45 km	Enhanced oil recovery	22
22	Execute	Alberta Carbon Trunk Line ("ACTL") with North West Sturgeon Refinery CO_2 Stream	2017	Alberta, Canada	Oil refining	Pre-combustion capture (gasification)	1.2-1.4	Pipeline, 240 km	Enhanced oil recovery	20

LSIP NO. 2014	PROJECT LIFECYCLE STAGE	PROJECT NAME	YEAR OF OPERATION	LOCATION	INDUSTRY	CAPTURE TYPE	CAPTURE CAPACITY (MTPA)	TRANSPORT TYPE	PRIMARY STORAGE OPTION	LSIP NO. 2013
23	Define	Sinopec Qilu Petrochemical CCS Project (formerly Sinopec Shengli Dongying CCS Project)	2016	Shandong Province, China	Chemical production	Pre-combustion capture (gasification)	0.5	Pipeline, 75 km	Enhanced oil recovery	24
24	Define	Yanchang Integrated Carbon Capture and Storage Demonstration Project	2016	Shaanxi Province, China	Chemical production	Pre-combustion capture (gasification)	0.46	Pipeline, 150 km	Enhanced oil recovery	43
25	Define	PetroChina Jilin Oil Field EOR Project (Phase 2)	2016-2017	Jilin Province, China	Natural gas processing	Pre-combustion capture (natural gas processing)	0.8	Pipeline, 35 km	Enhanced oil recovery	25
26	Define	FutureGen 2.0 Project	2017	Illinois, United States	Power generation	Oxy-fuel combustion capture	1.1	Pipeline, 45 km	Dedicated geological storage, onshore deep saline formations	29
27	Define	Rotterdam Opslag en Afvang Demonstratieproject (ROAD)	2017	Zuid-Holland, Netherlands	Power generation	Post-combustion capture	1.1	Pipeline, 25 km	Dedicated geological storage, offshore depleted oil and/or gas reservoir	30
28	Define	Sinopec Shengli Power Plant CCS Project	2017	Shandong Province, China	Power generation	Post-combustion capture	1.0	Pipeline, 80 km	Enhanced oil recovery	23
29	Define	Sargas Texas Point Comfort Project	2017	Texas, United States	Power generation	Post-combustion capture	0.8	Pipeline, 80 km	Enhanced oil recovery	New
30	Define	Medicine Bow Coal-to-Liquids Facility	2018	Wyoming, United States	Coal-to-liquids (CTL)	Pre-combustion capture (gasification)	2.5	Pipeline, distance not specified	Enhanced oil recovery	27
31	Define	Spectra Energy's Fort Nelson CCS Project	2018	British Columbia, Canada	Natural gas processing	Pre-combustion capture (natural gas processing)	2.2	Pipeline, 15 km	Dedicated geological storage, onshore deep saline formations	28
32	Define	White Rose CCS Project	2019-20	North Yorkshire, United Kingdom	Power generation	Oxy-fuel combustion capture	2.0	Pipeline, 165 km	Dedicated geological storage, offshore deep saline formations	42
33	Define	Don Valley Power Project	2019	South Yorkshire, United Kingdom	Power generation	Pre-combustion capture (gasification)	5.0	Pipeline, 165 km	Dedicated geological storage, with potential for enhanced oil recovery, offshore deep saline formations	35
34	Define	Hydrogen Energy California Project (HECA)	2019	California, United States	Power generation	Pre-combustion capture (gasification)	2.7	Pipeline, 5 km	Enhanced oil recovery	33

LSIP NO. 2014	PROJECT LIFECYCLE STAGE	PROJECT NAME	YEAR OF OPERATION	LOCATION	INDUSTRY	CAPTURE TYPE	CAPTURE CAPACITY (MTPA)	TRANSPORT TYPE	PRIMARY STORAGE OPTION	LSIP NO. 2013
35	Define	Texas Clean Energy Project	2019	Texas, United States	Power generation	Pre-combustion capture (gasification)	2.7	Pipeline, distance not specified	Enhanced oil recovery	31
36	Define	Peterhead CCS Project	2019	Aberdeenshire, United Kingdom	Power generation	Post-combustion capture	1.0	Pipeline, 120 km	Dedicated geological storage, offshore depleted oil and/or gas reservoir	44
37	Evaluate	Quintana South Heart Project	2018	North Dakota, United States	Power generation	Pre-combustion capture (gasification)	2.1	Pipeline, distance not specified	Enhanced oil recovery	45
38	Evaluate	Korea-CCS 1	2018	Either Gangwon Province or Chungnam Province, Korea	Power generation	Post-combustion capture	1.0	Shipping, distance under evaluation	Dedicated geological storage, offshore deep saline formations	47
39	Evaluate	Indiana Gasification	2019	Indiana, United States	Synthetic natural gas	Pre-combustion capture (gasification)	5.5	Pipeline, >700 km	Enhanced oil recovery	37
40	Evaluate	Riley Ridge Gas Plant	2018-2020	Wyoming, United States	Natural gas processing	Pre-combustion capture (natural gas processing)	2.5	Pipeline, distance not specified	Enhanced oil recovery	48
41	Evaluate	Mississippi Clean Energy Project (formerly Mississippi Gasification)	2019	Mississippi, United States	Chemical production	Pre-combustion capture (gasification)	4.0	Pipeline, distance not specified	Enhanced oil recovery	38
42	Evaluate	C.GEN North Killingholme Power Project	2019	North Lincolnshire, United Kingdom	Power generation	Pre-combustion capture (gasification)	2.5	Pipeline, 151-200 km	Under evaluation	39
43	Evaluate	Bow City Power Project	2019	Alberta, Canada	Power generation	Post-combustion capture	1.0	Pipeline, 40-90 km	Enhanced oil recovery	54
44	Evaluate	South West Hub (formerly South West CO_2 Geosequestration Hub)	2020	Western Australia, Australia	Fertiliser production	Industrial separation	2.5	Pipeline, 80-110 km	Dedicated geological storage, onshore deep saline formations	46
45	Evaluate	Huaneng GreenGen IGCC Project (Phase 2)	2020	Tianjin, China	Power generation	Pre-combustion capture (gasification)	2.0	Pipeline, 50-100 km	Enhanced oil recovery important, dedicated geological storage options under review	40

LSIP NO. 2014	PROJECT LIFECYCLE STAGE	PROJECT NAME	YEAR OF OPERATION	LOCATION	INDUSTRY	CAPTURE TYPE	CAPTURE CAPACITY (MTPA)	TRANSPORT TYPE	PRIMARY STORAGE OPTION	LSIP NO. 2013
46	Evaluate	Korea-CCS 2	2020	Korea	Power generation	Pre-combustion or oxy-combustion	1.0	Shipping, distance under evaluation	Dedicated geological storage, offshore deep saline formations	65
47	Evaluate	Shenhua Ordos CTL Project (Phase 2)	2020	Inner Mongolia Autonomous Region, China	Coal-to-liquids (CTL)	Pre-combustion capture (gasification)	1.0	Pipeline, 201-250 km	Dedicated geological storage, onshore deep saline formations	56
48	Evaluate	CarbonNet Project	2020's	Victoria, Australia	Under evaluation	Subject to industry partner selection	1.0-5.0	Pipeline, 130 km	Dedicated geological storage, offshore deep saline formations	51
49	Evaluate	Captain Clean Energy Project	2021	Scotland, United Kingdom	Power generation	Pre-combustion capture (gasification)	3.8	Pipeline, 358 km	Dedicated geological storage, offshore deep saline formations	53
50	Identify	China Resources Power (Haifeng) Integrated Carbon Capture and Sequestration Demonstration Project	2018	Guangdong Province, China	Power generation	Post-combustion capture	1.0	Pipeline, 150 km	Dedicated geological storage, offshore deep saline formations	New
51	Identify	Dongguan Taiyangzhou IGCC with CCS Project	2019	Guangdong Province, China	Power generation	Pre-combustion capture (gasification)	1.0-1.2	Shipping, 200-250 km	Dedicated geological storage, offshore depleted oil and/or gas reservoir	63
52	Identify	Shenhua / Dow Chemicals Yulin Coal to Chemicals Project	2020	Shaanxi Province, China	Chemical production	Industrial separation	2.0-3.0	Pipeline, <150 km	Dedicated geological storage, onshore deep saline formations	58
53	Identify	Shanxi International Energy Group CCUS project	2020	Shanxi Province, China	Power generation	Oxy-fuel combustion capture	2.0	Pipeline, distance not specified	Not specified	60
54	Identify	Shenhua Ningxia CTL Project	2020	Ningxia Hui Autonomous Region, China	Coal-to-liquids (CTL)	Pre-combustion capture (gasification)	2.0	Pipeline, 200-250 km	Not specified	62
55	Identify	Datang Daqing CCS Project	2020	Heilongjiang Province, China	Power generation	Oxy-fuel combustion capture	1.0-1.2	Pipeline, distance not specified	Dedicated geological storage, onshore deep saline formations	59

APPENDIX C: EXISTING CO_2 TRANSPORT INFRASTRUCTURE IN THE UNITED STATES

The information in this appendix was prepared in conjunction with the Energy Pipelines CRC.

Extensive networks of pipelines already exist around the world. In the US alone, there are about 800,000 km of natural gas and hazardous liquid pipelines, and 3.5 million km of natural gas distribution lines. Some 6,500 km of pipelines actively transport CO_2 today. In the US, around 50 CO_2 pipelines are currently operating, which transport approximately 68 Mtpa of CO_2. These onshore pipelines cross six provincial/state boundaries and one international border (into Canada). Much of the existing CO_2 pipeline infrastructure in the US was built in the 1980s and 1990s and delivers mainly naturally sourced CO_2 for EOR purposes.

The table below provides an overview of the main existing CO_2 EOR pipelines in the US and has been adapted from: *A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide, prepared by the Interstate Oil and Gas Compact Commission 2010 and submitted to the Southern States Energy Board, US.*

PIPELINE	OWNER/ OPERATOR	LENGTH (km)	DIAMETER (inches)	ESTIMATED MAXIMUM FLOW CAPACITY (Mtpa)	LOCATION (STATE/ PROVINCE)
Adair	Apache	24	4	1.0	Texas
Anton Irish	Oxy	64	8	1.6	Texas
Beaver Creek	Devon	72	8	1.6	Wyoming
Borger to Camrick	Chaparral Energy	138	4	1.0	Texas, Oklahoma
Bravo	Oxy Permian	351	20	7.0	New Mexico, Texas
Canyon Reef Carriers	Kinder Morgan	224	16	4.3	Texas
Centerline	Kinder Morgan	182	16	4.3	Texas
Central Basin	Kinder Morgan	230	16	4.3	Texas
Chaparral	Chaparral Energy	37	6	1.3	Oklahoma
Choctaw (Northeast Jackson Dome)	Denbury Onshore, LLC	294	20	7.0	Mississippi, Louisiana
Coffeyville – Burbank	Chaparral Energy	110	8	1.6	Kansas, Oklahoma
Comanche Creek (currently inactive)	PetroSource	193	6	1.3	Texas
Cordona Lake	XTO	11	6	1.3	Texas
Cortez	Kinder Morgan	808	30	23.6	Texas
Dakota Gasification (Souris Valley)	Dakota Gasification	329	14	2.6	North Dakota, Saskatchewan
Delta	Denbury Onshore, LLC	174	24	11.4	Mississippi, Louisiana
Dollarhide	Chevron	37	8	1.6	Texas
El Mar	Kinder Morgan	56	6	1.3	Texas
Eastern Shelf	Kinder Morgan	146	10	2.1	Texas
Enid–Purdy (Central Oklahoma)	Merit		8	1.6	Oklahoma

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PIPELINE	OWNER/ OPERATOR	LENGTH (km)	DIAMETER (inches)	ESTIMATED MAXIMUM FLOW CAPACITY (Mtpa)	LOCATION (STATE/ PROVINCE)
Este I to Welch	ExxonMobil	64	14	3.4	Texas
Este II to Salt Creek Field	ExxonMobil	72	12	2.6	Texas
Ford	Kinder Morgan	19	4	1.0	Texas
Free State	Denbury Onshore, LLC	138	20	7.0	Mississippi
Greencore pipeline	Denbury Greencore Pipeline LLC	373	20	14.0	Montana, Wyoming
Green Line I	Denbury Green Pipeline LLC	441	24	18.0	Louisiana
Joffre Viking	Penn West Petroleum, Ltd	13	6	1.3	Alberta
Llaro	Trinity CO_2	85	12	1.6	New Mexico
Lost Soldier/Werrz	Merit	47	Not specified	Not specified	Wyoming
Mabee Lateral	Chevron	29	10	2.1	Texas
McElmo Creek	Kinder Morgan	64	8	1.6	Colorado, Utah
Means	ExxonMobil	56	12	2.6	Texas
Monell	Anadarko	53	8	1.6	Wyoming
North Cowden	Oxy Permian	13	8	1.6	Texas
North Ward Estes	Whiting	42	12	2.6	Texas
Pecos County	Kinder Morgan	42	8	1.6	Texas
Pikes Peak	SandRidge	64	8	1.6	Texas
Powder River Basin CO_2 PL	Anadarko	201	16	4.3	Wyoming
Raven Ridge	Chevron	257	16	4.3	Wyoming, Colorado
Rosebud	Hess	19	12	2.6	New Mexico
Sheep Mountain	Oxy Permian	656	24	11.4	Texas
Shute Creek	ExxonMobil	48	30	23.6	Wyoming
Slaughter	Oxy Permian	56	12	2.6	Texas
Sonat (reconditioned natural gas)	Denbury Onshore, LLC	80	18	3.2	Mississippi
TransPetco	TransPetco	177	8	1.6	Texas, Oklahoma
Val Verde	Kinder Morgan	134	10	2.1	Texas
Wellman	PetroSource	42	6	1.3	Texas
White Frost	Core Energy, LLC	18	6	1.3	Michigan
West Texas	Trinity CO_2	97	12	1.6	Texas, New Mexico
Wyoming CO_2	ExxonMobil	180	20-16	4.3	Wyoming

APPENDIX D: OVERVIEW OF MAJOR CO_2 TRANSPORT R&D PROGRAMS

An overview of the major collaborative CO_2 Transport R&D programs is provided below and was prepared for the Institute by the Energy Pipelines CRC. These R&D initiatives are either ongoing or were completed in 2014.

Requirements for safe and reliable CO_2 transportation pipeline (SARCO2)

- **Project partners:** CSM (Italy), SZMF (Germany), Europipe (Germany), SMLP (Germany), V&M (Germany), Corinth Pipeworks (Greece), Eni S.p.A (Italy), GDF Suez (France), National Grid (UK), DNV (Norway).
- **Project aim:** To develop know-how to enable the determination of steel pipe requirements for anthropogenic CO_2 pipelines.
- **Research areas:** Full-scale testing on real sections of pipeline is part of this project in order to address the following specific research goals:
    - definition of toughness requirements of base material to control running ductile fracture propagation
    - definition of requirements to control crack initiation event such as corrosion and stress corrosion cracking phenomena, and
    - collecting experimental data related to the release of CO_2 during a pipeline failure.

DNV Joint Industry Project (JIP) - CO2PIPETRANS Phase 2

- **Project partners:** DNV (Norway), Arcelor Mittal (France), BP (UK), Endesa (Spain), Eni S.p.A (Italy), E.on (Germany), Gassco (Norway), Gassnova (Norway), Health and Safety Executive (UK), Maersk Oil (Denmark), Petrobras (Brasil), Petroleum Safety Authority (Norway), Shell (Netherlands/UK), V&M Tubes (Germany), Vattenfall (Sweden).
- **Project aim:** Close significant knowledge gaps through the collection of data mainly from real-world testing and to then incorporate this into an update of the existing *Recommended Practice for the Design and Operation of CO_2 pipelines DNV-RP-J202*.
- **Research areas:**
    - dense phase CO_2 release modelling and data validation – to make available suitable information and data from experimental work to assist development and validation of robust dense phase CO_2 depressurisation, release, and dispersion models. Data collected during two complimentary programs of medium-scale CO_2 release experiments conducted by BP and by Shell is now available
    - fracture arrest – to provide confirmation of theoretical models by performing full-scale fracture arrest testing, and
    - corrosion – to determine the corrosion mechanism and the corrosion rate in dense phase CO_2 for various amounts of impurities like O_2, SOx, NOx and H_2S.

CO_2 Liquid pipeline TRANSportation (COOLTRANS)

- **Project partners:** National Grid, Nottingham University, University College London, Leeds University, Kingston University, GL Noble Denton, Newcastle University, Atkins, Pipeline Integrity Engineers, Penspen, MACAW Engineering, Manchester University, Tyndall Centre, and Spadeadam. All partners are based in the UK.
- **Project aim:** To address knowledge gaps relating to safe design and operation of onshore (buried) pipelines for transporting anthropogenic, high pressure, dense phase CO_2.

- **Research areas:** There are six specific research areas, which are underpinned by a comprehensive program of full-scale tests. The research areas are:
    - thermodynamic characteristics of CO_2
    - fracture control (including two full-scale burst tests)
    - quantified risk assessment (QRA)
    - pipeline design and integrity
    - environmental and public perception studies, and
    - application of research findings.

Carbon Dioxide, Safety, Health & Environmental Risk (COSHER)

- **Project partners:** Kema (Netherlands), Gasunie (Netherlands), StatoilHydro (Norway), National Grid (UK), Total (France), GDF Suez (France), Petrobras (Brasil), Eni (Italy), Enagas (Spain), Gassco (Norway), Gassnova (Norway), Tokyo-Gas (Japan) and Air Liquide (France).
- **Project aim:** To gather data to support the development of models of the COSHER parties for the determination of safety zones/consequence distances of CO_2 transport.
- **Research areas:** As part of this project a series of controlled releases from high pressure CO_2 pipelines were completed in the second half of 2013. Areas of specific interest are:
    - CO_2 behaviour after release from high pressure pipelines (mass release rate, phase change)
    - the atmospheric dispersion of the CO_2, and
    - the 'chilling effect' on the pipeline wall due to sudden depressurisation.

Materials for Next Generation CO_2 Transport Systems (MATTRAN) Project

- **Project partners:** Newcastle University, Nottingham University, University College London, Leeds University, Cranfield University. All partners are based in the UK.
- **Project aim:** Providing the tools and information necessary for pipeline engineers to select appropriate materials and operating conditions to control corrosion, stress corrosion cracking and fracture propagation in pipelines carrying dense phase CO_2.
- **Research areas:** This research program is divided into the following work packages:
    - CO_2 stream composition
    - phase and dew point determination
    - pipeline specification
    - internal corrosion and degradation
    - internal stress corrosion cracking
    - fracture control, and
    - synthesis and dissemination.

Energy Pipelines CRC – CO_2 Pipelines Research

- **Project partners:** Energy Pipelines Cooperative Research Centre (CRC), University of Wollongong, Monash University, Australian National University, ACIL Tasman, Peter Tuft & Associates, Venton & Associates. All partners are based in Australia.
- **Project aim:** To allow a CO_2 pipeline to be designed and operated under the Australian Standard *AS 2885: Pipelines – Gas and Liquid Petroleum*.

- **Research areas:** The following research areas are covered:
  - equations of state
  - pipeline decompression
  - modelling CO_2 dispersion
  - limits for water content in CO_2 mixtures for safe transport in carbon steel pipe
  - public safety, community consultation and organisational requirements for CO_2 pipelines, and
  - cost-benefit study of the application of the results of the research.

Pipeline Research Council International (PRCI)

- **Project partners:** PRCI is a US-based research group with 78 member organisations and companies.
- **Research areas:** PRCI collaborated with Energy Pipelines CRC (in Australia) and the European Pipeline Research Group (EPRG) on a series of shock tube tests of dense phase CO_2 at the TransCanada Gas Dynamic Test Facility in Canada.

APPENDIX E: MONITORING TECHNOLOGIES AND THEIR APPLICATION

The table below describes the main purposes of the monitoring technologies shown in Table 9.1 of Chapter 9 (Storage).

Time-lapse (4D) seismic	Surface seismic surveys use echo-sounding techniques to map acoustic properties of rocks and fluids at depth. 3D surveys deploy seismic sources and receivers (geophones) on a grid pattern to build a full volumetric image of the subsurface, whilst '4D surveys' refers to repeated 3D surveys over time employed to track changes such as CO_2 migration. The technique has been successfully applied to offshore and onshore storage projects, but is relatively expensive. Onshore projects can also be logistically challenging, although deployment of a permanent geophone array can greatly reduce long term costs.
Satellite measurement of ground surface (InSAR)	InSAR monitoring measures very slight changes in land-surface elevation by comparing a series of radar-produced images taken from satellites, at millimetre scale which may result from a variety of natural or industrial processes, including geological storage. It has the potential to track subsurface CO_2 migration over a large area and at a relatively low cost.
Microseismic	Passive seismic or micro-seismic monitoring refers to the detection and measurement of seismic events, caused by subsurface movements ('events') that may be naturally or artificially induced; monitoring geophones can be deployed at surface or in wells. Seismic events induced by CO_2 injection are invariably too small to be felt and highly unlikely to raise a significant risk of damage, but can nevertheless be detected and used to assess the storage reservoir and confirm integrity.
Borehole temperature and pressure measurements	Measurements of pressure and temperature can be made at the wellhead, downhole at the reservoir level and from the well annulus (the interval between well casing and surrounding rock layers). These measurements are required to calibrate monitoring and predictive modelling activities, and can be used to confirm wellbore and storage integrity.
Geochemical soil analysis	Several well-established technologies can be used to analyse the chemical composition of gases present within soils above storage sites. The acquisition of representative baseline data is important to aid interpretation of subsequent monitoring during injection. Although relatively straightforward, monitoring campaigns can be labour and data intensive, so monitoring locations and frequencies can be tailored to the unique risk assessment profile of each onshore site and adjusted over time.
Chemical tracers	Tracers are substances (fine particles, liquids or soluble gases) that may be added to CO_2 in order to 'finger print' the injected stream, to assist tracking subsurface migration or identify potential leakage. Detection of tracers is made at sampling points such as monitoring wells within the reservoir.
Cross-hole electrical resistance tomography	Electrical resistance tomography (ERT) measures the electrical resistivity in the reservoir, which can increase in the presence of CO_2, to map the movement of the plume. The technique images the reservoir using electrical measurements between electrodes in two or more boreholes up to a few hundred metres apart.
Surface gravimetry	This technique requires repeated, high-precision measurements of gravity at surface to give information on movement of fluids in the subsurface; as such it can be applied to CO_2 injection to give information on migration within the reservoir. The achievable resolution is relatively low, so this technique can be used to complement other monitoring technologies such as seismic.
Downhole fluid chemistry	Changes in downhole fluid chemistry can be monitored via samples collected from wells. Sampling equipment can be installed in the storage reservoir to track migration of injected CO_2 and effects on saline groundwater or other fluids present, or in zones above the reservoir, to confirm storage integrity. Baseline sampling and measurements prior to injection are important to aid interpretation of data.
Vertical seismic profiling	Vertical seismic profiling (VSP) is comparable to 4D seismic but with geophones installed at intervals downhole in wells, allowing detailed imaging of the acoustic properties of the reservoir and surrounding strata. VSP can provide high resolution imaging of CO_2 migration around monitoring wells and can be used to provide assurance of storage integrity, but over a more defined area with a lower surface footprint compared to surface (4D) surveys.

Note: 'Borehole temperature and pressure measurements' covers both 'pressure in injection well' and 'downhole pressure and temperature' from Table 9.1.

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APPENDIX G: ABBREVIATIONS AND ACRONYMS

% per cent

°C degrees Celsius

3D three dimensional

2DS 2°C Scenario

ACTL Alberta Carbon Trunk Line

ADB Asian Development Bank

ADNOC Abu Dhabi National Oil Company

ADP Ad hoc Working Group on the Durban Platform for Enhanced Action (UNFCCC)

AR Assessment Report

APEC Asia-Pacific Economic Cooperation

AS Australian Standard

ASME American Society of Mechanical Engineers

ASU air separation unit

bar A bar is a metric unit of pressure where 1 bar is equal to 100 000 pascal

CCS carbon capture and storage

CCEMC Climate Change and Emissions Management Corporation

CCOP Coordinating Committee for Geoscience Programmes (East and Southeast Asia)

CCSI Carbon Capture Simulation Initiative

CCUS carbon capture utilisation and storage

CCWG Climate Change Working Group

CENBIO USP Brazilian Reference Center on Biomass, University of Sáo Paulo

CDM Clean Development Mechanism

CEM Clean Energy Ministerial

CEPAC Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (Brazil)

CfD Contract for Difference

CLC chemical looping combustion

CNPC China National Petroleum Corporation

CO_2 carbon dioxide

CO_2e carbon dioxide equivalent

CO_2CRC Cooperative Research Centre for Greenhouse Gas Technologies

COP Conference of the Parties (UNFCCC)

COURSE 50 CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50 (Japan)

CPU CO_2 Purification Unit

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CSA	Canadian Standards Association
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CSLF	Carbon Sequestration Leadership Forum
CTCN	Climate Technology Centre and Network
CTL	coal-to-liquids
DECC	Department of Energy and Climate Change (UK)
DNA	Designated National Authority
DOE	Department of Energy (US)
DRI	direct reduced iron
DSDBI	Victorian Department of State Development, Business and Innovation (Australia)
EAGLE	Coal Energy Application for Gas, Liquid and Electricity Project (Japan)
EC	European Commission
ECRA	European Cement Research Academy
EEA	European Economic Area (EU)
EEPR	European Energy Programme for Recovery
EIA	Energy Information Administration (US)
EIA	environmental impact assessment
EMEA	Europe, Middle East and Africa
ENGO	environmental non-government organisation
EOR	enhanced oil recovery
EP	European Parliament
ESI	Emirates Steel Industries
ESCAP	Energy Saving CO_2 Absorption Process
ETS	Emissions Trading System (Europe)
EU	European Union
EPA	Environmental Protection Agency (US)
EPS	Emissions Performance Standard (US)
FAS	flow assurance study
FEED	front-end engineering design
FGD	flue gas de-sulfurisation
FID	final investment decision
FOAK	first-of-a-kind
FPSO	floating production storage and offloading
GEF	Global Environment Facility
GCC	Gulf Cooperation Council (Middle East)
GCF	Green Climate Fund (UNFCCC)

GHG	greenhouse gas
GJ/t	gigajoule per tonne
GPC	Gas Processing Centre
GT	gigatonnes
GW	gigawatts
H_2	hydrogen
H_2O	water
H_2S	hydrogen sulphide
HECA	Hydrogen Energy California Project (US)
HPU	hydrogen production unit
HSE	health, safety, and environment
IBDP	Illinois Basin-Decatur Project (US)
IDDRI	Institute for Sustainable Development and International Relations
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IGCC	Integrated gasification combined cycle
IGFC	Integrated gasification fuel cell
INDC	intended nationally determined contributions (UNFCCC)
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
J-POWER	Electric Power Development Company (Japan)
JFY	Japanese fiscal year
JICA	Japan International Cooperation Agency
JIP	joint industry project
JISF	Japan Iron and Steel Federation
JV	joint venture
KG/S	kilograms per second
KACST	King Abdulaziz City for Science and Technology (Saudi Arabia)
KCCSA	Korean Carbon Capture and Storage Association
KFUPM	King Fahd University of Petroleum & Minerals (Saudi Arabia)
KAUST	King Abdullah University of Science and Technology (Saudi Arabia)
KAPSARC	King Abdullah Petroleum Studies and Research Center (Saudi Arabia)
KM	kilometres
KWH	kilowatt-hour
LNG	liquefied natural gas
LSIP	large–scale integrated project

m	metres
mm	millimetres
MASDAR	Abu Dhabi Future Energy Company
MEA	Monoethanolamine
METI	Ministry of Economy, Trade and Industry (Japan)
MMV	monitoring, measurement and verification
MOST	Ministry of Science and Technology (China)
MRV	monitoring, reporting and verification
MSR	Market Stability Reserve (EC)
MTU	mobile test unit
Mt	million tonne/s
Mtpa	million tonnes per annum
MW	megawatts
MWe	megawatts of electrical output
MWh	megawatt-hour
MWth	megawatt thermal
N_2	nitrogen
NCCC	National Carbon Capture Center (US)
NDC	nationally determined contributions (UNFCCC)
NDE	Nationally Designated Entity (UNFCCC)
NDRC	National Development and Reform Commission (China)
NEDO	New Energy and Industrial Technology Development Organisation (Japan)
NER300	The European Commission's New Entrants Reserve funding program
NETL	National Energy Technology Laboratory (US)
NGCC	natural gas combined cycle
NGL	natural gas liquids
NGO	non-government organisation
NOx	nitrous oxide
NSPS	New Source Performance Standard (US)
NWIP	New Work Item Proposal (ISO)
O_2	oxygen
OECD	Organisation for Economic Cooperation and Development
PEMEX	Petróleos Mexicanos
PCC	post-combustion capture
PSA	Pressure Swing Adsorption
PSAG	Private Sector Advisory Group (UNFCCC)

PTRC Petroleum Technology Research Centre (Canada)

QCCSRC Qatar Carbonates and Carbon Storage Research Centre

R&D research and development

RD&D research, development and demonstration

RFA Regulatory Framework Assessment (Canada)

RITE Research Institute of Innovative Technology for the Earth (Japan)

ROAD Rotterdam Opslag en Afvang Demonstratie Project (The Netherlands)

S&ED Strategic and Economic Dialogue

SABIC Saudi Basic Industries Corporation

SBI Subsidiary Body for Implementation (UNFCCC)

SBSTA Subsidiary Body for Scientific and Technological Advice (UNFCCC)

SCC Standards Council of Canada

SDSN Sustainable Development Solutions Network

SECARB Southeast Regional Carbon Sequestration Partnership (US)

SER Sorption Enhanced Reforming

SEWGS Sorption Enhanced Water Gas Shift reactor

SMR Steam Methane Reformer

SOx sulphur dioxide

SNG synthetic natural gas

SYNGAS synthetic gas

t tonne/s

TC Technical Committee (ISO)

TCEP Texas Clean Energy Project (US)

TCM Technology Centre Mongstad (Norway)

TEC Technology Executive Committee (UNFCC)

TEM Technical Expert Meetings (UNFCCC)

TIC Technology Innovation Centre (for CCS) (Saudi Arabia)

TRIG™ Transport Integrated Gasification (technology)

TRL technology readiness levels

tpa tonnes per annum

tpd tonnes per day

UAE United Arab Emirates

UIC Underground Injection Control

UK United Kingdom

ULCOS Ultra-Low CO_2 Steelmaking consortium (France)

UN-ESCWA United Nations Economic and Social Commission for Western Asia

UNFCCC United Nations Framework Convention on Climate Change

US United States (of America)

VSA vacuum swing adsorption

WA Western Australia

WG working group (ISO)

WMP Weyburn–Midale CO_2 Monitoring and Storage Project (Canada)

WS Work Stream (UNFCCC)

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