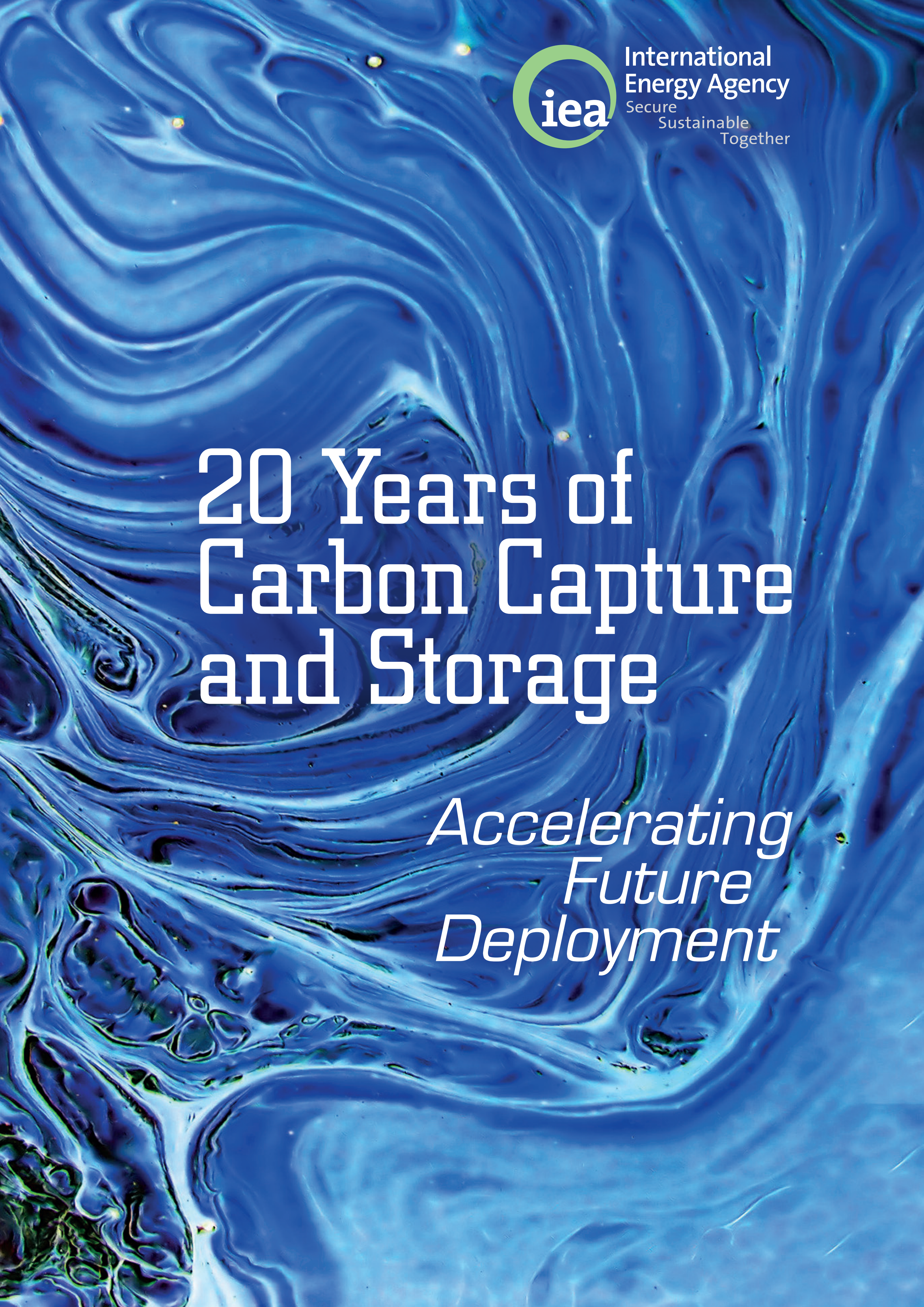

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20 Years of Carbon Capture and Storage

Accelerating Future Deployment

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INTERNATIONAL ENERGY AGENCY

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- Improve transparency of international markets through collection and analysis of energy data.
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Foreword

The success of the Paris Agreement could represent a major turning point for carbon capture and storage (CCS). As political leaders, global governments, businesses and other key stakeholders now turn their attention to the *how* of fulfilling the ambitions of Paris, a greater focus on CCS must necessarily follow.

International Energy Agency (IEA) scenario analysis has consistently highlighted that CCS will be important in limiting future temperature increases to 2°C, and we anticipate that this role for CCS will become increasingly significant if we are to move towards "well below 2°C". Why is this? Because there is no other technology solution that can significantly reduce emissions from the coal and gas power generation capacity that will remain a feature of the electricity mix for the foreseeable future. No other technology solution is capable of delivering the deep emissions reductions needed across key industrial processes such as steel, cement and chemicals manufacturing, all of which will remain vital building blocks of modern society. In the future, it may be a pivotal technological solution for removing large amounts of carbon from the atmosphere – a likely requirement as we move to limit temperature increases to well below 2°C. In short, deployment of CCS will not be optional in implementing the Paris Agreement.

It is therefore significant that we should be marking 20 years of operation of the Sleipner CCS project just as the Agreement is ratified and entering into force. This is a milestone that deserves to be acknowledged, not just for the enormous contribution the project has made to advancing CCS knowledge and experience, but as tangible proof that large-scale application of CCS technologies is not new. CCS is already a reality and has been for some time. There are now 21 large-scale CCS projects operating or under construction throughout the world, in addition to more than 100 smaller-scale projects.

Behind this is a large and dedicated group of global researchers, technology developers, utilities and service providers who have been working to develop CCS to the point that there are no insurmountable technology barriers to safe deployment. The IEA Technology Collaboration Programmes, among other international collaborative efforts, have provided essential support in this regard. What is missing is a strengthened climate response to support CCS investment. The need for policy action is now urgent if we are to maintain current momentum in CCS project development to meet the Paris goals.

My hope is that this publication will provide a positive reminder of how far CCS has come in 20 years, while also showing how much further and faster we need to go to keep CCS on track to meet climate goals. CCS has matured from a "promising technology", as described by the Intergovernmental Panel on Climate Change almost two decades ago, but now we must act to fulfil its potential.

Dr. Fatih Birol
Executive Director
International Energy Agency

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Executive summary

The Paris Agreement provides a framework for stronger climate action that will increase the need for carbon capture and storage (CCS). The global community agreed in Paris to a more ambitious temperature target of "well below 2°C", to pursue efforts towards 1.5°C and to balance emissions during the second half of this century. This will require rapid and extensive deployment of all low-emissions technologies, including CCS. CCS remains the only technology solution capable of delivering significant emissions reductions from the use of fossil fuels in power generation and industrial processes. It can also play an important role in delivering future "negative emissions" which, according to the Intergovernmental Panel on Climate Change (IPCC) become increasingly important under more ambitious mitigation scenarios. CCS is the potential "sleeping giant" that needs to be awakened to respond to the increased ambition of the Paris Agreement.

Two decades of experience and growing recognition by climate experts

2016 marks a significant milestone, with two decades of successful CCS operations at Sleipner. Since 1996, the Sleipner project in Norway has been separating carbon dioxide (CO_2) from a natural gas production facility and injecting it in the Utsira sandstone formation some 800-1 100 metres beneath the seabed. The project has now safely and permanently stored close to 17 million tonnes (Mt) of CO_2. Sleipner is significant not because it was the first large-scale CO_2 capture and injection project – three projects had already been capturing CO_2 for enhanced oil recovery (EOR) in the United States – but because Sleipner was the first project to have permanent, dedicated CO_2 storage with associated CO_2 monitoring as an objective.

Recognition of the role of CCS has continued to grow since the 2005 IPCC Special Report on CCS. The 2005 report was a major turning point in terms of recognition by climate experts of the role of CCS in constraining future temperature increases. This recognition has continued to evolve, with the IPCC Fifth Assessment Report (AR5) in 2014 highlighting that the availability of CCS and bioenergy with CCS (BECCS) will be "critical in the context of the timing of emissions reductions". The AR5 also found that many climate models were unable to achieve atmospheric concentrations of about 450 parts per million (ppm) CO_2-eq – equivalent to temperature increases of around 2°C – under limited availability of CCS. It is now anticipated that CCS will be a feature of the 2018 IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emissions pathways.

CCS is moving forward, albeit slowly

The global portfolio of large-scale projects continues to expand and diversify. The number of large-scale CCS projects in operation has expanded to 15, with six more expected to come online within the next two years. The size of dedicated CO_2 storage projects is also growing, with the world's largest project at the Gorgon liquefied natural gas (LNG) plant in Australia expected to commence injecting more than 3 $MtCO_2$ per year from 2017. The global CCS project portfolio now includes a coal-fired power plant with CCS at Boundary Dam in Canada, the world's first iron and steel CCS project in Abu Dhabi, as well as natural gas processing, hydrogen, fertiliser and coal gasification plants with CCS. Projects currently under construction will further diversity this portfolio, including a bioethanol plant in the United States. The experience with CCS projects to date underscores the reality that CCS is not just a so-called "clean coal technology", but a technology capable of addressing emissions from a wide range of power and industrial processes.

Research and development efforts have delivered technology advances. More than 20 years of dedicated CCS research and development have delivered significant advances across capture, transport and storage technologies. The costs and energy penalty of post-combustion capture technologies have been reduced with technologies now being applied on a commercial scale; a new technology for CO_2 capture from natural gas combined-cycle plants is being scaled up with benefits including high efficiencies and net water production. Major advances have been made in the measurement, monitoring and verification (MMV) of CO_2 storage, which have contributed to greater confidence in the potential and suitability of deep saline formations as a permanent CO_2 storage option. Research and development efforts will continue to be important in refining and improving CCS technologies, but major breakthroughs and cost reductions will likely only be achieved through actual deployment at scale.

Increased recognition of CCS has not been matched with increased support

CCS deployment has been hampered by fluctuating policy and financial support. Following the release of the 2005 IPCC Special Report on CCS and in the lead-up to the 2009 Copenhagen climate negotiations (COP15) there was a period of considerable momentum in CCS. More than USD 30 billion in public funding announcements were made and G8 leaders pledged to build 20 new large-scale CCS demonstration projects. However, this momentum was not maintained as early CCS deployment proved to be more complex, expensive and politically challenging than anticipated. Of the USD 30 billion in public funding announcements, only around USD 2.8 billion was actually invested in large-scale CCS projects between 2007 and 2014.

Policy certainty and management of future liabilities will be important for CCS investment. Questions regarding the allocation of responsibilities among project developers and governments over the long-term storage of CO_2 still need to be resolved in some regions. The management of the risk of future CO_2 leakage (however unlikely) should distinguish between the local environmental and safety impacts and the broader impact on global climate change mitigation efforts (referred to in this report as “climate-related leakage risk”).

CCS is central to a 2°C pathway: As part of the least-cost portfolio for power and as an essential mitigation solution in industry

In the 2°C scenario (2DS), CCS delivers 94 gigatonnes (Gt) of CO_2 emissions reductions in the period through 2050. This amounts to 12% of the cumulative emissions reduction task in the energy sector. Around 56% or 52 Gt of total CO_2 captured is from the power sector, predominately from coal-fired power generation (80%); 31% or 29 Gt is captured from industrial processes; and 14% or 13 Gt is captured from fuel transformation. Of the 94 $GtCO_2$ captured in the 2DS, BECCS delivers around 14 Gt of “negative emissions” over the period through 2050, primarily from biofuel production. These negative emissions are able to compensate for higher emissions elsewhere in the energy sector.

Without CCS, the transformation of the power sector will be *at least* USD 3.5 trillion more expensive. In a “no CCS in power” scenario variant of the 2DS, deployment of renewable technologies would need to be expanded by an additional 1 900 GW by 2050 over and above the 2DS requirements. This is equivalent to around four times the total wind and solar PV capacity additions achieved in the last decade. In parallel, coal-fired power generation would need to be virtually eliminated, with early retirements and stranding of assets on a significant scale. The reduced reliance on fossil fuels and the increased rate of deployment of renewables beyond that already contemplated in the 2DS would also present considerable challenges, including for existing energy networks, particularly within a 2050 timeframe.

CCS is essential in industry. For some industrial processes, such as the production of chemicals iron and steel, and cement, there are limited alternatives to CCS for deep emissions reductions. The 29 $GtCO_2$ captured in industry in the 2DS represents around 20% of the cumulative emissions reductions from this sector through 2050. The remainder of the emissions reductions are achieved through energy efficiency, fuel or feedstock switching, and deployment of innovative processes. However the potential for these options to contribute to further reductions in emissions may be limited. If CCS were not available, it is likely that much of the 29 $GtCO_2$ reductions achieved by CCS would need to be offset by efforts in other sectors.

The "well-below 2°C" target requires CCS, but we are not on track

Faster deployment of CCS could support the shift from 2°C to the Paris Agreement target of well below 2°C. In the 2DS, industrial emissions become the largest source of annual emissions by 2050, accounting for 45% (7 $GtCO_2$) of global emissions that year. Greater penetration of CCS could help to reduce these remaining industrial emissions and bridge the gap between a 2°C target and well below 2°C. In contrast, the power sector is virtually decarbonised in the 2DS and accounts for only 9% or 1.4 $GtCO_2$ of annual remaining emissions in 2050. Yet the cumulative emissions from power generation through 2050 represent 29% (or 280 Gt) of total emissions. Faster deployment of CCS on coal-fired power generation could reduce cumulative emissions by 35 $GtCO_2$ through 2050 and earlier deployment on gas-fired power generation could deliver an additional 10 $GtCO_2$ in emission reductions.

The current pace of CCS deployment is out of step with Paris ambitions. Notwithstanding significant advances in CCS technologies over the past 20 years, the pace of CCS deployment has fallen short of initial expectations and is not consistent with a 2°C pathway, let alone one well below 2°C. The pipeline of new large-scale CCS projects is shrinking rather than growing, from 77 in 2010 to around 38 today, and no projects have progressed to construction since 2014. Even if all projects under consideration today were to proceed to operation, the entire CCS project portfolio would collectively capture less than one-sixth of the CO_2 capture requirements in the 2DS in 2025.

Accelerating the pace of CCS deployment: The next 20 years

Targeted financial support and development of CO_2 storage resources remain the keys to catalysing CCS. The introduction of financial incentives and the identification and characterisation of CO_2 storage resources are well-recognised as priorities for supporting CCS deployment, including in the IEA *Technology Roadmap for CCS* (2013). The increased ambitions of the Paris Agreement have heightened the need for these measures, but also the need for new approaches and a renewed focus on the key challenges in order to achieve faster and more widespread CCS deployment.

Retrofitting of CCS is needed to reconcile today's reality of more than 1 950 GW of existing coal-fired power plants and the 2°C pathway. Coal currently generates around 40% of global electricity and coal-fired power generation contributes 30% of energy-related CO_2 emissions globally. The ability to retrofit CCS to coal power plants can help to reverse the "lock-in" of emissions while limiting the economic and social cost associated with the premature closure of these plants. China alone currently has around 900 GW of coal-fired power and the IEA has assessed that more than one-third of this could be suitable for CCS retrofit. Confidence in the availability of CO_2 storage and appropriate planning for the addition of CO_2 capture facilities (including ensuring that new plants under construction are retrofit-ready) will be important to maximise future retrofit opportunities.

Negative emissions from BECCS take on increased importance as the world seeks to achieve a net balance of emissions in the second half of the century. The role of negative emissions in achieving more ambitious climate targets was analysed in the IPCC AR5 and is now receiving more attention following Paris. BECCS is the most mature of the negative emission technology options and could generate as much as 10 $GtCO_2$ of negative emissions per year. The world's first large-scale BECCS project, the Illinois Basin Decatur Project in the United States, will commence in 2017, capturing 1 $MtCO_2$ per year from a bioethanol plant. However, widespread deployment will require that technical, economic and social challenges associated with the technology are addressed, particularly the availability of sustainable biomass and access to CO_2 storage sites.

Encouraging low-carbon "clean industrial products" that are produced using CCS could reduce the emissions footprint of key materials such as steel, cement and chemicals. The global demand for industrial products such as crude steel, cement and various chemicals and petrochemicals is expected to be sustained and even increase over the coming decades, even under the IEA 2DS. Chemicals, steel and cement all have significant carbon footprints, and CCS is a key technology to achieve deep cuts in the associated carbon emissions. A combination of market "push" and "pull" levers, such as regulations, incentive mechanisms, and stimulating consumer interest, can help to create the demand for "clean industrial products", and to incentivise the investment in CO_2 capture in various industrial processes.

Novel EOR practices that include monitored CO_2 storage ("EOR+") can produce verifiable, net emissions reductions. EOR is expected to continue to act as a major driver for CCS by providing an additional revenue stream for projects, with interest in EOR now expanding outside of the United States, including in the Middle East, South East Asia and China. Modifying current EOR practices to increase CO_2 utilisation rates and provide for MMV – or "EOR+" – presents an opportunity to maximise the climate benefit of these operations. Where oil produced using EOR+ substitutes for oil extracted through other techniques, significant net emissions reductions can be achieved. The volume of the CO_2 injected and stored can significantly outweigh the emissions from combusting the oil that is subsequently produced. Commercial interest in EOR+ could also encourage further investment in CCS deployment.

Disaggregating the CCS value chain and promoting a storage-driven approach could be effective in facilitating greater levels of investment. The development of CO_2 storage resources remains critical for widespread deployment of CCS. Separating out CO_2 storage development as a distinct business, partially insulated from the different operational and risk profiles of capture and transport, could present an attractive investment proposal for entities with subsurface expertise. This approach would need to be complemented by appropriate policy frameworks and may be a particularly effective strategy for supporting CCS investment by state-owned enterprises.

CCS must be part of a strengthened global climate response

The future for CCS will ultimately depend on a significant strengthening and expansion of the global climate response. The Paris Agreement marked an important and historic milestone with the potential to shape future CCS deployment. The importance of CCS grows with climate ambition and it is now even more critical for achieving a well-below 2°C target. However, there is a major gap between this and today's actions: the Nationally Determined Contributions (NDCs) pledged in the lead-up to Paris are, in the aggregate, consistent with future temperature increases of 2.7°C. Bridging this gap will require high levels of political commitment and a significantly strengthened climate policy response. The pace and intensity with which governments now undertake this task will ultimately determine the future of CCS deployment.

Introduction

The Paris Agreement represents an historic milestone for the energy sector and confirms the globally-agreed target of limiting future temperature increases to "well below 2°C", as well as pursuing efforts towards 1.5°C. Global emissions are to peak "as soon as possible", with rapid reductions thereafter to "achieve a balance between anthropogenic emissions by sources and removals by sinks" in the second half of this century. Achieving these ambitions will require a much faster and more extensive transformation of the energy sector that will challenge current climate and energy policy frameworks.

Carbon capture and storage (CCS) will be an essential technology for achieving this transformation. It is the only solution for deep emissions reductions from industrial processes and from fossil fuel use in the power sector. CCS may also be needed to deliver "negative emissions", which become increasingly important for addressing carbon budget overshoot and compensating for "stubborn" emissions as temperature targets approach 2°C and below.

After more than 20 years of technology and project experience, CCS has been proven in many applications and is ready for deployment. Fifteen large-scale projects are now operating globally across a range of applications, including on coal-fired power generation, and six more are expected to commence within the next two years. However, the lack of policy support for CCS has meant that the pace of deployment has fallen well behind that of other low-emissions technologies, and there is a risk that the current momentum in CCS project deployment will stall by 2020.

The ratification of the Paris Agreement could be an important turning point for CCS. Success in achieving the ambitions of the Agreement will depend on a considerably strengthened global climate policy response. Significantly, the Agreement also provides a framework for action in both the medium term, with the Nationally Determined Contributions (NDCs) covering the period to 2030, and the long term, with Parties encouraged to submit mid-century low-emissions development strategies. This will require governments to look beyond short-term emissions reduction options to ensure that those technologies needed for deep emissions reductions in the future are also supported.

In the IEA 2°C scenario (2DS), CCS delivers 94 Gt of CO_2 emissions reductions across industry and power generation through 2050, including nearly 8 Gt through 2030. A rapid acceleration of current deployment efforts will be essential to keep this outcome within reach, underpinned by targeted financial incentives and support for CO_2 storage development. New approaches and refocusing of efforts could also contribute to reinvigorating CCS deployment efforts. Moving to a well-below 2°C target will require even greater deployment of CCS.

This publication marks 20 years of operation of the Sleipner CCS project in Norway. Sleipner is a major technology milestone which confirms the feasibility of safe, permanent storage of CO_2 in deep saline formations. Its contribution towards improved understanding of CO_2 storage and CCS more widely has been immense. Chapter 1 presents a review of progress in CCS since the commencement of Sleipner in 1996, including advances in capture, transport and storage technology development, project deployment and policy experience. Chapter 2 provides an expanded analysis of the role of CCS in the 2DS; examines the implications of CCS not being available in the 2DS; and considers the potential contribution of CCS to achieving a well-below 2°C target. Finally, Chapter 3 looks at the need to accelerate CCS deployment and explores novel approaches and renewed areas of focus to achieve this. The publication also includes personal commentaries from global CCS experts.

1. Two decades of progress

Key highlights

Twenty years of operation of the Sleipner project represents a major milestone and builds on many decades of experience with carbon capture and storage (CCS) technologies. As the world's first dedicated CCS project, Sleipner shows that very large quantities of carbon dioxide (CO_2) can be safely and permanently stored in deep saline formations.

Since 1996, the number of large-scale CCS projects has grown to 15, with a further 6 projects to commence operation before 2018. A continued expansion of this portfolio is critical to significantly reduce costs and refine the technology.

Progress in CCS has been achieved with only limited policy and financial support. This is despite growing recognition of the potential contribution of the technology since the 2005 Intergovernmental Panel on Climate Change (IPCC) Special Report on CCS.

Strengthened policy frameworks, new business models and increased practical experience to deliver technology improvements by "learning by doing" will all be important in positioning CCS for widespread deployment.

The lessons from more than 20 years of CCS experience provide a strong foundation to accelerate CCS deployment in pursuit of the Paris Agreement climate goals.

Two decades of operation of the Sleipner project have coincided with considerable progress in the development, demonstration and deployment of CCS. During this time, the global portfolio of large-scale projects in operation has grown to 15 and now includes a coal-fired power plant with CCS. Important technology developments have been made across the CCS value chain of CO_2 capture, transport and storage, including reductions in the costs and energy penalty of capture technologies and improved techniques for monitoring stored CO_2. International collaboration continues to grow and the policy and regulatory frameworks required to support CCS deployment are now much better understood.

Yet the pace of CCS deployment has fallen short of initial expectations and remains out of step with growing recognition by climate experts of the importance of CCS as a climate mitigation tool. To a large extent, this reflects that governments have struggled to provide the policy and financial support needed to shepherd the technology through the capital-intensive early deployment phase. The lack of adequate support coupled with first-of-a-kind technology challenges have contributed to the cancellation of 22 advanced large-scale CCS projects[1] since 2010.

Understanding these challenges and reflecting on the achievements of the last 20 years can play an important role in accelerating the deployment of CCS in the next 20 years.

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[1] Advanced projects are defined as those in the "define" stage of project development as described by the Global CCS Institute methodology.

1.1 CCS continues to be essential

CCS is the only technology capable of delivering significant emissions reductions from the use of fossil fuels in power generation and industrial applications. When combined with bioenergy, CCS can also remove CO_2 from the atmosphere and generate "negative emissions" – a potentially critical option for limiting future temperature increases to 2°C or below.

The future contribution of CCS is routinely overlooked in many mainstream climate and energy policy discussions, arguably overshadowed by the rapid expansion and cost reductions achieved by renewable energy technologies and the increasing attention given to the impact of energy efficiency on energy demand. At the same time, there is a perception that CCS will not be needed in the short to medium term. While there is no question that renewables and energy efficiency are a significant and critical part of the global climate response, the scale of the challenge means that all technologies, including CCS, will be needed to reduce emissions across all parts of the energy system.

In industry, there are limited substitutes for CCS to reduce emissions associated with certain processes. Emissions from industry accounted for around 26% of global CO_2 emissions in 2013, or 8.9 $GtCO_2$ each year. While there are some emissions in industrial processes which can be reduced through energy efficiency and switching to low-carbon heat and electricity generation, CCS is one of the only options available to address the bulk of emissions generated from chemical reactions inherent in the process of iron, steel and cement production. It is also the only option available to address emissions from natural gas processing, where CO_2 is stripped from the extracted gas to meet market specifications. CO_2 storage provides an alternative to the current practice of venting this CO_2 into the atmosphere.

Within the electricity sector, CCS provides a solution to reducing emissions from current and future coal and gas-fired power generation plants. These plants will remain a feature of the energy mix for many decades to come, particularly in developing countries where governments face the challenge of reconciling energy security, economic development and environmental objectives in parallel with ambitious electrification programmes (IEA, 2016a). In the IEA 2°C scenario (2DS), more than half of CCS deployment is in power generation and of this almost 75% occurs outside of the OECD (see Section 2.1.2). The value of CCS as a retrofit option for existing power generation infrastructure is discussed in Section 3.2.

1.2 IPCC Special Report on CCS: A major milestone amidst fluctuating policy support

Over the past two decades, recognition of the role of CCS has evolved in tandem with global understanding of climate threats and mitigation options. In 1995, the IPCC in its Second Assessment Report briefly acknowledged CCS as a "promising technology". The report noted that "the removal and storage of CO_2 from fossil fuel power-station stack gases is feasible" but that "for some longer term CO_2 storage options, the costs, environmental effects and efficacy of such options remain largely unknown" (IPCC, 1995).

A decade later, the IPCC produced its Special Report on Carbon Dioxide Capture and Storage (SRCCS) which became a major turning point, raising the profile of CCS technology among climate experts and securing its recognition and acceptance as a key option for reducing global CO_2 emissions (Gale et al., 2015). By 2014, the IPCC Fifth Assessment Report (AR5) identified CCS as being critical to achieving more ambitious climate targets: "many models could not achieve atmospheric concentration levels of about 450 parts per million (ppm) CO_2-eq by 2100 … under limited availability of key technologies, such as bioenergy, CCS, and their combination" (IPCC, 2014a). The IPCC analysis also found that, without CCS, the cost of achieving atmospheric concentrations in the range of 430-480 ppm CO_2-eq would be 138% higher.

In 2018, the IPCC will deliver a special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emissions (GHG) pathways. In light of the findings of AR5, there is a strong expectation that CCS, including bioenergy with CCS (BECCS), will be a feature of this report.

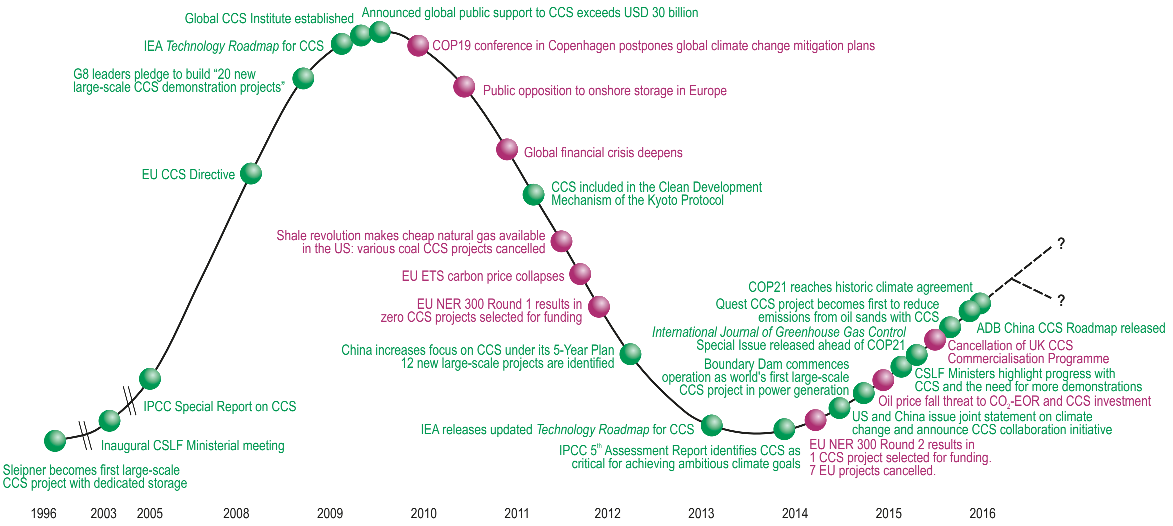
Policy support fluctuates despite growing recognition

Although recognition of CCS by climate experts has increased over time, policy and financial support has fluctuated sharply, partly in response to global climate change policy developments and economic conditions (see Figure 1.1). There was considerable momentum prior to the release of the IPCC Special Report on CCS, including with the first ministerial-level meeting of the Carbon Sequestration Leadership Forum (CSLF) in 2003. This momentum continued to build in the years leading up to the Copenhagen COP15 climate negotiations in 2009, with the EU CCS Directive in 2008; G8 leaders committing to launching 20 large-scale CCS projects by 2010; the release of the first IEA roadmap for CCS and the establishment of the Global CCS Institute (GCCSI) in 2009. By 2010, cumulative public funding commitments for CCS totalled more than USD 30 billion (GCCSI, 2010).

However, much of this momentum was lost when Copenhagen failed to fulfil expectations and as governments continued to grapple with the global financial crisis. More than 20 advanced large-scale CCS projects were cancelled between 2010 and 2016 and the announced funding commitments were either scaled back or withdrawn across Europe, the United States and Australia. More recently, the 2015 cancellation of the United Kingdom’s GBP 1 billion CCS Commercialisation Programme while in the final stages of project selection and just days before COP21, dealt a major blow to CCS, and resulted in the cancellation of two highly prospective and important projects – White Rose and Peterhead. The Peterhead CCS project was the only advanced project proposing to apply CCS to gas-fired power generation, and White Rose would have been the first demonstration of oxy-fuel capture technology at scale. Additionally, the recent commodity market downturn has significantly reduced the interest and capacity of oil, gas and coal companies to invest in CCS.

Yet there is still cause for optimism. In 2015, China confirmed its strong interest in CCS with the announcement of a bilateral CCS initiative with the United States as well as the release of the China CCS Roadmap, developed by the Asian Development Bank and the National Development and Reform Commission. Globally, six large-scale projects are expected to commence operation within the next two years, including two further projects in power generation. In the lead-up to the Paris negotiations in 2015, the International Journal of Greenhouse Gas Control also released a Special Issue which marked ten years since the IPCC Special Report on CCS and provided an influential and important update of technical progress in CCS. The subsequent success of the Paris COP21 negotiations has also reinvigorated global climate policy and challenged governments to accelerate the transition to near zero net emissions. The post-Paris period may therefore be fertile ground to regain momentum in CCS, as well as an opportunity to adopt new approaches and thinking in CCS deployment.

Figure 1.1 • CCS policy and political support over time



Source: Adapted from SBC Energy Institute (2016), Low Carbon Energy Technologies Fact Book Update: *Carbon Capture and Storage at a Crossroads*.

1.3 The global portfolio of CCS projects

Global deployment of CCS has progressed in spite of fluctuating and limited policy support. The number of large-scale[2] CCS[3] projects in operation has grown from 3 to 15[4] since Sleipner first started in 1996 (see Table 1.1). These projects are capable of capturing up to 28 million tonnes (Mt) of CO_2 every year, but more importantly they are providing the critical hands-on experience needed to deliver technology cost reductions, to refine policy and regulatory frameworks, and to pave the way for widespread deployment of CCS across power and industrial applications.

The drivers for these projects are varied: early CCS projects all involved processes in which CO_2 was routinely separated anyway, such as in natural gas processing, combined with demand for CO_2 for enhanced oil recovery (EOR). Since the early 1970s, EOR has underpinned CCS development in the United States, with 11 of the 15 projects currently operating supplying CO_2 for EOR.

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[2] Large-scale projects are defined according to the Global CCS Institute as "projects involving the capture, transport, and storage of CO_2 at a scale of at least 800 000 tonnes of CO_2 annually for a coal–based power plant, or at least 400 000 tonnes of CO_2 annually for other emissions-intensive industrial facilities (including natural gas–based power generation)".

[3] For the purposes of this publication, projects which use CO_2 for EOR are also broadly included in references to "CCS projects"; although in practice they represent large-scale utilisation of CO_2 rather than dedicated CO_2 storage operations.

[4] This does not include the In Salah project, which operated between 2004 and 2011.

Table 1.1 • Large-scale CCS projects in operation or under construction

Project name	Country	Operation date	Source of CO_2	CO_2 capture capacity (mtpa)	Primary storage type
OPERATING PROJECTS					
Val Verde Natural Gas Plants	US	1972	Natural gas processing	1.3	EOR
Enid Fertilizer CO_2-EOR Project	US	1982	Fertiliser production	0.7	EOR
Shute Creek Gas Processing Facility	US	1986	Natural gas processing	7.0	EOR
Sleipner CO_2 Storage Project	Norway	1996	Natural gas processing	0.9	Dedicated
Great Plains Synfuel Plant and Weyburn-Midale Project	Canada	2000	Synthetic gas	3.0	EOR
In Salah CO_2 Storage*	Algeria	2004	Natural gas processing	1.0/0.0	Dedicated
Snøhvit CO_2 Storage Project	Norway	2008	Natural gas processing	0.7	Dedicated
Century Plant	US	2010	Natural gas processing	8.4	EOR
Air Products Steam Methane Reformer EOR Project	US	2013	Hydrogen production	1.0	EOR
Coffeyville Gasification Plant	US	2013	Fertiliser production	1.0	EOR
Lost Cabin Gas Plant	US	2013	Natural gas processing	0.9	EOR
Petrobras Lula Oil Field CCS Project	Brazil	2013	Natural gas processing	0.7	EOR
Boundary Dam Carbon Capture and Storage Project	Canada	2014	Power generation	1.0	EOR
Quest	Canada	2015	Hydrogen production	1.0	Dedicated
Uthmaniyah CO_2 EOR Demonstration Project	Saudi Arabia	2015	Natural gas processing	0.8	EOR
Abu Dhabi CCS Project	United Arab Emirates	2016	Iron and steel production	0.8	EOR
UNDER CONSTRUCTION					
Illinois Industrial Carbon Capture and Storage Project	US	2017	Chemical production	1.0	Dedicated
Kemper County Energy Facility	US	2016	Power generation	3.0	EOR
Petra Nova Carbon Capture Project	US	2016	Power generation	1.4	EOR
Alberta Carbon Trunk Line ("ACTIL") with Agrium CO_2 stream	Canada	2017	Fertiliser production	0.3-0.6	EOR
ACTIL with North West Sturgeon Refinery CO_2 stream	Canada	2017	Oil refining	1.2-1.4	EOR
Gorgon Carbon Dioxide Injection Project	Australia	2017	Natural gas processing	3.4-4.0	Dedicated

Source: Global CCS Institute, data current as of end-August 2016.

Note: EOR = enhanced oil recovery

* Injection at the In Salah project has been suspended since 2011, when the project was capturing around 1.0 Mtpa.

Government regulations or incentives have also been an important driver for projects, particularly in Norway and Canada. These include a CO_2 tax on upstream oil and gas production in the case of the Norwegian projects, Sleipner and Snøhvit. In Canada, regulations on coal-fired power station emissions as well as direct financial assistance underpinned investment in the world's first coal-fired power unit with CCS at Boundary Dam. Direct financial support from governments has been important in at least four of the currently operating projects, and features in all six of the projects expected to commence operation in the next two years.

1.3.1 The first large-scale CO_2 capture projects: 1970s and 1980s

Sleipner was the first large-scale project in which dedicated geological storage of CO_2 was the goal, however the history of CCS and of its constituent technologies extends many years before Sleipner. Important lessons have been learnt from large-scale projects incorporating aspects of CCS since the early 1970s. Together with Sleipner, these early projects paved the way for an ever-increasing expansion of CCS projects from 2000 onwards.

Val Verde, Texas

Underground deposits of natural gas can contain significant CO_2 content – as much as 70% – which must be removed to meet technical specifications before the natural gas is sold and used. Techniques for removing CO_2 from natural gas streams to meet these requirements have been in use since the 1930s (Rochelle, 2009). While there have been small-scale uses for the CO_2 captured, usually the vast bulk of the separated CO_2 has been vented to the atmosphere.

In the early 1970s, the first large-scale use for some of this waste CO_2 was pioneered by the oil and gas industry in the southern United States. Starting in 1972, a group of oil companies decided to try injecting CO_2 into a producing oil field to supplement other production enhancement techniques, in an attempt to produce an even greater fraction of the oil in place. This activity subsequently developed further and became known as CO_2-enhanced oil recovery, CO_2-EOR. Typically, 1 tCO_2 used in EOR will allow for the recovery of approximately 2 to 3 additional barrels of oil.

The CO_2 for the Val Verde project was initially sourced from a waste stream of by-product CO_2 from several natural gas processing facilities in the Val Verde area of southern Texas. Instead of being vented, the CO_2 that had already been separated from the natural gas stream was compressed and transported through the first large-scale, long distance CO_2 pipeline to an oilfield several hundred kilometres (km) away. The CO_2 was then injected into the SACROC (Scurry Area Canyon Reef Operators Committee) Unit of the Kelly Snyder Field in Scurry County, West Texas.

As this was the first large-scale CO_2 injection project,[5] important lessons were learnt from all aspects of Val Verde-SACROC for subsequent CO_2-EOR and dedicated storage projects, including injection techniques, CO_2 behaviour in underground reservoirs, ultimate CO_2 storage rates, and effects on petroleum production ratios. Extensive research has been carried out by the range of petroleum companies which have had interests in the fields since the 1970s, and by academic institutions such as the University of Texas. This use of captured CO_2 for EOR provided an important opportunity for demonstrating all components of CCS: capture, transportation and storage (Parker et al., 2011).

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[5] With more than one million tonnes of CO_2 captured, transported and injected.

Early expansion of CO_2-EOR in the United States

The response of the SACROC petroleum reservoirs to the injected CO_2 convinced several other major oil companies of the viability of this technique. It also became obvious that while a fraction of the CO_2 injected returned to the surface with the extra oil production, a large part remained underground in the reservoir. The small fraction which came to the surface was re-injected and therefore, over time, the amount of CO_2 which remained underground increased.

In the 1980s, two further projects were developed in the United States using industrially-produced CO_2 for EOR: the Enid Fertiliser plant and Shute Creek natural gas processing facility. The Enid Fertiliser plant in Oklahoma uses a process which results in a high-purity, high-concentration CO_2 off-gas stream. Since 1982, around 680 000 t a year of this CO_2 has been compressed and transported 225 km from the plant to depleted oil fields in southern Oklahoma for EOR purposes (GCCSI, 2016a).

The Shute Creek facility in Wyoming processes natural gas from the nearby LaBarge field, which has a 65% CO_2 content. The need to find a use for this CO_2 was recognised from the start of field development planning (Parker et al., 2011). Since the commencement of operations in 1986, 4-5 Mtpa of CO_2 from Shute Creek has been sold for EOR in Colorado and Wyoming. The expansion of the project in 2010 increased the CO_2-EOR capacity to around 7 Mtpa, making Shute Creek one of the largest projects in the world. A further 400 000 t/yr of CO_2 is disposed of as part of a concentrated acid gas stream of about 60% hydrogen sulphide and 40% CO_2, which is injected into a carefully selected section of the same reservoir from which it was produced. Significant research has been undertaken in relation to the Shute Creek project over the years by both the project operator ExxonMobil and other academic and research organisations, leading to process improvements, new technologies and lessons learnt that can be applied to other CCS projects.

The EOR activity in the 1980s and 1990s was supported by the United States federal government, with a fiscal regime that favoured CO_2-EOR over production from new oil fields (Dooley, Dahowski and Davidson, 2010). The interest and activity of the US Department of Energy continues today, with both research through its National Energy Technology Laboratory and through continuing fiscal incentives.

1.3.2 A major milestone: The first dedicated CO_2 storage project at Sleipner

From around the mid-1980s to the mid-2000s, oil and gas prices were weak, and operators were reluctant to make the significant investments necessary for CO_2-EOR projects. During this period, however, three large-scale CCS projects were developed in which the goal was dedicated storage of the CO_2.

The first of these projects was Sleipner, in the Norwegian part of the North Sea. In 1990, it became clear in concept planning that the natural gas in the Sleipner West reservoir contained about 9% CO_2, which far exceeded the customers' specifications. The CO_2 content would have to be reduced before natural gas from the field could be sold (Statoil, 2016).

In 1991, the Norwegian government introduced an offshore CO_2 tax as an effort to reduce emissions from Norwegian offshore oil and gas activities. This tax would have applied to any CO_2 that was released into the atmosphere after being separated from Sleipner West gas. The CO_2 tax was one of the triggers for operator Statoil's subsequent plans to separate the CO_2 offshore and inject it into deeper geological layers under the CO_2 platform, rather than simply venting it into the atmosphere. The layer contains porous sandstone filled with saltwater. The CO_2 is trapped under a 700-metre thick layer of sealing rock.

Production from Sleipner West started in 1996, and since then about 1 Mtpa of CO_2 has been separated and stored. From the beginning of the project, Statoil has focused on sharing information and experience from Sleipner. The subsurface storage of CO_2 has been mapped in various research projects. Seismic surveys and other measurements show that the storage and behaviour of CO_2 underground are in line with the plans established prior to injection.

Sleipner paved the way for two more dedicated CO_2 storage projects associated with natural gas processing. The In Salah natural gas project in Algeria commenced operations in 2004 and was designed with CO_2 storage and monitoring in mind. Important research and intensive monitoring of CO_2 storage were conducted over the first seven to eight years of project life (Ringrose et al., 2013). Carbon dioxide injection was suspended in 2011 as the future injection strategy was reviewed, although the comprehensive site monitoring programme continues. The project also presents an excellent project closure study opportunity (the world's first). The Snøhvit liquefied natural gas (LNG) project in the far north of Norway started production in 2008 and injects the CO_2 separated from the natural gas stream into non-petroleum bearing rock formations. The Snøhvit project also employs a comprehensive monitoring and verification programme to investigate the behaviour of CO_2 underground (GCCSI, 2016b).

Commentary 1 • 20 years of the Sleipner CCS project, Norway

Olav Skalmeraas

Vice President, Statoil

The Sleipner CO_2 capture and storage (CCS) project in offshore Norway is the world's first industrial-scale CCS project, and marks its 20-year milestone of operations in 2016.

CO_2 injection started on 15 September 1996, and since then a steady stream of insights from this project have been shared with numerous research projects globally, helping to build confidence and competence in support of this vital greenhouse gas reduction measure. The IPCC reports of 2007 (AR4) and 2014 (AR5) have used the Sleipner project as a landmark to inspire and inform action on climate change mitigation. By 2016 the Sleipner project had stored 16 million tonnes (Mt) of CO_2 in the Utsira sandstone formation which, with the addition of 4 Mt from the Snøhvit CCS project in offshore northern Norway, pushes Norway past the 20 Mt storage milestone for the 20th year of operations at Sleipner.

This pioneering project emerged after discussions in 1990 to find a concept solution for the Sleipner West gas and condensate field in the North Sea. The natural gas in the reservoir contained about 9% CO_2 and needed to be reduced significantly to reach commercial specification. In 1991, the Norwegian authorities introduced a CO_2 emissions tax as an effort to reduce greenhouse gas emissions from Norwegian offshore oil and gas activities. The additional investments required to compress and re-inject the removed CO_2 amounted to approximately USD 100 million (in 1996). The CO_2 tax was one of the triggers for Statoil's plans to separate the CO_2 from the gas offshore and inject it into deep geological layers near the gas and CO_2 processing platform. Norwegian CO_2 taxes are applied differently to different industry sectors, and for the offshore oil and gas sector the CO_2 quota price is currently around USD 60 per tonne.

Sleipner is an industrial project in which CCS was implemented as part of a gas field development. The bold and pioneering business decision to deploy CCS, despite the lack of similar experiences elsewhere, led to a lot of interest in the project as a demonstration of the concept of geological disposal of CO_2 captured from industrial activities. The Sleipner CO_2 monitoring programme which was needed to ensure secure long-term storage has included time-lapse seismic, gravity field monitoring and marine and seabed surveys. Some of these programmes were able to benefit from research funding from the European Union, Norway and worldwide in order to develop specific technologies for wider deployment of CO_2 storage. Many lessons learnt from this industrial-scale demonstration project were adopted as best practices, and lessons from Sleipner were used as a guide for the EU Directive on geological storage of carbon dioxide (adopted by the European Parliament in 2009). Modifications to the London Protocol and the OSPAR Convention to permit CO_2 storage in offshore geological formations have also used Sleipner as a benchmark reference.

In terms of long-term safety, the injected CO_2 will remain in the storage unit (Utsira sandstone) for thousands of years, in a similar way that natural gas has been trapped in deep geological formations for millions of years. The Utsira sandstone is a very extensive and highly porous sandstone filled with salt water (a saline aquifer formation) and the CO_2 is trapped under an 800-metre thick layer of ceiling rock preventing any seepage into the atmosphere.

The subsurface storage of CO_2 has been mapped in various research projects, partly funded by research funds from the European Union and the Norwegian Research Council. Seismic surveys and gravity field measurements have been especially valuable and show that the storage and extent of CO_2 underground are in line with the plans established prior to injection. Statoil has recognised the value of this project by sharing information and experience from Sleipner with numerous research networks and institutions globally, with the Norwegian institutions SINTEF and the Norwegian University of Science and Technology being central to these efforts. Many technical articles have been published on modelling and monitoring CO_2 storage using the data from Sleipner, helping to build confidence in the concept and improving our understanding of the processes involved.

The CO_2 capture is achieved using a conventional monoethanolamine (MEA) process, although Sleipner was the first project to implement this process on an offshore platform. In continuous operation since 1996, the project continues past this year's 20-year landmark, and has now begun to process and store CO_2 from neighbouring gas fields in the Sleipner area. Statoil, with its partners ExxonMobil and Total in the Sleipner Licence and along with numerous research partners are proud of this pioneering CCS project – the first to demonstrate the feasibility of safe, long-term storage of CO_2 in deep underground formations. The Sleipner CCS project has received several technology awards including the Carbon Sequestration Leadership Forum (CSLF) Global Achievement Award in 2011.

Since starting injection in 1996, several other industrial-scale CCS projects have emerged (in Norway, Canada, the United States, Australia and elsewhere). However the value of the Sleipner project is quite unique and will continue to be used to strengthen and build up CCS globally. It is often said that "the world needs a thousand Sleipners" to address the climate challenge. While this ambition is clear, each low-carbon project (including CCS, renewable energy, and hydrogen energy) builds on the experience of previous projects. Sleipner shows that our society can control GHG emissions from industrial processes and from fossil fuel combustion "brick by brick" and project by project. We hope the Sleipner 20-year milestone will inspire others for many years to come.

The Norwegian government recently announced completion of feasibility studies for the next large-scale CCS project in Norway, where CO_2 captured from onshore industrial sites will be stored in offshore saline aquifers. This next generation project will build heavily on the Sleipner experience and focus on bringing costs down, using new novel technologies and finding the most cost-efficient ways to construct, operate and monitor the storage of CO_2. If a positive decision by the Norwegian government to proceed with the next phase of this large-scale CCS project is made it would be an unique opportunity to have a first-of-a-kind industrial CCS value chain where CO_2 is transported by ship and stored in an offshore formation.

However, equally important as technology and monitoring improvements for the further deployment of CCS is to establish business models that balance risk and reward in such a way that each part of the value chain can attract industrial companies. In most cases, this would only be possible if the business models are tailored to the different challenges and opportunities along a value chain. As CCS in the medium term will be in a pre-commercial phase this will require a strong public-private partnership structure where governments take on the role as a value chain integrator and guarantor as well as tailoring financial support to complement the current low price of CO_2.

Twenty years of successful CO_2 storage operations could be replicated, but barriers such as business models, regulatory issues and commercial drivers need to find solutions through concrete projects. Commercial companies have shown interest but without active and close public-private partnerships, the prospects for a wide deployment of CCS would see significant setbacks.

1.3.3 A CO_2-EOR revival in the United States spurs industrial CCS projects

From 2000 onwards, and particularly since 2010, there has been renewed interest in the use of CO_2 for EOR, initially in North America[6] but more recently in other oil-producing countries.[7] The first of this wave of CO_2-EOR projects started in 2000, taking gas from the Great Plains Synfuel Plant in North Dakota, United States, across the Canadian border to the Weyburn and Midale oil fields in Saskatchewan, Canada. The Great Plains plant converts coal into synthetic natural gas in a process that results in a CO_2 stream which is very dry and about 95% pure. Around 3 Mtpa of CO_2 is compressed and transported.

The IEAGHG Weyburn-Midale CO_2 Monitoring and Storage project was conducted alongside CO_2-EOR operations between 2000 and 2012. This international research project, hosted by Canada's Petroleum Technology Research Centre, is considered to be the largest full-scale CCS field study ever conducted. It included the study of mile-deep seals that contain the CO_2 reservoir, CO_2 plume movement, and the monitoring of permanent storage. The international consortium sponsoring this project included six governments or government-sponsored agencies and ten international energy companies. The IEA Greenhouse Gas R&D Programme (IEAGHG) supported the initial establishment of the programme, the ongoing technical programme of work and also undertook a formal expert review of the project.

Between 2010 and 2013, four further CO_2-EOR projects in the United States were developed using industrially-sourced CO_2 (see Table 1.1). These projects demonstrate the applicability of CCS to a wide range of industrial processes. They also include the Century Plant natural gas processing facility in Texas, which is the largest CO_2 capture project in the world with a capacity of 8.4 Mtpa.

These have since been joined by two CO_2-EOR projects outside North America. The Petrobras Lula Oil Field CCS Project is located approximately 300 km off the coast of Rio de Janeiro, Brazil. Since 2013, CO_2 has been separated from the natural gas stream associated with oil production, and re-injected into the producing oil reservoirs. The ultra-deep waters make the Lula field a pioneer in CO_2-EOR development, with the deepest CO_2 injection well in operation. In 2015, operations started at the Uthmaniyah CO_2-EOR demonstration project in Saudi Arabia. This takes CO_2 from a natural gas liquids processing unit, to a part of the giant Ghawar oilfield, the world's largest. The project duration is expected to be three to five years, and is designed to determine incremental oil recovery, estimate sequestered CO_2, address uncertainties including migration of CO_2 within the reservoir, and identify any operational concerns. The project includes a comprehensive monitoring and surveillance plan which will be important in verifying the permanent storage associated with these EOR activities (see further discussion of the value of this in Section 3.5).

1.3.4 The CCS project portfolio continues to expand – for now

CO_2 capture from power generation: The Boundary Dam CCS Project

All of the large-scale projects which commenced operations before 2014 used CO_2 which was produced in high concentrations either as part of an industrial process (such as in fertiliser

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[6] The history of CO_2-EOR spans several decades in the United States and Canada. Currently some 140 projects are in operation, producing 300 000 barrels of oil (bbl) per day, that is, 0.35% of global oil production. However, much of the CO_2 used for EOR in North America is from natural sources and as such is not akin to CO_2 storage for climate change purposes, although it has been able to drive the development of relevant technologies and techniques.

[7] The *Oil and Gas Journal* produces a *Worldwide EOR Survey*, which details the extent and nature of EOR operations globally.

production) or by the inherent need to separate CO_2 from other gases (such as in natural gas processing). While these CO_2 streams would ordinarily have been released to the atmosphere, it was a relatively simple process to compress the gas for transportation to an underground reservoir or oil field instead.

In conventional coal-fired or natural gas-fired electricity generation, large amounts of CO_2 are produced during combustion of the fuel in air, but only as a small fraction of the flue gas stream. The bulk of the waste gas in this case is nitrogen compounds, as nitrogen is the major component of air. Separating CO_2 from the other flue gases after combustion of the fuel is more expensive.

The first large-scale project in which CO_2 was separated from power station flue gases is the Boundary Dam Carbon Capture and Storage project in Saskatchewan, Canada, which commenced operations in 2014. The Boundary Dam CCS Project rebuilt a 115 megawatt coal-fired generation unit with carbon capture technology capable of reducing GHG emissions by up to 1 Mtpa of CO_2 each year. The captured CO_2 is sold and transported by pipeline to nearby oil fields in southern Saskatchewan where it is used for EOR (SaskPower, 2016a). CO_2 not used for EOR will be stored in the Aquistore Project, a research and monitoring project which analyses the effects of storing CO_2 deep underground in a layer of brine-filled sandstone (SaskPower, 2016a).

Canada was among the first countries in the world to make laws on emission reduction for coal-fired power plants. In 2011, the federal government announced strict performance standards for new coal-fired units and units that have reached the end of their useful life. Rebuilding the ageing Number 3 unit at Boundary Dam with carbon capture technology enabled the project operator, SaskPower, to meet these standards, while selling the CO_2 for EOR provided a revenue stream to help offset the added cost involved in carbon capture. In addition, the project received CAD 240 million in capital support from the Canadian government.

The operational experience gained from the Boundary Dam project has given SaskPower confidence that the capital costs of the next plant could be reduced by 25 to 30% and operating costs by 25% (IEAGHG, 2015). As of August 2016, the project has surpassed 1 Mt of CO_2 stored (SaskPower, 2016b). The announcement of the establishment of the SaskPower and BHP Billiton CCS Knowledge Centre will also promote the sharing of information and learning from the Boundary Dam project globally.

Reducing emissions from Canadian oil sands: The Quest project

The most recent dedicated storage project is the Quest CCS project in Canada, which commenced operations in November 2015. In September 2016, the project announced that it had reached a major milestone in capturing and storing 1 $MtCO_2$ from Shell's Scotford upgrader (Shell Canada, 2016a). The captured CO_2 is transported via a 60 km pipeline to a site where it is injected and permanently stored in the Basal Cambrian Sand, a geological formation more than 2 000 metres underground. The Scotford upgrader and the Quest project are part of the 255 000-barrel-per-day Athabasca Oil Sands Project. The project received considerable financial support – around CAD 865 million – from the Canadian and Alberta governments and has an extensive information sharing programme as well as longstanding and frequent stakeholder outreach and engagement activities, including with the local community (Shell Canada, 2016b).

The next wave of projects

In addition to the 15 operational projects, as of October 2016 there are 6 under construction and a further 5 in the advanced stages of project definition. These projects will broaden the project portfolio in important areas, including demonstrating pre- and post-combustion capture technologies for coal-fired power generation and bioethanol production. While these projects can draw from the experience of the successful projects described above, as well as lessons from those projects that did not proceed (see Box 1.1), they are anticipated to advance the CCS effort by providing further commercial experience, enabling key technologies to be refined and leading to further cost reductions. Notably, 12 of the 17 large-scale projects in earlier stages of development are being led by state-owned enterprises (SOEs). This continues a historical trend of SOE participation as almost one-third (seven) of the projects in operation or under construction are owned, or majority owned, by state-owned enterprises. Section 3.6.6 includes a discussion on the implications of SOE engagement in the development and deployment of CCS.

The overall trends, however, raise concerns. The number of integrated CCS projects which have failed to reach a financial investment decision (FID) outnumbers the successful projects by a factor of two to one. In 2010, the GCCSI stocktake of large-scale CCS projects had 77 projects at various stages of development; by late-2016 this list had shrunk to 38 projects. There is significant potential for stagnation in global project development from around 2020 given the shrinking number of projects in the early to mid-stages of development.

Box 1.1 • Lessons from projects that did not proceed

For every large-scale CCS project that has been operating or has commenced construction since 2010, there are at least two projects that have been cancelled.[8] This is not unexpected: these first-of-a-kind projects are often technically complex and require significant capital investment and policy support. Decisions not to proceed to an FID have reflected a mix of commercial, technical, policy, social and economic considerations. Three examples are briefly explored below.

The **FutureGen 2.0** Oxy-fuel with CCS project in Illinois, United States was cancelled in large part due to the withdrawal of USD 1 billion in federal funding. The project was required to spend the funds, committed under the *American Recovery and Reinvestment Act* of 2009, by 30 September 2015. The funding was withdrawn by the Department of Energy as it determined that the project was highly unlikely to meet this deadline. The design of the stimulus funding arrangements did not provide the flexibility needed for first-of-a-kind technology deployment in this case.

The **ZeroGen** integrated gasification combined cycle (IGCC) with CCS project in Queensland, Australia undertook detailed pre-feasibility work which saw cost estimates escalate by 46% compared to earlier scoping studies. This was due to additional scope and local influences, including exchange rates and domestic productivity factors. At AUD 6.9 billion, these detailed cost estimates identified that public support both in the development phase as well as the operating phase would be required "beyond that thought likely to be available" (Garnett, Greig and Oettinger, 2012). In addition, the only CO_2 storage option that the project was able to investigate proved to be unsuitable, underscoring the value of a) examining multiple storage options and b) commencing work on storage in advance of major investment in the capture facility.

The cancellation of Shell's **Barendrecht** CCS project in the Netherlands, in response to intense opposition from the local community and municipal and provincial governments, has been well documented (Feenstra, Mikunda and Brunsting, 2010). The project has been important in demonstrating the importance of building trust with the local community and of early engagement with key stakeholders. It also established a strong preference within Europe to focus future development efforts on the considerable offshore CO_2 storage opportunities rather than further onshore storage.

1.3.5 Pilot projects are making a significant contribution

The global CCS development and demonstration effort currently underway extends well beyond the portfolio of large-scale, integrated CCS projects. There have been a very large number of

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[8] This includes large-scale CCS projects across all stages of the project development cycle.

smaller-scale projects that have made, or are making, a significant contribution to understanding of CCS technologies. Projects at pilot, bench and laboratory scale have numbered into the hundreds. These smaller projects are evidence of the breadth of global interest in CCS, with projects in Australia, Canada, China, Chinese Taipei, France, Germany, Japan, Korea, the Netherlands, Norway, Spain, the United Kingdom and the United States. While much attention has been focused on projects in Europe and North America, significant pilot-scale projects and R&D activities are now also occurring in Asia and the Middle East (GCCSI, 2016c).

Among these projects are those examining a wider range of capture techniques, across more industries, than has so far been attempted on a large-scale. For example, projects in both Norway and Chinese Taipei are testing CO_2 capture from cement manufacturing, while a project in Japan is aimed at reducing CO_2 emissions in the iron and steel manufacturing sector. A project in Canada plans to apply carbon capture technology to a paper mill (CO_2 Solutions, 2016). Many of the smaller projects are examining different ways of capturing CO_2 from coal-fired power stations, with the aim of scaling up these processes. Operational experience with CO_2 capture from gas power was provided through a smaller-scale CO_2 capture plant (100 000 t/year) in Bellingham, United States, which operated from 1991 to 2005 and provided CO_2 for food and industrial applications.

Some projects are critical for building national and international knowledge and understanding of CO_2 storage. The CO2CRC Otway Project in Australia, which began CO_2 injection in 2008, is one of the world's largest CO_2 storage demonstrations, with more than 80 000 tonnes of CO_2 injected and stored in a variety of geological formations. The project is also testing advanced monitoring technologies and techniques with the aim of reducing CO_2 storage costs.

The Tomakomai project in Hokkaido, Japan, which started operations in April 2016 stores CO_2 from a hydrogen production unit and will be particularly significant in demonstrating the viability of CO_2 storage in Japan. Tomakomai is also an example of the important role that these smaller-scale projects are playing in supporting CCS awareness and engagement among local communities and the general public. For example, the project hosts visits to the demonstration site which attracted more than 1 500 people in 2014 alone (Japan CCS Co, 2016).

These projects are among more than a hundred smaller-scale CCS projects, test centres and other initiatives identified by the GCCSI as making a significant contribution. Continued investment in these projects will remain important in supporting future CCS deployment and in developing the next generation of CCS technologies.

1.3.6 Investment in large-scale CCS projects

There has been relatively limited investment in large-scale CCS projects to date, in part due to the absence of targeted policies. The exception to this has been investment in projects which can secure an income stream from the sale of CO_2 for EOR in established markets in North America. These early CO_2-EOR projects, together with Sleipner, account for much of the CCS investment prior to 2005 (see Figure 1.2). Since this time, government funding programmes have played more of a role in leveraging private investment[9] in large-scale CCS projects. Approximately USD 12.3 billion of public and private capital has been invested since 2005, with 91% (USD 11 billion) invested between 2009 and 2012. This investment corresponded to the establishment of large public funding programs in Australia, Canada, Europe, the United Kingdom and the United States during that time period.

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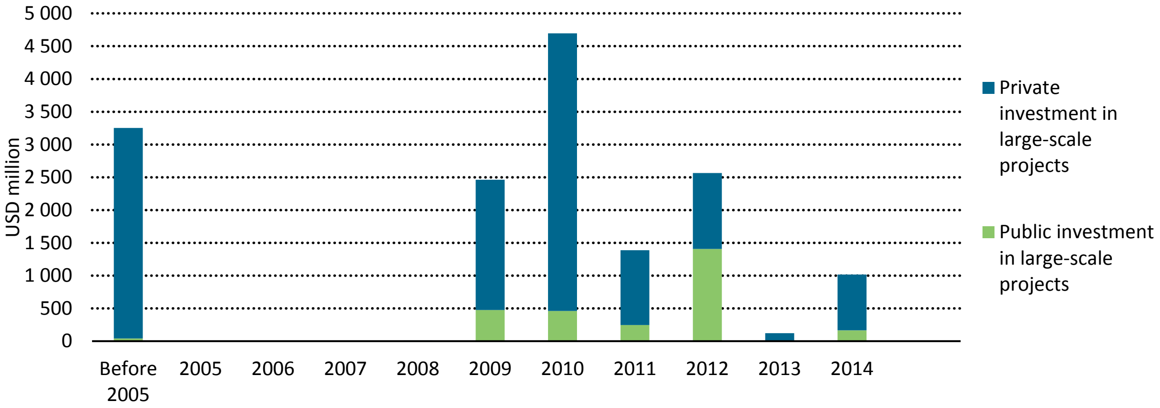
[9] Private investment includes all non-grant funding for capital costs of large-scale CCS projects that have made investment decisions, including investments by state-owned enterprises.

Of the USD 12.3 billion in total capital investment since 2005, 77% (USD 9.5 billion) has been private. Almost 60% of this private investment was in the United States and 23% in Canada, much of which has been tied to either oil and gas production or to supplying CO_2 on a commercial basis for injection for EOR. The approximately USD 2.8 billion of public funds invested between 2007 and 2014 is a small portion of the almost USD 30 billion in public funding commitments made around this time (GCCSI, 2010).

Figure 1.2 • Private and public and investment in large-scale CCS projects (2005-2014)



Source: BNEF (2016), Clean Energy Investment Trends.

1.4 Technology developments: CO_2 capture, transport, storage and use

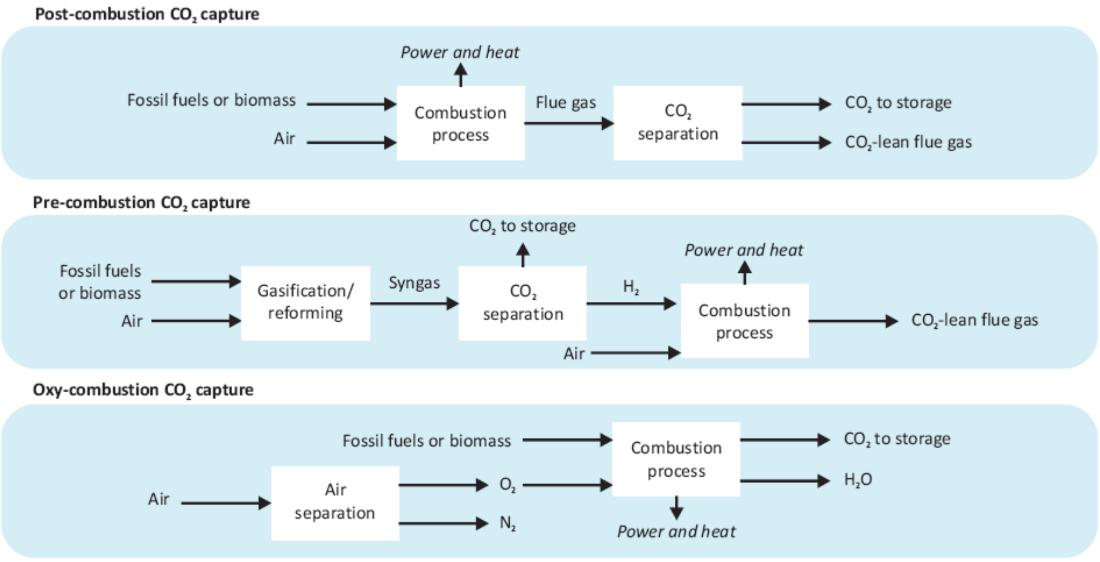
In addition to the progress of projects described in the previous section, advances in CCS component technologies have been achieved, albeit at different rates. Post-combustion capture (PCC) based on solvents is emerging as the most mature CO_2 capture technology, although all capture technologies can benefit from further development at scale to reduce costs and energy penalties. Emerging technology options such as supercritical CO_2 cycles could offer advantages for CO_2 capture from natural gas combined-cycle plants as well as coal-based synthetic gas (syngas), including high efficiencies and net production of water. CO_2 transport is a relatively mature technology but still holds opportunities for further innovation, including for non-pipeline transport. For CO_2 storage, deep saline formations have firmed as the largest and most prospective geological storage option, and there is now a high degree of confidence in their suitability for permanent storage. Significant advances have been made in the measurement, monitoring and verification (MMV) of stored CO_2, with improved techniques that are less intrusive and more accurate.

1.4.1 Advances in CO_2 capture technologies

Post-combustion capture

Amine-based PCC is today the most developed of the CO_2 capture options (see Figure 1.3). The separation of CO_2 with amine-based solvents was already mature PCC technology in some industries when the IPCC Special Report on CCS was published in 2005. Since then, advances have been made in terms of scaling up and deploying amine-based systems for PCC. The first PCC-based commercial scale power plant at Boundary Dam Unit 3 commenced operation in 2014; at full capacity it is capable of capturing up to 1 Mtpa of CO_2. The capture technology is a proprietary, first-generation solvent-based system developed by Cansolv Technology. Cansolv has tested a second generation advanced solvent at the Technology Centre Mongstad (TCM) as part of the Front-End Engineering and Design (FEED) study for the Peterhead project in the United Kingdom, and claims to offer significant advantages over the solvent being used at Boundary Dam. In 2016-2017 a second PCC-based coal-fired power plant will begin operation at the NRG Parish project in Texas, United States. This project will employ a proprietary solvent manufactured by Mitsubishi Heavy Industries (MHI) and will operate at a scale of 240 megawatts electrical (MWe), a significant increase in size over Boundary Dam Unit 3. PCC development is therefore in part being driven by technology vendors.

Figure 1.3 • CO_2 capture technologies



Source: IEA (2012a), *Energy Technology Perspectives 2012*.

One significant development in capture technology development has been the capture test centres that have been built in the last 10 years. The TCM, the National Carbon Capture Centre (NCCC) in Alabama and the Shand Carbon Capture Test Facility in Saskatchewan are playing a significant role in developing post-combustion based capture. Aker Clean Carbon, Carbon Clean Solutions Ltd, and Alstom/GE have also tested their proprietary technologies at TCM, while Hitachi is testing at Shand. Capture system testing at the scale of the test centres can then be confidently up-scaled. Thus with Ion Engineering testing at TCM this year, and Huaneng Group demonstrating at similar scale in China there is a growing number of PCC technology vendors from around the world that can offer designs for commercial scale capture plants with guarantees. This creates a very a healthy competitive market for PCC technology which can only help to drive down the costs of capture in the long term. In addition, the TCM owners have conducted several tests with monoethanolamine (MEA) in order to establish public baselines for various performances with which amine technology vendors can compare their proprietary technologies.

Significant progress has been made by technology vendors to reduce the energy penalty associated with amine sorbent regeneration. Since these processes were first considered, the energy penalty has been reduced by some 50% and now approaches the thermodynamic limit. While gradual improvement is still possible, this means that significant further reductions must come from a new generation of technologies (Idem, 2015).

Oxy-fuel combustion

CO_2 capture by oxy-fuel combustion (see Figure 1.3) has also experienced considerable advances in the last decade with all aspects of the technology investigated on a wide range of experimental scales and using robust modelling tools (Stanger, 2015). The technology can be applied in power generation but could also be particularly well suited for some large-scale industrial applications (such as cement, steel or oil refining).

Oxy-fuel technology has been successfully tested on a relatively small scale; with a 30 MW retrofit oxy-fuel pilot project at Callide in Australia operating between 2012 and 2015; a 30 MW pilot project at Schwarze Pumpe in Germany operating from 2008 to 2014; and the 30 MW Total Lacq project operating between 2010 and 2013. The Lacq project, Europe's first end-to-end CCS project, was based on gas, rather than coal, combustion. China's Huazhong University of Science and Technology has also recently commissioned a 35-MW oxy-fuel combustion test facility which will provide an important knowledge base for the development of large-scale demonstration in China around 2020.

Although these projects have been, or will be, instrumental in providing the confidence to progress to large-scale oxy-fuel applications, the recent cancellation of the FutureGen 2.0 and White Rose projects means that there are currently no projects being planned to demonstrate this technology at scale.

Pre-combustion capture (Integrated gasification combined cycle)

Pre-combustion CO_2 capture or integrated gasification combined cycle (IGCC) process routes use commercially mature equipment for producing a syngas (by reforming and partial oxidation or solid fuel gasification) or for separating the H2/ CO_2 resulting from the water gas shift reaction (see Figure 1.3). Physical solvent systems such as Selexol and Rectisol have been established technologies for capture in the chemical industries for decades. The Rectisol process has been applied at scale at the Dakota Gasification facility in the United States and the Kemper County IGCC project, also in the United States, will apply Selexol technology. Pre-combustion CO_2 capture can be applied in the short term to high CO_2-emitting industries including the chemical (gas and coal-based), iron and steel industries.

Supercritical CO_2 cycles

Supercritical CO_2 cycles are now recognised as an option for capturing CO_2 from natural gas combined cycles or coal-based syngas. In these cycles, fuel gas is combusted at high pressure using high-purity oxygen, moderated by recycled CO_2 and/or H2O, and the resulting hot high-pressure gas is expanded in a turbine to generate electricity. IEAGHG has undertaken an independent evaluation of these cycles and has assessed that they show considerable promise compared to conventional natural gas cycles with CCS. The supercritical CO_2 cycles offer major advantages in their high cycle efficiencies, compact size, high capture rates, and importantly they can be net producers, not consumers, of water. In March 2016, NETPower (one of the developers of these supercritical CO_2 cycles) began construction of a 50 MW plant in La Porte, Texas that should demonstrate the key aspects of the technology. Commissioning is expected to begin in late 2016 or early 2017.

Novel capture technologies

In the last 10 years a very substantial body of scientific and technical literature has been published on novel capture technologies in an attempt to: demonstrate these concepts at increasing pilot scales; test and model the performance of key components within the laboratory environment; investigate and develop improved functional materials; optimise full process schemes for a range of industrial applications; and undertake cost studies. A particular focus of research has been on specific processes that have experienced a substantial increase in their technical readiness level: chemical looping combustion for solid fuels, post-combustion calcium looping systems, CO_2 separation at low temperature by solids adsorbents and polymeric membranes for post-combustion. A much wider range of emerging systems and their variants is being investigated at the conceptual level and at smaller scales. These offer additional opportunities for substantial reductions in cost and energy penalties in CO_2 capture in power generation and large-scale industrial systems (Jansen, 2015).

1.4.2 Transport

The transport of CO_2 via pipelines is a mature technology, with practical experience spanning several decades, mostly in North America. There has been an extensive CO_2 pipeline network in the United States, mainly carrying natural CO_2, since the mid-1980s as a result of CO_2-EOR. Pipeline transport of CO_2 is a well-regulated, safe and mature option for transport of CO_2. The knowledge on pipeline transport was extensively catalogued in the IPCC Special Report on CCS and little has changed technically. The one significant new pipeline development is the offshore underwater pipeline in the Barents Sea for the Snøhvit project. Information available in the literature on CO_2 pipelines has been updated (IEAGHG, 2013a) and provides more specific information on planning aspects, standards and operating codes, but again reinforces its mature nature.

There has also been considerable interest in the development of pipeline networks in Europe, Australia and Canada to transport CO_2 from inland to regional hubs for future distribution to offshore storage sites. The financing and regulation of such infrastructure projects has gained attention over the last few years. Separate construction and funding of pipeline networks in regions where there is no CO_2-EOR industry could mean reduced start-up costs for new CCS projects (see Section 3.6).

Ship transport of CO_2 was also included as a consideration in the IPCC Special Report on CCS. The shipping of CO_2 is now more cost-effective over long distances (>2 400 km) than transport through pipelines. Interest in shipping of CO_2 in coastal regions such as the Baltic Sea, Norway, Japan and South Korea has grown in recent years but a shipping transport network has not yet been fully developed. In comparison with pipelines, ship transportation provides a more flexible solution with regard to quantities transported and can facilitate the growth of a portfolio of CO_2 at a hub which later could be converted into a pipeline network.

Commentary 2 • Progress in the geological storage of CO_2

Professor Sally Benson

Director, Precourt Institute for Energy and Professor of Energy Resources Engineering, Stanford University

Thinking back over the past 20 years it is rather remarkable how much progress has been made since the idea of capturing and storing CO_2 was first introduced in the mid-1990s. Even a decade ago, experience with CO_2 injection into deep geological formations for the purpose of CO_2 storage was limited to the pioneering Sleipner project, the Weyburn project, and the In Salah project which had just begun. Since then, there have been 15 industrial-scale CCS projects injecting nearly 30 of CO_2 ($MtCO_2$) per year. In 2005 the IPCC[10] concluded that the "risks [of CO_2 storage] should be the same as for other analogous activities such as CO_2-EOR and natural gas storage." The successful experience for CO_2 storage over the past two decades supports this assertion. Abandoned or poorly constructed wells were anticipated to create the greatest risks for leakage and the one documented case of leakage to the ground surface, which occurred at the In Salah Project in Algeria, was caused by CO_2 migration up an unplugged exploration well.

In addition to the practical experience these projects have provided, these large-scale projects, together with over 25 pilot-scale R&D projects, have greatly increased our understanding of the physical and chemical processes affecting storage security. Four major processes contribute to storage security; structural and stratigraphic trapping; solubility trapping; residual gas trapping; and mineral trapping. In 2005, the relative contributions of each of these trapping mechanisms to storage security and the time frames over which they operated were highly uncertain. Now, through worldwide R&D efforts, these mechanisms are understood more fully and the role of site-specific attributes on the trapping processes is clear. For example, in small closed structural traps, trapping will be dominated by retention underneath the seal and the contributions from the other trapping mechanisms will be minimal. On the other hand, in open hydrodynamic traps, solubility and residual trapping will be large and relatively rapid. For highly reactive rocks such as basalt, a significant fraction of the CO_2 may be immobilised through mineral trapping on the scale of years to decades.

These commercial and pilot-scale projects have also resulted in an explosion of monitoring technology. Back in 2004, monitoring was dominated by seismic imaging, resistivity saturation tool (RST) logging for measuring CO_2 saturations, and U-tube sampling of reservoir fluids. Now, a wide variety of monitoring tools are available for tracking CO_2 plume migration in the storage reservoir, detecting leakage in overlying aquifers, measuring changes in groundwater quality, geo-mechanical deformation, induced seismicity, and surface leakage. Drawing from the sophisticated suite of seismic, electrical resistivity, Interferometric Synthetic Aperture Radar (InSAR), tilt, pressure, chemical, tracer, and gas flux monitoring; "fit-for-purpose" monitoring programmes can be designed and implemented for assuring the safety and security of CO_2 storage projects in almost every conceivable situation.

Significant progress has also been made in assessing regional, national, and global storage capacity. In 2005, there was no consensus on the definition of storage capacity or any standardised methods for assessing it. Few bottom-up assessments had been completed. Consequently, the estimated capacity was so uncertain that it was only possible to conclude that the global CO_2 storage capacity was in the range of 10^3 to 10^4 GT CO_2. Now, standardised terminology has been developed, capacity estimates have been harmonised, and detailed bottom-up assessments have been carried out in many regions of the world. Importantly, injectivity limitations, excessive pressure buildup, and geo-mechanical constraints have also been identified. The must be considered when assessing both the total storage capacity, as well as, the rate at with the storage capacity can be utilised. These must be considered

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[10] Chapter 5 of the IPCC Special Report on CO_2 Capture and Storage (2005).

when assessing both the total storage capacity, as well as the rate at which the storage capacity can be utilised. These studies support earlier conclusions that the capacity for CO_2 storage is sufficiently large for deployment of CCS at the scale needed to play a significant role (10-15%) in CO_2 mitigation globally.

The technical discipline of "storage engineering" has also emerged over the past decade. In 2005, reservoir simulation methods were limited, lacked validation in a laboratory or through field experiments, and included only some of the processes important for designing and managing CO_2 storage projects. Reservoir engineering for storage projects was largely confined to assessing how many injection wells were needed to assure adequate injectivity to accommodate the desired quantity of CO_2. Now, commercial and research simulation models include all the trapping processes and geo-mechanical effects, and have been calibrated by comparison to field-scale projects. Detailed validation of the simulation codes using laboratory data has also been done. The discipline of "storage engineering" has also been expanded to include: optimisation of solubility, residual gas and mineral trapping; active pressure management through water extraction; and remediation and contingency planning in the event of leakage.

While there is certainly more to learn if CO_2 storage is to be implemented to the scale needed to reduce emissions by 10-15% with CCS, this has been an extraordinary decade of learning by any measure. Today, a strong and talented cadre of engineers and scientists have the knowledge, tools, and skills to design and operate CO_2 storage projects safely and securely. Now, we need to launch the next generation of projects that will accelerate the scale-up of CCS before it is too late. Is it needed? Yes. Will it be hard? Yes. But it's worth it.

1.4.3 Storing CO_2

Global storage resources and integrity

In the early years, CO_2 storage analysis was focused on a broad range of storage options, including deep saline formations, depleted oil and gas fields, coal seams, and basalts as well as consideration of storage in shales, salt caverns and abandoned mines. Early estimates of the global storage potential were summarised in the IPCC SRCCS, which identified deep saline formations as offering the greatest potential for geological storage of CO_2 (see Table 1.2). Since that time, further analysis has refined these numbers but has not changed the fact that deep saline formation capacity is the largest overall.

Table 1.2 • Estimates of global CO_2 storage capacity

Reservoir type	Estimate of storage capacity $GtCO_2$	
	Lower	Upper
Oil and gas fields	675	900
Un-minable coal seams	3-15	200
Deep saline formations	1 000	Uncertain, possible 10^4

Source: IPCC (2005), *Special Report on Carbon Dioxide Capture and Storage*.

In the late 1990s several tests were conducted on the potential for direct CO_2 injection into bituminous coal seams; all were largely unsuccessful. Since then interest in coal seams as a potential storage option has declined. Over the past 10 years the focus on storage research has narrowed down to principally looking at deep saline formations. This is because much was unknown about these formations (oil and gas companies have tended to drill through them to the commercial stratigraphy below that is of value to them) and because they are the largest geological storage resource. In recent years there have been some small-scale injection trials into basalt formations and some theoretical work on storage potential in shales; otherwise, these other storage options have not been progressed substantially.

With regard to storage integrity, the IPCC SRCCS considered that "for well-selected, designed geological storage sites the vast majority of the injected CO_2 will gradually be immobilised by various trapping mechanisms and in that case be retained for millions of years. Because of the trapping mechanisms identified storage would become more successful over longer time frames" (IPCC, 2005).

Since 2005, extensive research has been undertaken both in the laboratory and at pilot injection test sites that have acted as field laboratories. At the time of the IPCC SRCCS, only two dedicated CO_2 storage projects were underway, Sleiper and the IEAGHG Weyburn CO_2 Monitoring and Storage Project in Canada. In 2013, IEAGHG reviewed the information from 45 small-scale injection projects and 43 large-scale injection projects that had been completed or were still in operation at that time (IEAGHG, 2013b). Small-scale projects were considered to be those injecting less than 100 000 t, though the majority of projects inject considerably less (<15 000 t). The research results from the laboratory and fields tests were summarised in the 2015 Special Issue of the International Journal on Greenhouse Gas Control (Gale et al., 2015). This body of research concluded that CO_2 storage is by and large a safe operation if storage sites are properly selected, characterised and managed, thus reinforcing the message in the IPCC SRCCS.

Research from engineered CO_2 release projects and studies of natural analogues has been extensive over the last six years, with some 14 engineered release projects completed or underway. This research has drawn some important conclusions on what happens if leakage does occur from a storage reservoir, namely that the impacts of CO_2 leakage are generally quite limited in space and time, and that the surface expression of leaks is usually in isolated small areas (Jones et al., 2015).

Monitoring, verification and risk assessments

The range of techniques that can be applied to monitor CO_2, either in the deep surface or on the surface has grown extensively in the last 20 years. Many shallow monitoring methods have developed in parallel with the assessment of environmental impact, reflecting societal concerns about leakage to the near-surface. Shallow-focused monitoring methods have also been exploited extensively, and have played an important role in countering leakage allegations at Weyburn and providing assurance that the environmental impacts of hypothetical leakages are undetectable above natural variability in key parameters.[11]

Very significant progress has been made in deep-focused monitoring techniques. Specific examples are marine seismic monitoring at Sleipner and the combination of pressure and seismic imaging at Snøhvit. Another success story for monitoring of reservoir-level processes was at In Salah, where ground surface displacements were detected by the new (in terms of application to CCS) method of InSAR, the measurement of ground surface displacement from satellite platforms. The common theme in these examples, which now emerges for many projects at all scales, is the ability of the available techniques for monitoring and interpretation to test containment and conformance.

Risk assessment has become a mature field over the past decade, with a range of both qualitative and quantitative methodologies now available. Methods to study risk through large-scale stochastic simulations have been developed and linked to risk assessment of various proposed project sites. While the technical risks identified for geological storage have not changed significantly, public perception, financial aspects and regulation have become more prominent in risk assessment. Among the technical risks, wellbore integrity continues to be the most

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[11] Refer to the discussion on climate-related leakage risks vs. environmental impacts in Section 1.5.3.

prominent. However, the nature and frequency of wellbore failure has been better quantified over the decade, and concerns about the chemical stability of properly completed wellbore cements in particular have been reduced.

1.4.4 Large-scale deployment to deliver further cost reductions

Reducing the cost of CCS, particularly CO_2 capture, continues to be a major priority for research and development. Over the last 20 years there have been a significant number of techno-economic analyses on CCS-based plants undertaken by groups that include the US Department of Energy, the Electric Power Research Institute (EPRI), IEAGHG, the Massachusetts Institute of Technology (MIT), the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) and many others (Rubin et al., 2015). The first major attempt at comparing the costs of CCS plant was undertaken in the IPCC SRCCS in 2005. The costs of capture and compression were identified as the single largest cost component of the CCS system and should be the centre of activity to reduce overall CCS plant costs. A recent review of published cost data (Rubin et al., 2015) shows that the costs calculated for the three principal capture technologies are very similar to those extrapolated from the SRCCS report and range from USD 63 to USD 150 per megawatt-hour (MWh), depending on the technology. No single option stands out as the preferred option from a capital costs perspective.

The potential for future cost reductions based on both top-down and bottom-up analyses suggests that cost saving through system learning and replication could run to 15% for combustion-based plant and 20% for gasification technology. Initial attempts to model the costs of installing new capture technologies such as advanced membranes and solvents indicate a potential cost reduction of 20% compared to amine-based systems. However, these cost projections must be treated with some caution because these technologies are still at an early stage of development.

The Boundary Dam CCS Project has provided an indication of the “learning by doing” cost reductions that can be achieved through large-scale deployment (see Section 1.3.4). However, the pace at which these cost reductions will manifest themselves in practice will depend to a large extent on the rate of deployment. The nature of CCS plants, with relatively higher capital requirements, longer development times and multiple applications, may mean that this learning curve could be more protracted than for more modular technologies. However, the experience of renewables technologies highlights the fact that targeted policies and government commitment can spur innovation which delivers growth and cost reductions beyond the original expectations.

Commentary 3 • Future R&D priorities for CO_2 capture

Professor Kelly Thambimuthu, FTSE*

Chairman IEA Greenhouse Gas R&D Programme (IEAGHG)

In 1991, 12 countries within the IEA membership acted to create the GHG technology collaboration program (GHG TCP – IEAGHG). I have the pleasure of being with this ground-breaking IEA technology collaboration programme since its birth.

From the very beginning, optimism was high that CCS was able to tackle the challenges posed by fossil fuels for climatic change. After all, components of this technology – capture, pipeline transport and gas storage underground already existed and were in use in some form industrially worldwide. As a result, implementation of the first commercial application of CCS soon followed in 1996, with the pre-combustion capture of CO_2 from natural gas using an amine-based process in Norway's offshore Sleipner project. The commercial implementation of this project was also facilitated by policy in the form of an offshore Norwegian tax on carbon emissions. However, many challenges were identified for the wider application of post-combustion CO_2 capture from ambient pressure, oxygenated (flue gas) streams that form the bulk of industrial and utility GHG emissions globally.

In practical terms, the challenges identified for post-combustion capture were to be expected. CO_2 capture and ancillary support technologies such as cryogenic air and other gas separations (that alternatively enrich a CO_2 stream) emerged from proven applications in high-pressure, pre-combustion (oxygen depleted, fuel gas) systems in the oil, gas and chemical industries. Many of these pre-combustion capture technologies have been in use since the turn of the 20th century. Their adaption to post-combustion (flue gas) streams faced challenges in tackling the impact of oxidised impurities, and/or scale up to handle much higher volumetric gas flows at ambient pressure, and with it, marginally higher energy penalties and costs of CO_2 capture. Sustained research and development since 1991 has yielded many positive outcomes. A number of vendors now offer large-scale and more energy efficient, amine-based, post-combustion (and also pre-combustion and select oxy-fuel) CO_2 capture technologies for both industrial and utility applications. Some of these are currently being implemented in a handful of commercial demonstrations of CCS and in one large BECCS application worldwide.

So one might legitimately ask – what is the problem? The problem particularly for the emerging post-combustion and oxy-fuel capture technologies, as for all "first-of-a-kind" technologies, is that these early commercial plants will need to be put on a deployment pathway that will spur competition, technology learning and associated changes that will reduce the redundancies of overdesign, energy penalties and the cost of CO_2 capture. As it stands now, CO_2 capture represents some 70% of the total cost of a CCS project; this can be reduced by competition and technology learning. Alas, the impact and speed of technology learning and cost reduction that would inevitably follow is without question being hampered by a marked absence of targeted policy measures and incentives that would assist the initial roll out of these first generation capture plants.

Efficiency is the hallmark of any quest to promote the sustainable use of energy and to reduce GHG emissions. In this respect it is very much part of the goal in rolling out CCS. Many innovative developments to reduce the energy penalties and/or to improve the overall efficiency and cost of CO_2 capture integrated systems are also underway. Some of these have been focused on improving process integration of the above-mentioned first generation and first-of-a-kind technologies – hitherto adapted, as we noted, from existing pre- and post-combustion capture technologies, but also for their use with incremental improvements to existing industrial processes and power generation cycles. Other more radical approaches are focused on combining, in varying degrees, the development of entirely novel capture systems, and with it novel industrial processes and power generation cycles that permit a more transformative change in energy efficiency and process integration.

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[*] Fellow of the Australian Academy of Technological Sciences and Engineering

The development of improved or new solvents, adsorbents, membranes, improved industrial processes in steel, cement making and higher efficiency gas turbine and ultra-supercritical steam-based power generation plant are some examples of the former moderate, but incremental approach. Many of these developments thus would go hand in hand with technology learning and competition arising from the more widespread deployment of the first-of-a-kind CCS plants that is currently being delayed. Novel oxy-combustion or solids looping-based capture technologies combined with novel industrial processes and gas, hybrid steam turbine or fuel cell-based power cycles are examples of the second more radical approach. For both approaches, the deployment of relatively large-scale BECCS plants that use identical technology is also feasible.

Hence, there is a significant opportunity for improvements in the energy efficiency and cost of CO_2 capture through more widespread deployment of the currently emerging crop of first-of-a-kind or first generation technologies in the period from 2020 to 2030, and with ongoing research, development and demonstration (RD&D) for the deployment in the time frame beyond 2050 of much more radical, second generation technologies. The latter will not occur without the former, and a key element of success is to stimulate a critical mass for market growth and demand during this decade.

So let us ask once more – what is the problem? All of this will amount to nought without targeted policy measures and incentives by governments worldwide to stimulate the rollout of several market-ready technologies for CCS and BECCS. As repeated time and time again by global energy systems modelling by the IPCC, IEA and others, CCS and BECCS are an invaluable part of the portfolio of energy technologies required to cost-effectively mitigate climatic change in the 2°C and below scenarios. However, it is not technology but absent policy that challenges us in this decade!

1.4.5 CO_2 utilisation

Opportunities for utilising CO_2 could act as a potential driver to develop CCS but will not replace the need for large-scale geological storage. The allure of CO_2 use is straightforward: instead of paying to dispose of CO_2 as a waste, firms that generate vast quantities of it would be paid to deliver it as a commodity to willing buyers.

Millions of tonnes of CO_2 are used in industry each year. The largest single source of this is EOR, with some 70 $MtCO_2$ used annually, although two-thirds of the quantities used are actually from natural CO_2 sources. In time this could be replaced with CO_2 captured from power and industrial facilities and, with appropriate site characterisation and monitoring, could provide a permanent storage solution (see discussion on "EOR+" in Section 3.5). Other current large-scale uses (in the millions of tonnes per year) include urea yield boosting, carbonated drinks, water treatment and pharmaceutical processes. However, these uses are relatively limited when considered from the perspective of tackling climate change: for example, the global beverage industry uses around 8 Mt CO_2 each year, which is approximately 0.5% of the CO_2 that would need to be captured and stored in the 2DS by 2030. Most of these alternative large-scale uses also do not offer a permanent storage solution.

Emerging CO_2 utilisation opportunities such as mineral carbonation and CO_2 concrete curing have the potential to provide long-term storage in building materials, but again the potential contribution of these measures to climate change is likely to be limited as demand for these products becomes saturated (IEA, 2014a). The proposed conversion of CO_2 to liquid fuels could potentially displace fossil fuel use (thereby reducing emissions) but requires extensive energy use and would not deliver the same net climate benefit as geological storage because in such conversion the CO_2 is ultimately re-released.

This is not to suggest that opportunities for use of CO_2 should not be pursued, but their future role should be assessed against a framework which includes consideration of the following:

- **Emissions reductions:** The impact of a CO_2 usage depends primarily on whether it achieves an emissions reduction. To what extent can the use in question reduce anthropogenic emissions into the atmosphere? To analyse this issue requires a good understanding of the fate of the utilised CO_2. Alternatively, does the use displace more carbon-intensive fuel consumption elsewhere in the economy? This requires an understanding of both the used CO_2 and of the displaced consumption.
- **Financial contribution:** Utilisation can also have an indirect climate change mitigation benefit. For example, it can create a profitable business opportunity which acts to stimulate increased investment, which in turn leads to innovation in CCS. Alternatively, payments for utilisation can help to cover the cost of running capture equipment whose gas flue is then in part stored.
- **Scalability of use:** Can the use be scaled up to drive the building and operation of large-scale capture facilities? Large point sources will potentially capture (i.e. produce for eventual use) several million tonnes of CO_2 annually. Therefore sufficient demand is critical. Opportunities for CO_2 utilisation are likely to be limited to niche applications with relatively small-scale CO_2 requirements (with the exception of EOR); these may have value at a local or industrial level, but are not considered an alternative to large-scale geological storage of CO_2.

The 2005 IPCC SRCCS identified CO_2 utilisation as a modest climate mitigation opportunity and this remains the case today. Beyond EOR, the contribution of CO_2 utilisation to emissions reduction efforts is likely to be limited in the absence of major technical breakthroughs. It should therefore not be positioned as an alternative to geological storage of CO_2.

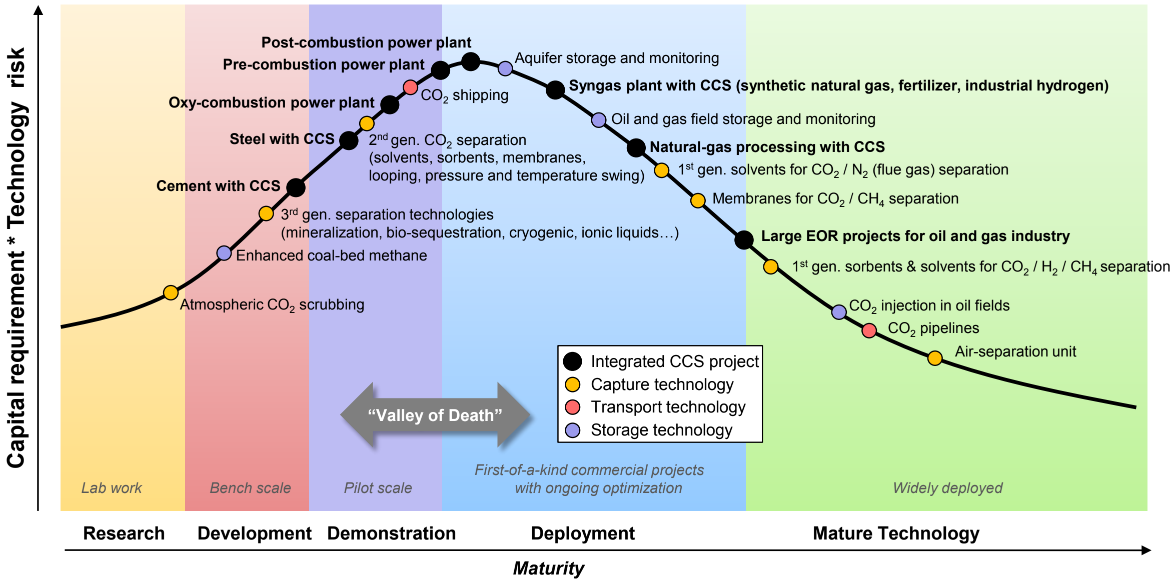
1.5 CCS policy and regulatory frameworks

Over the last two decades, a range of policy and regulatory measures have been adopted by governments in an attempt to facilitate and incentivise CCS deployment. The mix of measures has varied depending on national or regional circumstances, but can broadly be considered as falling into the following three categories:

a) climate-based regulation which may require or encourage CCS
b) targeted policy incentives specifically designed to support CCS
c) regulation of CCS operations, notably to facilitate safe and effective storage of CO_2.

The nature of the required policy support changes as the technology matures. Efforts to move the technology from research and development and piloting phases through to the early deployment phase – that is, through the so-called “valley of death” – involve increased support (see Figure 1.4), which has proven more challenging for governments and industry. First-of-a-kind CCS projects are capital intensive, carry technology and integration risk, and offer limited commercial value for proponents beyond technical learning. Accordingly, the level and complexity of the policy support needed to accelerate CCS through the early deployment phase increases by an order of magnitude compared with the research and development stages. Understanding the nature and scope of existing policy support can help to highlight where greater governmental support and engagement is required.

Figure 1.4 • Investment risk curve of CCS technologies and integrated plants



Source: Reprinted from SBC Energy Institute (2016), Low Carbon Energy Technologies Fact Book Update: *Carbon Capture and Storage at a Crossroads*.

Note: In practice, the nature and extent of support needed by different technologies across the deployment curve will differ significantly. The various phases would also overlap rather than being distinct stages.

1.5.1 Climate-based regulation

At the national level, various climate-based regulations that are not CCS-specific, but more general in nature, have so far proven effective in incentivising CCS in certain specific circumstances. The Norwegian CO_2 tax for offshore oil and gas production is a prime example, having provided the impetus for investment in Sleipner and Snøhvit. In the longer term, a carbon price is expected in many jurisdictions to promote shifts to low and zero-carbon technologies, such as CCS. While global carbon markets are expanding, they are unlikely to mature fast enough with a sufficiently robust price to support technology investment in CCS at the scale and pace needed in the near term to achieve ambitious climate targets.

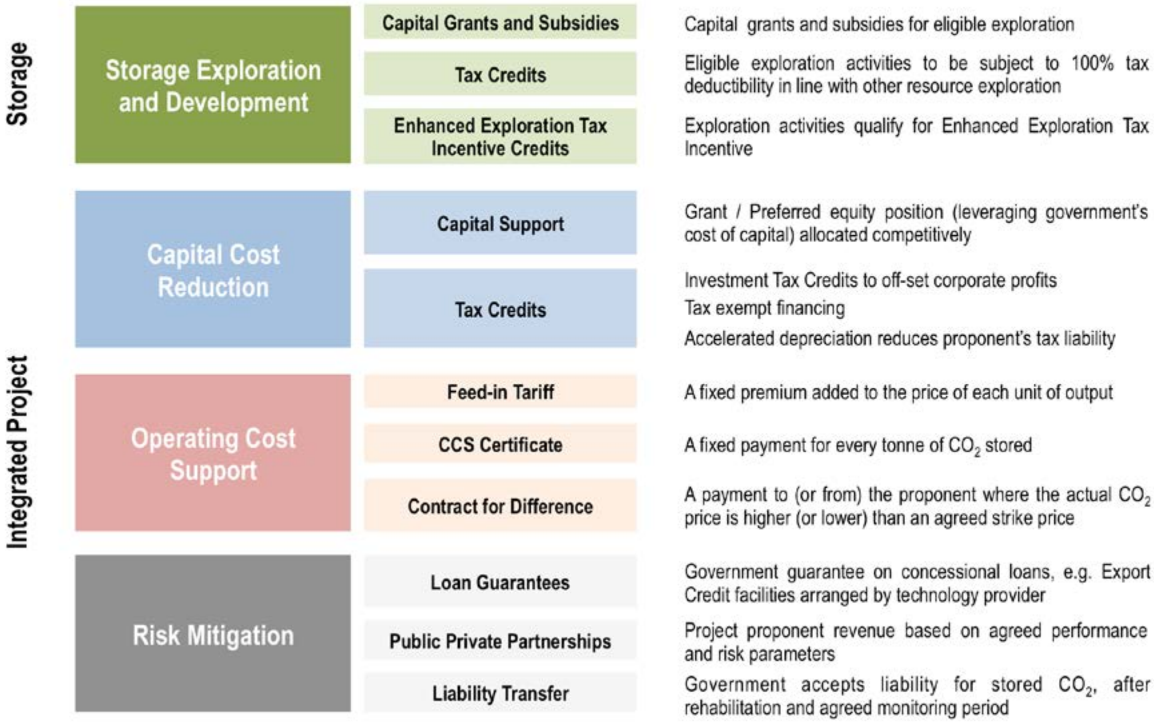
Emissions standards for coal-fired power generation have also played a role in supporting early CCS deployment. The decision to retrofit Unit 3 at Boundary Dam in Canada was in response to the introduction of strict performance standards for new coal-fired units and units that have reached the end of their useful life. The Canadian federal government also contributed CAD 240 million to the project, which was undertaken by SaskPower, a power utility fully owned by the Province of Saskatchewan. Similarly, emissions standards in the United States, together with direct financial support, have been key factors behind the two large-scale CCS projects currently under construction.

From a global policy perspective, CCS has always been covered implicitly by the United Nations Framework Convention on Climate Change (UNFCCC) process and the Kyoto Protocol. It has received growing recognition and attention under these frameworks. As highlighted in Section 1.2, the IPCC 2005 SRCCS helped focus attention on CCS as a mitigation technology in the global climate negotiations. CCS received further explicit recognition in 2011 when it was included in the Clean Development Mechanism (CDM). While the CDM has not provided direct incentives to CCS, it is widely anticipated that any future mechanism developed under UNFCCC will follow these principles (Dixon, McCoy and Havercroft, 2015).

1.5.2 CCS-targeted policy incentives

Programmes that specifically target CCS have been an important part of the policy landscape to promote the implementation of CCS. Various targeted CCS incentive mechanisms have been considered or deployed by different jurisdictions (see Figure 1.5).

Figure 1.5 • Policy incentives for CCS



Storage	Storage Exploration and Development	Capital Grants and Subsidies	Capital grants and subsidies for eligible exploration
		Tax Credits	Eligible exploration activities to be subject to 100% tax deductibility in line with other resource exploration
		Enhanced Exploration Tax Incentive Credits	Exploration activities qualify for Enhanced Exploration Tax Incentive
Integrated Project	Capital Cost Reduction	Capital Support	Grant / Preferred equity position (leveraging government's cost of capital) allocated competitively
		Tax Credits	Investment Tax Credits to off-set corporate profits Tax exempt financing Accelerated depreciation reduces proponent's tax liability
	Operating Cost Support	Feed-in Tariff	A fixed premium added to the price of each unit of output
		CCS Certificate	A fixed payment for every tonne of CO_2 stored
		Contract for Difference	A payment to (or from) the proponent where the actual CO_2 price is higher (or lower) than an agreed strike price
	Risk Mitigation	Loan Guarantees	Government guarantee on concessional loans, e.g. Export Credit facilities arranged by technology provider
		Public Private Partnerships	Project proponent revenue based on agreed performance and risk parameters
		Liability Transfer	Government accepts liability for stored CO_2, after rehabilitation and agreed monitoring period

Source: Reprinted from Greig, C et al. (2016), Energy Security and Prosperity in Australia – A Roadmap for CCS.

Financial support is crucial: Designing effective programmes is challenging

Targeted government financial support programmes have been particularly important in enabling projects to become operational. More than half of the portfolio of large-scale CCS projects currently operating or under construction have benefited from capital grant funding. This type of support is becoming increasingly important in expanding the project portfolio. Of the 13 projects which have commenced operation or construction since 2012, 10 have benefited from some form of capital funding.

Between 2007 and 2010, around USD 30 billion in CCS funding initiatives was announced globally (GCCSI, 2010). This included significant (>USD 1 billion) CCS funding programmes in Australia, Canada, the European Union, Norway, the United States and the United Kingdom. Several of these were included in stimulus packages following the global financial crisis. Not all this announced funding was ultimately expended on CCS projects. In fact, less than USD 3 billion in public funds were actually invested between 2007 and 2014 (see Section 1.3.6). These programmes have been unable to fulfil their original objectives for a variety of reasons, including mismatches between regulatory deadlines and sponsor timetables, and inadequate support for the operational phase (see Box 1.2).

In spite of the challenges experienced in delivering these large capital funding programmes, much of the current momentum in large-scale project deployment stems from these commitments. For example, the Quest CCS project in Canada, which commenced operations in

2015, secured funding from the Alberta CCS Fund and the Canadian Clean Energy Fund in 2009. The Kemper County IGCC, Petra Nova and Illinois Industrial CCS projects all secured government funding through the US Clean Coal Power Initiative in 2008, 2009 and 2010, respectively, and all are expected to come online in 2016-17. These time frames also highlight that there can be a significant lag between government funding commitments and project commissioning.

Box 1.2 • Designing government funding programmes: Lessons learnt

Approximately USD 30 billion in CCS funding programmes announced across Australia, Canada, Europe, the United Kingdom and the United States between 2007 and 2010 were originally earmarked to support as many as 35 large-scale CCS projects. To date, only seven projects are operating or under construction, having received support from these programmes. All are in Canada or the United States. The reasons why these programmes have delivered a relatively limited number of projects are complex, reflecting the stage of technology development as well as the costs involved for these first-of-a-kind projects. However, some key themes and programme design lessons are described below.

Lack of flexibility in project milestones: Many programme guidelines have included prescriptive selection and eligibility criteria, including pre-determined time frames for reaching financial closure and project commissioning. This has limited the number of projects able to apply for funding and, in some cases, has encouraged projects to modify their proposals to comply with funding criteria rather than to meet technology or business needs. For example, it has been reported that the Kemper Country IGCC Project started construction with only 15% of the plant designed in order to meet funding-related milestones. This has subsequently been a factor for significant cost overruns at the project (New York Times, 2016). The FutureGen 2.0 project was ultimately cancelled after the Department of Energy determined that it could not spend the USD 1 billion in grant funding under the American Recovery and Reinvestment Act (ARRA) by the 30 September 2015 deadline (see Box 1.1). While the ARRA was specifically designed as a stimulus programme and therefore included short-term spending targets, this situation highlights that these deadlines may not provide the flexibility needed for the successful development of integrated CCS technology projects at this scale.

Focus on full-chain projects: Programmes in the United Kingdom and Australia (for example) were premised on the development of an integrated, full-chain CCS business model where the storage resource would need to be identified and developed either in advance or in parallel with the capture and transport components. For Australian Flagship projects shortlisted in 2009, the characterisation of storage has proven problematic and time-consuming, and ultimately the available funding has been heavily focused on storage exploration activity. In the United Kingdom, the full-chain structure "was a significant challenge to both debt and equity investors in all parts of the CCS chain", particularly for the White Rose project (CCSA, 2016). The unique challenges of full-chain projects are discussed in Chapter 3.

Limited or no operational support: Many funding programmes have focused on capital support without complementary operational support, either in the form of targeted mechanisms or a carbon price. For projects, this means that the long-term additional operating costs associated with CO_2 capture and storage either need to be built into the up-front capital requirements or that a specific "demonstration" period must be agreed, beyond which the capture and storage may not be operated. The United Kingdom's CCS Commercialisation Programme addressed this issue with the parallel introduction of a contracts-for-difference (CFD) scheme that would have facilitated the long-term operation of the power projects. A review of this programme suggested that the proposed CFD arrangements would have met the needs of the candidate projects (CCSA, 2016).

Future infrastructure costs: CCS projects without access to existing transport and storage infrastructure must necessarily build this investment into the project, increasing the headline project costs. In the United Kingdom, both the White Rose and Peterhead projects had sized transport infrastructure to accommodate future CCS projects. This has added to their project costs but has provided the potential to significantly reduce the cost of the next projects. National Grid Corporation estimated that the transport and storage unit costs of future projects would have dropped by 60-80% using infrastructure put in place by the White Rose project (CCSA, 2016). The "oversizing" of transport and storage infrastructure is eminently sensible to support future CCS deployment, but these benefits risk being overlooked when assessing current project costs and "value".

External budget pressures: The long lead times for developing integrated CCS projects, particularly the time frames for characterising CO_2 storage, have contributed to the vulnerability of large government funding programmes to external budget pressures over time. The cancellation of the United Kingdom's CCS Commercialisation Programme in 2015, after 4 years of planning, is the highest-profile example of this. In Australia, the AUD 1.9 billion CCS Flagships programme has been progressively scaled back since 2009 to around AUD 300 million today.

Measures to address higher operating costs are necessary

Project experience over the past 20 years has highlighted the importance of addressing higher operating costs for CCS. The initial emphasis of many funding programmes had been on capital support; however it became increasingly apparent that CCS projects operating in competitive markets would also need assistance to compensate for the ongoing impact on the costs of production. The introduction of operating support measures can, in turn, increase the ability of the project to raise private capital and reduce the up-front subsidy requirements.

The level and nature of support will be determined by the specific industry and market and could include direct subsidies tied to production or feed-in-tariffs in the power sector. The United Kingdom introduced feed-in tariffs, with a CFD, for power generated from plants equipped with CCS. This complemented the capital support on offer through the UK CCS Commercialisation Programme. Carbon dioxide storage tax credits have also been introduced in the United States to incentivise the injection of CO_2 for enhanced oil recovery or dedicated geological storage.

1.5.3 Regulating CCS operations: Capture, transport and a special focus on CO_2 storage

Carbon capture and storage projects, as with any other large-scale industrial project, will be subject to a number of regulatory and permitting requirements. Most of the regulation pertaining to a CCS project would apply to any industrial or energy project of a similar scale, particularly as it pertains to CO_2 capture and transport. However CO_2 storage will involve specific regulation in many jurisdictions, primarily to ensure appropriate site selection and safe operation while also providing clarification of the long-term responsibilities associated with permanent storage. A unique aspect of regulating CO_2 storage as a climate solution is the potential adverse impact, however unlikely, of CO_2 leakage on national or global climate change mitigation efforts (the "climate-related leakage risk").

Regulating capture, transport and storage activities: Similarities to other industries

The regulation of CO_2 capture projects will likely be embedded in the permitting process for the host facility, be it a power station or industrial production facility. It may include environmental impacts, occupational health and safety, and, possibly, emissions controls and reporting. Pipelines for transporting CO_2 will also be subject to land permits and environmental controls similar to other pipeline projects. Many aspects of CO_2 storage are similar to other subsurface operations in the oil and gas industry and therefore regulation often builds on existing oil and gas legislation. While CO_2 storage is similar to other regulated activities, there are several key aspects which make dedicated regulation necessary (see Box 1.3).

Regulating for safe and effective CO_2 storage: A specific area of focus

Specific regulations for CCS mostly pertain to the CO_2 storage component. They focus on ensuring proper selection and operation of a CO_2 storage facility, the long-term retention of CO_2 and the associated liabilities, as well as management of the pore space. These regulations are designed to ensure the safe and effective storage of CO_2 (see Box 1.3) while also serving to reassure the public that storage operations are being managed appropriately. CO_2 storage regulation has also been important from the perspective of project developers who require a clear view of the legal treatment of CCS projects and their responsibilities, particularly after injection ceases.

Considerable experience in the implementation of CO_2 storage regulatory regimes has been accumulated over the last decade. The 2005 IPCC SRCCS looked into national regulations in North America, Japan, Europe and Australia and concluded that there was a lack of regulations specifically relevant for CO_2 storage (IPCC, 2005). However, since then storage regulation has been addressed, albeit in different ways, through the adoption of more than 50 legal instruments (Dixon, McCoy and Havercroft, 2015). These instruments have been applied in a number of jurisdictions, including in the European Union, Japan, the United States, Canada and Australia.

Box 1.3 • Key aspects of regulatory frameworks for CO_2 storage

In many countries, aspects of CO_2 storage operations are governed by existing natural resource extraction and mining laws but specific legislation may also be required to facilitate the safe and effective geologic storage of CO_2.

Ensuring a legal basis for CCS. In some jurisdictions, existing laws may prohibit the use of pore space for the disposal of fluids. A legal and regulatory framework as well as amendments to existing laws may be required to allow for CO_2 injection.

Property rights and management of pore space. CO_2 storage consumes a finite natural resource and regulation is needed to manage competition for access and exploitation of storage resources in the pore space, as with other scarce natural resources. In a number of jurisdictions, such as Australia and the United Kingdom, access to pore space and the right to use pore space for storage has been aligned with oil and gas frameworks. In other jurisdictions, including parts of the United States, regulation may be needed to facilitate access where subsurface rights are under private ownership.

CO_2 storage site selection and operation. Appropriate storage site selection is the key to ensuring CO_2 storage is safe and effective and for mitigating and managing risks associated with CO_2 storage. Selecting a site with suitable geology which is well understood will greatly reduce the chance of CO_2 leaking from the reservoir. It is also more likely that the CO_2 plume will behave as expected in a well-selected site. Accordingly, site selection is a prominent aspect of most CO_2 regulation.

Risk allocation over time: managing long-term responsibilities for stored CO_2. A key issue for regulators and project proponents is the management of the long-term responsibility for the risks associated with the possibility of CO_2 leakage into the atmosphere (see discussion of "climate-related leakage risk" below) or elsewhere. Although the risk of leakage from a well-selected storage site is low and declines over time, given that the intent of CO_2 storage is for it to be retained permanently, the storage continues long after injection stops and the site is closed. Accordingly, CO_2 storage regulation often defines the ownership of injected CO_2 and liability for the CO_2 not only during injection, but also post-injection and post site closure. Some jurisdictions have put in place arrangements for the government to take responsibility for the CO_2 or indemnify the storage operator once certain conditions are met after the closure of the site. For example, the European Commission CCS Directive provides for the transfer of responsibility of the site back to the competent authority provided that certain conditions have been met (European Commission, 2011).

Managing "climate-related leakage risk": A concern unique to CCS

One unique aspect of ensuring the effectiveness of CO_2 storage stems from the very purpose of CCS operations as a climate change mitigation tool, namely permanently storing CO_2 to reduce GHG emissions. As a result, to the extent that CO_2 leakage will adversely affect climate mitigation efforts, it represents a "climate-related leakage risk" that is distinguishable from, for example, local environmental risks such as CO_2 migrating into water resources. In contrast to other clean energy technologies, such as renewables and energy efficiency measures that operate to avoid generating CO_2 in the first instance, CCS aims to remove and store CO_2 that has already been produced, with the resultant climate benefits dependent upon this storage being permanent.

This climate-related leakage risk has typically been addressed in storage regulations through requirements for careful site selection and monitoring to ensure that any potential leak is detected well before CO_2 reaches the surface. Based on experience to date with CO_2 storage (e.g. in the context of EOR), the likelihood of CO_2 migrating outside an appropriately developed and operated site is very low, and it is even less likely that CO_2 would reach the surface and be released into the atmosphere.

In the event that CO_2 does reach the surface, its impact from a climate change mitigation perspective will have to be evaluated and managed within the context of a country's national emissions and related reductions programmes as well as its impact at an aggregated global level. For example, any CO_2 which enters the atmosphere may need to be offset elsewhere through other measures (such as renewables expansion or stronger energy efficiency standards) to ensure national and global emissions budgets are not exceeded. The leakage may also trigger emissions reduction regulations or carbon pricing mechanisms that create liabilities for project participants,[12] a risk that is currently uninsurable in some jurisdictions (CCSA, 2016).

In assessing the potential magnitude of this risk, it is important to recognise that any leak is likely to represent a very small fraction of the CO_2 actually being stored (assuming, for example, robust site assessments), and in practice leaked amounts are likely to be very small in comparison to national carbon budgets, let alone global levels. However, given the centrality of CO_2 storage to the use of CCS as a climate change mitigation technology, this risk does receive attention in climate change discussions – perhaps to an extent that well exceeds the likelihood of any significant actual impact on mitigation efforts given the technologies and processes available to manage storage.

Specific international legal issues for CO_2 storage: The marine treaties

In addition to national-level laws pertaining to CO_2 storage, developments with two international marine treaties are relevant for CCS. The OSPAR Convention protects the marine environment in the north-east Atlantic. In force since 1992, OSPAR was not drafted with CO_2 storage in mind, and the treaty included provisions prohibiting certain CO_2 storage options. The provisions were amended in 2007 by the treaty Parties, removing the prohibitions on sub-seabed storage of CO_2 (Dixon, McCoy and Havercroft, 2015).

The London Convention and Protocol are global agreements regulating dumping of wastes at sea. The Protocol represented two critical issues for CCS: it prohibited offshore storage of CO_2 and

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[12] Leakage can have an associated uncertain financial impact on project participants. For example, leakage can occur at a time in the future when CO_2 prices may be very different from the time of storage (or even introduced after the actual storage took place) and are difficult to predict. The potential for a long time interval between initial storage and subsequent leakage can create a financial liability that is difficult to estimate. For example, in the future the project operator may have to pay a penalty based on a carbon price in effect at that time that is currently difficult to predict.

also prohibited the transboundary movement of CO_2 for the purposes of sub-seabed storage. Two amendments have since been enacted to the Protocol. The first one, allowing for CO_2 storage in sub-seabed formation, came into force in 2007. The second amendment, allowing for cross-border transport of CO_2 for storage purposes was passed in 2009; however this amendment is still awaiting ratification and is hence not yet in force. The London Protocol therefore presents an obstacle for Parties to the protocol seeking to export their CO_2 to another country for storage.

1.6 Expanding global CCS collaboration

1.6.1 Global collaboration on R&D and policy

International collaboration on CCS has increased markedly in the last 25 years. New initiatives have brought together governments, industry, academia and civil society groups to coordinate efforts to drive CCS technologies forward (see Box 1.4). These collaborations have been instrumental in facilitating the global dissemination of experience and lessons across CCS technologies, project development and policy implementation. They have enabled research synergies to be identified and have ensured that key lessons from early project development experience could be transferred to the next wave of projects. Many of the global collaborations have also played an important role in ensuring visibility for CCS technologies as part of wider technology portfolios.

Box 1.4 • Key international collaboration on CCS

The **IEA Greenhouse Gas R&D Programme (IEAGHG)** is an international collaborative research programme established in 1991 as a "Technology Collaboration Programme" (TCP) under the IEA. As part of the IEA Energy Technology Network, IEAGHG operates independently with its own membership and financing, but with 5-year mandates from the IEA. IEAGHG studies and evaluates technologies that can reduce GHG emissions from the use of fossil fuels. While the remit of IEAGHG is wider than just CO_2, the work is very much concentrated on CCS technology, economics and policy-related matters. IEAGHG membership covers both industry and government, and also includes several public research organisations. IEA GHG membership has grown from 12 member countries and the European Commission in 1991, to 32 members representing 15 countries today.

CCS collaboration takes place at ministerial level, under the **Carbon Sequestration Leadership Forum (CSLF)** which was established in 2004. The CSLF states as its mission to facilitate the development and deployment of carbon capture, use and storage (CCUS) technologies via collaborative efforts that address key technical, economic and environmental obstacles. Every two years, CSLF energy ministers gather to discuss the current status and future priorities for CCS. The CSLF also promotes awareness and champions legal, regulatory, financial, and institutional environments that can be conducive to CCS.

The **Global CCS Institute (GCCSI)** was founded in 2009 and is active in promoting the development, demonstration and deployment of CCS. The GCCSI gathers relevant groups of stakeholders from across the globe, including government, industry, research community and civil society, to drive the adoption of CCS. The Institute performs analysis, shares expertise, builds capacity and provides advice to its members and more widely, on the potential and challenges of CCS.

International CCS test centres such as the Technology Centre Mongstad and the National Carbon Capture Centre have also brought organisations together to test and develop CCS solutions. Various test centres have recently established an **International CCS Test Centre Network** to share knowledge of the technological developments, construction and operational experience associated with CO_2 capture from flue gas. The network also intends to establish performance indicators and promote technology standardisation.

1.6.2 Regional and bilateral collaboration

Several regional CCS collaborations have also emerged in recent times and are contributing to the development of regional strategies for CCS deployment. For example the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) has brought together various industries, governments, research, civil society and the European Commission, to provide information and to advance CCS technology in Europe. ZEP has also served as an advisor to the European Commission on the research, demonstration and deployment of CCS.

In North America, the North American Carbon Capture & Storage Association (NACCSA) has supported the development of a carbon dioxide capture, use and storage industry in the United States and Canada. With the long tradition of CO_2-EOR, utilisation has traditionally played a much bigger role in North American CCS discussion than in Europe. As opposed to the wide membership of ZEP, NACCSA has traditionally been an industry group with the mission to represent the interests of its members towards policy makers and law makers.

The Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) is an intergovernmental organisation which facilitates and coordinates the implementation of applied geoscience programmes in the region. The CCOP CO_2 Storage Mapping Program has a focus on enhancing capacity and capability in the assessment of geological sites for the storage of CO_2.

These three examples serve to illustrate the diversity of regional CCS initiatives and are by no means exhaustive of the many CCS collaborations underway.

In addition to these regional initiatives, multiple bilateral CCS partnerships have been established over the past decade. Perhaps the most notable partnership was signed between the United States and China in late 2014, which included a commitment to undertake a major CCS project in China. China has also entered bilateral agreements with Europe, the United Kingdom and Australia, among others. The Canada-United States Clean Energy Dialogue maintains a standing bilateral working group on CCS that convenes bi-national workshops and joint research projects between national labs. These partnerships are among the many initiatives which provide a valuable platform for sharing technology developments and increasingly for direct collaboration on CCS projects.

1.6.3 Future CCS collaboration

Continuing to increase and expand international CCS co-operation across research, development and deployment will be important for accelerating the future pace of deployment. A major opportunity for this is the establishment of Mission Innovation, a global initiative announced by 20 countries during the Paris COP21 climate negotiations to encourage clean energy innovation. Mission Innovation could increase public R&D investment in clean technologies from USD 15 to USD 30 billion.[13] In announcing the launch of the initiative, seven of the 20 countries specifically mentioned CCS, including Brazil, Canada, France, Norway, Saudi Arabia, the United Arab Emirates and the United States. Other countries, including China, Australia and Japan did not specifically mention CCS in their pledges, however they have demonstrated significant commitments to developing CCS.

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[13] In addition, 28 high-profile investors pledged in parallel through the Breakthrough Energy Coalition to invest in early-stage technology development that emerges from Mission Innovation initiatives. This could provide further opportunity for industry-government partnerships in the future, although it is unlikely to be targeted at large-scale CCS deployment efforts.

1.7 Key lessons from 20 years of CCS experience

More than 20 years of experience with CCS projects, technology and policy frameworks throughout the world has produced a significant body of knowledge. Experience has increased, technologies have improved and projects have multiplied. However, the progress is too slow to support the emissions reductions required to limit global temperature increase to below 2°C and there is a risk that it will grind to a halt unless progressive policy sparks new projects very rapidly. The lessons derived from past experience can provide an important base from which to accelerate the deployment of CCS in the next 20 years. While it is virtually impossible to catalogue all lessons, and many of them will be specific to national or regional circumstances, a number seem particularly universal. These key lessons have been grouped into seven broad categories below.

1.7.1 Significant progress has been made in spite of limited support

CCS has moved forward significantly in the past 20 years. The technologies themselves are proven, from capture, via transport to geological storage. Technologies have been improved and scaled up. In addition, the number of large-scale projects has increased, providing experience on how CCS works in practice. CCS is now ready for deployment.

However, recognition by many governments of the important role for CCS in achieving global climate goals has not translated into commensurate policy and financial support. Although more than USD 30 billion in funding was announced for large-scale CCS projects between 2007 and 2010, only USD 2.8 billion in public funds was actually invested between 2009 and 2014. Limited new funding for CCS projects has been announced in recent years, and several existing programmes have been curtailed or stopped. The October 2016 announcement by the Norwegian government that it will invest around EUR 40 million to progress detailed engineering studies for three industrial CCS projects is a welcome development, but remains an exception.

Beyond the wave of six CCS projects expected to commence operation within the next two years, there is very little movement in the CCS project pipeline. Without targeted support, it is unlikely that the current momentum in project deployment will be maintained, with progress likely to stall by 2020. This will substantially inhibit the availability of CCS to contribute to medium and long-term climate targets.

1.7.2 Long-term commitment and stability in policy frameworks is critical

The programmes undertaken by governments to support the development of large-scale projects have to date under-delivered in terms of projects in operation and in funds expended. Many of these programmes have been highly prescriptive with very ambitious time frames, limiting the number of eligible projects and in some cases requiring the withdrawal of funds from prospective and well-advanced projects that fail to meet pre-determined regulatory milestones (see, for example, discussion of government programmes in Box 1.2). In designing funding programmes, many have failed to appreciate the relatively long time frames involved in developing CCS projects. It is telling that projects that received funding commitments from the US Clean Coal Power Initiative between 2008 and 2010 are only just coming online in 2016 and 2017.

Maintaining large funding programmes over these time frames demands significant political commitment, as programmes can be vulnerable when budget pressures emerge. This proved to be the case in the United Kingdom, when the GBP 1 billion CCS Commercialisation Programme was abruptly cancelled in its late stages. The National Audit Office concluded that this decision could remove the option of CCS contributing meaningfully to decarbonisation before 2030 with a high chance of significantly increasing the cost of meeting the United Kingdom's 2050 emissions reduction target (National Audit Office, 2016).

1.7.3 Early opportunities for CCS deployment exist, but must be cultivated

CCS deployment has already begun in circumstances where a combination of economic, regional and project-specific factors, together with government policies, have aligned to support investment in large-scale CO_2 capture and storage. The Sleipner project is a good example of this: the introduction of a CO_2 tax for offshore oil and gas production combined with low CO_2 capture costs, subsurface expertise, favourable geology, corporate social responsibility and relatively high margins came together to secure investment in a world-first CCS project.

Commercial or semi-commercial opportunities for CCS have also emerged in the United States, underpinned by a demand for CO_2 for EOR, an extensive CO_2 transport network and high-purity CO_2 sources. The availability of tax credits for CO_2 storage and CO_2-EOR are also helping to ensure the commercial viability of these projects.

These early CCS projects in "sweet spots" have played an important role in demonstrating the viability of CCS technologies, contributing to learning-by-doing technology cost reductions and enhancing the global knowledge base, all while minimising the amount of public support needed (IEA, 2015a). There is a strong case for governments to focus on identifying and cultivating these sweet spots as a priority for early CCS deployment, recognising that they are unlikely to emerge organically in the absence of a sufficient market signal.

In parallel with these early deployment opportunities, there will still be a need to invest in the more challenging CCS applications if widespread deployment is to be accelerated. This includes investment in those industrial processes that do not produce a high-purity stream of CO_2 (such as iron, steel and cement production) as well as in power generation.

1.7.4 No CCS without the "S": CO_2 storage must come first

Access to geological storage is potentially the most significant impediment to widespread CCS deployment. There is little point in capturing large quantities of CO_2 without access to a storage site. Fortunately, there is a high degree of confidence that global storage resources are more than adequate to accommodate future requirements, even under highly ambitious scenarios. For example, estimated geological storage resources in the United States is between 2 376 Gt and 21 000 Gt, around 1 500 Gt in China, and 78 Gt in the United Kingdom (GCCSI, 2016d). To put this in context, the cumulative global storage requirements between now and 2050 in the 2DS are 94 Gt.

Significant further work is required to convert this theoretical storage capacity into "bankable", practical storage facilities, where there is a high degree of confidence that desired amounts of CO_2 can be injected at desired rates. This will require a detailed understanding of the capacity, containment and injectivity of the prospective site(s), as well as the commercial and cost aspects and any regulatory or social barriers to development. Experience has demonstrated that this process can take anywhere from 1 to 15 years, depending on the storage option (IEAGHG, 2011a) and may ultimately represent a higher proportion of future CCS costs than currently estimated.

Confidence in future storage capacity will also be very important to inform the long-term climate and energy policy decisions being made by governments today. The size and location of bankable CO_2 storage capacity will have implications for new investment in energy-intensive power generation and industry. It is also critical to assessing whether CCS will be available as an option to address emissions from existing infrastructure. The better the understanding of storage prospects, the better informed these important policy and planning decisions can be.

Developments in transport will affect the accessibility of storage sites for capture sources. For example, with further development of the CCS industry, CO_2 could (at a cost) be transported over longer distances by ships to regions which are more endowed with large-scale storage capacity, analogous to developments in the LNG and NG sector.

1.7.5 The role of CCS goes well beyond a "clean coal technology"

CCS has often been characterised as a "clean coal technology", underpinned by an expectation that its primary role will be to reduce emissions from coal-fired power generation. While this may indeed be the case in some regions in the future, most notably in China (see Section 3.2), the experience of the last 20 years has highlighted the diversity of CCS applications and particularly the essential role of CCS in addressing emissions in industrial processes. As described in Chapter 2, CCS in industry and fuel transformation accounts for 44% of the total emissions reductions achieved from CCS deployment in the 2DS. CCS deployment on gas-fired power generation will also be important in achieving climate goals, with 250 GW of gas-fired power generation capacity equipped with CCS in 2050, generating 1 485 TWh of electricity.

It is notable that the oil and gas sector has played a major role in CCS deployment to date, both in terms of the number of projects applying CCS to natural gas processing, and in terms of the role of EOR in providing a revenue stream for projects. Furthermore, the industry has provided the subsurface skills and expertise necessary to support the development of CO_2 storage facilities. These strong linkages between CCS development and the oil and gas sector can have implications for CCS development during periods of sustained low oil prices, where EOR projects become less economic and the capacity of the sector to invest in new technology endeavours is reduced.

1.7.6 Many more projects are needed

The number of integrated CCS projects which have failed to reach an FID outnumbers the successful projects by a factor of two to one. There are many reasons for this, ranging from inadequate financial or policy support; withdrawal of government funding programmes; lack of access to commercial CO_2 storage sites; higher than estimated project costs; changed market conditions; and local community opposition. Many projects do not get past the "identify" stage of development. For projects that are further along the project development pathway, the process of undertaking pre-feasibility and feasibility studies may identify financial, technical or social issues that on balance mean that a decision to proceed is not taken. This is a normal and prudent approach to project development and one that is applied to all major infrastructure investment decisions.

The reality that not all projects will proceed emphasises the need to ensure that more projects are entering the CCS project pipeline. Governments should also seek to maximise the rate of success of advanced projects by reducing the possibility of policy uncertainty or inadequate support.

1.7.7 Community engagement is essential

Successful deployment of CCS will involve improved efforts to ensure local communities and the general public understand and accept the technology. Permanent geological storage of CO_2 is a relatively new concept for many people, and will raise legitimate concerns about safety and risks, particularly among those who experience this concept for the first time.

Projects such as Shell's Quest project in Canada have demonstrated the value of early and extensive stakeholder and community engagement. For Quest, this engagement commenced several years before seeking regulatory approvals and ensured that the local community could provide input to project development. Any necessary adjustments were made while the project was still in the early planning stages. Quest also employed third-party advisors, including leading academics, to provide an independent review of the storage component of the project. This ultimately assisted in securing community support for the project.

Project-level engagement can be enhanced when supported by broader CCS communications. Governments, non-government organisations (NGOs) and the scientific community can help inform communities not only by describing the activities that comprise a CCS project, but also being proactive in communicating the role of CCS as one element of an effective global or national response to climate change. This includes ensuring that CCS is included in national energy policy frameworks, alongside today's other "mainstream" low-carbon technologies.

Commentary 4 • 20 years on: A personal perspective

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I first became aware of the concept of CCS (it was called geological disposal of carbon dioxide in those days) in 1990, shortly after I took up the position of Director of the British Geological Survey (BGS). There, a small group of talented people were quietly undertaking research into carbon dioxide. In 1993, this was to evolve into the European Commission Joule II study of the storage potential of the United Kingdom, Norway, France, Germany and the Netherlands. This was the first of many regional storage assessments that essentially asked the question "does CCS have the potential to make deep cuts in stationary emissions of CO_2?" Joule II clearly showed that CCS had that potential. Sleipner commenced in 1996, and by the mid-1990s, I sought to influence UK power companies and Whitehall policy makers on the merits of CCS – with limited success at that time, it has to be said! But over the next decade, a number of other initiatives were to strengthen the case.

In North America, pioneering storage projects such as the Frio Brine Project in Texas and the Weyburn Project in Saskatchewan were important for the acceptance of CCS in North America. The seven Regional Carbon Sequestration Partnerships (RCSP) were not officially underway until 2003, but were preceded by decades of experience in transporting and injecting carbon dioxide for EOR projects. RCSP, EOR and North American demonstration projects were to have a global impact. In Japan, research by RITE in Japan, including demonstration projects such as Nagaoka, was similarly important in "spreading the word" on CCS.

I returned to Australia in 1998. At that time, there was little or no discussion on the mitigation potential of CCS in Australia. But I was able to assemble an outstanding team of researchers from universities and government, and with support from industry, initiated the GEODISC (Geological Disposal of Carbon) Project to assess the storage potential of the Australian continent and its continental shelf. GEODISC showed that CCS indeed had very significant potential for Australia and I was able to use this as a platform for establishing the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) in 2003 and subsequently for developing the Otway Project.

The decision in 2003 by the IPCC to produce a Special Report on Carbon Dioxide Capture and Storage (published in 2005) was a watershed for CCS. I was privileged to be co-ordinating lead author (with Sally Benson) for the chapter on storage. The IPCC Special Report helped to establish a benchmark for our state of knowledge on capture, transport, use and storage of CO_2. Along with the Carbon Sequestration Leadership Forum (established 2003), it encouraged more regional assessments of

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storage capacity and highlighted the need for a systematic approach to capacity. It also encouraged policy makers to consider the mitigation potential of CCS more seriously, which they did.

By 2005-2006, there was much talk about bringing down the cost of CCS and deploying it at a commercial scale in the coming decade. A large number of countries including Britain, the United States and Australia announced competitions and other mechanisms for CCS deployment and a number of large-scale CCS projects were also announced by industry. So, by 2008, there was optimism that CCS would soon be deployed at a commercial scale. Australia announced the GCCSI and the G8 spoke optimistically about 20 CCS projects by 2020. And then there was Copenhagen, the global financial crisis, projects cancelled, government funding cut-backs, commodity price falls and industry funding cut-backs. By 2010-11 it was a very different scene, with people and politicians taking an increasingly pessimistic view of CCS.

I did not and do not now share that pessimism; indeed, optimism is a prerequisite for anybody who has been in the CCS business as long as I have! There are many reports and reviews by the IEA, IPCC, UNFCCC and other bodies that show CCS must be part of the mitigation mix. But we did get some things wrong. We underestimated the complexity, the cost and the time to build large-scale CCS projects (despite knowing that first-of-a-kind are always like that). We overemphasised the likely role of CCS in power generation (after all, there are other ways of generating low-carbon electricity) and underemphasised the important role for CCS in industrial processes (where only CCS can do the job). We let the reality (and branding) of CCS be subsumed by “clean coal” and to date we have done poorly in the battle for the hearts and minds of politicians, policy makers and the public.

But none of this is irreversible and we have achieved a lot over the past 20 years: Boundary Dam offers a remarkably good story as does CO_2-EOR, and Decatur demonstrates the feasibility of linking biofuels with CCS – BECCS. There are ongoing technology innovations, outstanding field research and demonstration storage projects continue to prove we can safely store CO_2 and there is increasing confidence that storage capacity is very large. Also, new CCS funding models are emerging and industry is re-engaging with CCS. But it will take more than good news stories to change the current mind-set. To do that, we need a new narrative emphasising the need for a “mitigation mix” including CCS (alongside renewables) as a cost-effective and essential clean energy technology applicable to a range of fuels. We need to develop a dialogue with the renewables lobby, look for areas of commonality, investigate hybrid technologies and develop a broader coalition for CCS. And, of course, underlying all of this is the fact that without CCS we are not going to meet the aspirations of COP21.

So yes, after 20 years and despite disappointments and frustration with the, at times, slow rate of progress, I remain confident that CCS is an essential part of a low-carbon future – indeed it has to be otherwise there will not be a low-carbon future!

2 Towards well below 2°C: An increased role for CCS

Key highlights

In the International Energy Agency (IEA) 2°C scenario (2DS), carbon capture and storage (CCS) delivers 12% of the cumulative emissions reductions needed up to 2050, capturing around 94 gigatonnes (Gt) of carbon dioxide (CO_2). Almost 14 Gt of this is "negative emissions" from bioenergy with CCS (BECCS) which act to compensate for emissions elsewhere in the energy system.

The availability of CCS is particularly important in industrial processes – primarily in the production of iron and steel, chemicals and cement – with more than 28 Gt of emissions captured cumulatively from these processes in the 2DS before 2050. Alternatives to CCS in these sectors are limited.

CCS can reduce the cost of transforming the power sector. Alternative pathways to achieve the 2DS in power may be possible without CCS, but would be challenging in practice and would require at least USD 3.5 trillion in additional investment.

Faster and more extensive deployment of CCS could shift the energy sector from a 2°C pathway to well below 2°C. In the 2DS, there are still more than 7 Gt of emissions from industrial processes in 2050, which could be reduced with CCS. The power sector is virtually decarbonised in the 2DS, but faster deployment of CCS before 2050 could deliver significant emissions reductions.

The Paris Agreement has raised the level of climate ambition and signalled a collective global commitment to limit future temperature increases to "well below 2°C". The success of Paris must now be followed by action to identify and implement the technology pathways and associated policies required to achieve this target.

This chapter analyses the role for CCS within the IEA 2DS[14] and the potential for CCS to contribute to moving to a target below 2°C. It will also examine the implications if CCS were not available to reduce emissions in the power or industry sectors.

2.1 Achieving 2°C – a key role for CCS

The deployment of all low-emissions technologies, including CCS, will be essential to limit energy sector emissions to levels consistent with limiting global temperature increases to below 2°C. In the IEA *Energy Technology Perspectives 2016* (*ETP*) 2DS (see Box 2.1), a portfolio of technologies is deployed as part of a least-cost transition pathway. These technologies include renewables, energy efficiency, nuclear energy, fuel switching and CCS.

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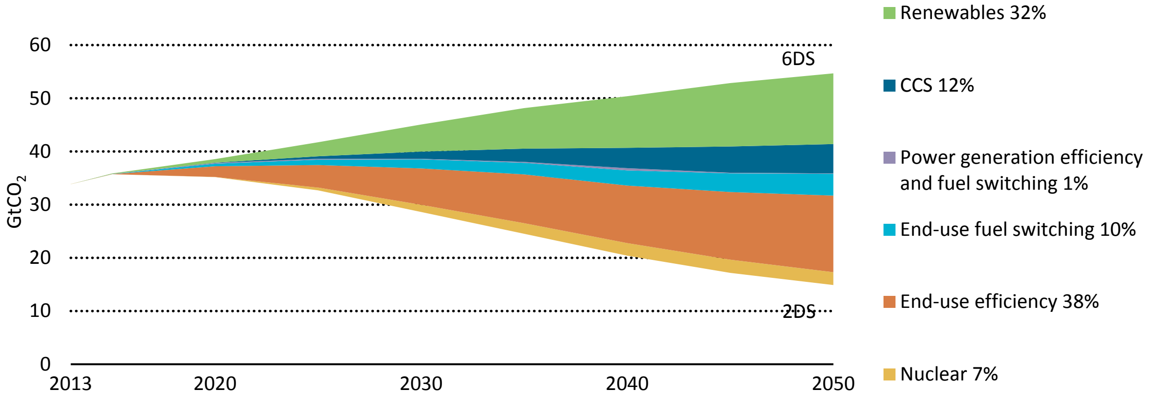
[14] Based on *Energy Technology Perspectives 2016* (IEA, 2016b).

Box 2.1 • The "2DS" of the IEA *Energy Technology Perspectives*

The *ETP* 2DS lays out an energy system deployment pathway and an emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C. The 2DS sets the target of cutting CO_2 emissions by almost 60% by 2050 (compared with 2013), reaching a cumulative emissions level of about 1 000 $GtCO_2$ from 2013 to 2050. Carbon emissions from fuel combustion and industrial processes are projected to continue their decline after 2050 until carbon neutrality is reached. The 2DS identifies changes that help ensure a secure and affordable energy system in the long run, while emphasising that transforming the energy sector is vital but not enough on its own. Substantial effort must also be made to reduce greenhouse gas (GHG) emissions in non-energy sectors.

CCS accounts for around 12% of the cumulative emissions reductions needed through to 2050 (see Figure 2.1). Under the 2DS, 94 $GtCO_2$ is captured and stored between 2013 and 2050, including almost 14 $GtCO_2$ in "negative emissions" from BECCCS which act to compensate for emissions elsewhere in the energy system.

Figure 2.1 • CCS is a key contributor to global emissions reductions[15]



Source: IEA (2016b), *Energy Technology Perspectives 2016*.

2.1.1 Examining the CCS contribution to achieving 2°C

The 94 Gt of CO_2 captured and stored by CCS through 2050 under the 2DS comprises emissions from the power, industry and fuel transformation sectors. The power sector accounts for the majority of CO_2 captured, at 52 $GtCO_2$ or 55% of the total CO_2 captured through 2050 in the 2DS. Roughly 29 $GtCO_2$ or 31% of the total CO_2 captured is in industry, predominately from the production of chemicals (38%), iron and steel (33%) and cement (29%). The fuel transformation sector accounts for the remainder of the captured CO_2, with 13 $GtCO_2$ captured from biofuel production and gas processing (see Figure 2.2).

Moving to a 2°C pathway will require an order-of-magnitude increase in current CCS deployment. Annually captured CO_2 would need to be increased from around 28 $MtCO_2$ today to around 6.1 $GtCO_2$ in 2050, requiring average growth of more than 15% per year. Under the 2DS, emissions captured increase each decade through 2050, rising from less than 8 Gt through 2030,

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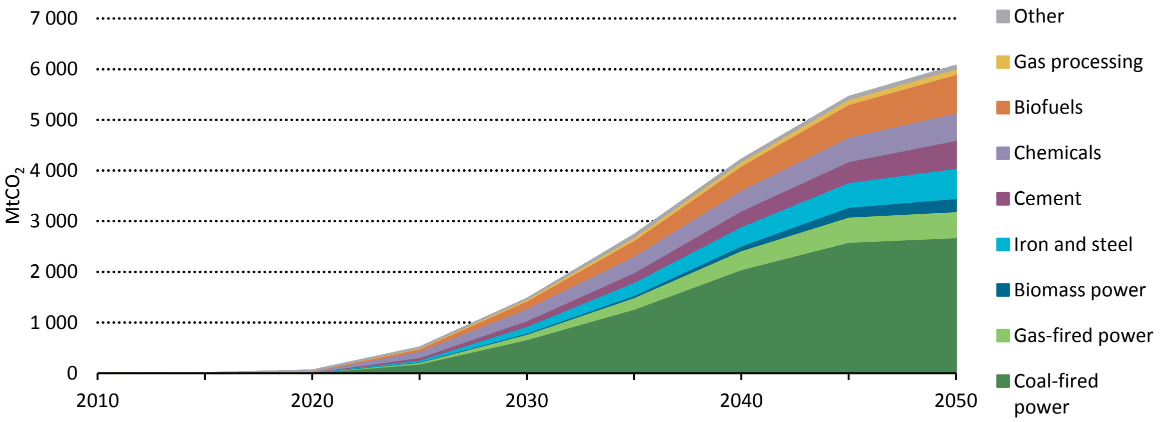
[15] This graph presents the share of emissions reductions under the 2DS relative to the 6°C scenario (6DS). The 6DS is largely an extension of current trends and assumes a small amount of future CO_2 capture through 2050 of 60 $MtCO_2$ in total. In the 6DS, primary energy demand and CO_2 emissions (including process and feedstock emissions in industry) grow by about 60% from 2013 to 2050, with about 1 700 $GtCO_2$ of cumulative emissions.

to nearly 30 Gt from 2031 to 2040, to over 50 Gt from 2041 to 2050 (see Table 2.1). This trend is reflected across the power, industry and other transformation subsectors.

Figure 2.2 • Power and industry are the predominant sources of CO_2 captured in the 2DS



Source: Derived from IEA (2016b), *Energy Technology Perspectives 2016*.

Significant investment in CCS will be needed to generate these outcomes. CCS investment in power generation reaches a total of around USD 2.2 trillion through 2050 and the investment in CCS for the fuel transformation sector totals USD 1.3 trillion. An aggregate figure for industry is more difficult to estimate[16] (see Table 2.1).

Table 2.1 • Growing capture across sectors in the 2DS and related aggregate investment needs

	Cumulative capture through 2030 ($GtCO_2$)	Cumulative capture through 2040 ($GtCO_2$)	Cumulative capture through 2050 ($GtCO_2$)	Investment expenditures (USD tln)
Power	4.0	20.0	52.0	2.2
Industry	3.0	11.0	29.0	n/a
Other transformation	0.9	5.0	13.0	1.3
TOTAL	**7.9**	**36.0**	**94.0**	n/a

2.1.2 CCS in the power sector

CCS plays an important role in reducing emissions in the power sector in the 2DS, with 52 $GtCO_2$ captured cumulatively to 2050. By 2050, there is around 850 GW of electricity generation capacity equipped with CCS, generating 5 000 TWh or 12% of global power.

The vast majority of CO_2 captured in the power sector comes from coal-fired power plants, which account for more than 40 $GtCO_2$ or around 80% of total CO_2 captured in the sector through 2050.[17] In 2050, 570 GW of coal-fired capacity with CCS is operational, representing nearly three-

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[16] Estimates of the necessary investment in the industrial sector are challenging, given that CO_2 capture is likely to be part of a broader process optimisation, and so the related investments are difficult to segregate from other costs.

[17] Various factors affect the carbon intensity of power generation under the *ETP* analysis. For example, the 2DS assumes capture rates on power of 85% to 95%, depending on the technology. Current CCS technology also involves an energy penalty that reduces plant efficiencies between 7% and 10% as additional energy (electricity, steam or heat) is used for the capture process. As a result, with CCS more energy is needed to supply the same amount of electricity output to the grid. For example, under a simplified calculation, an ultra-supercritical coal-fired power plant with a net efficiency of 45% and whose coal has a carbon content of 95 $ktCO_2/PJ$ has a carbon intensity for its power generation of 760 gCO_2/kWh. With an 85% CO_2 capture rate, the carbon intensity of each kWh generated with CCS drops to 114 gCO_2/kWh. However, to the extent that the plant's

quarters of total coal-fired capacity and generating 3 300 TWh or 8% of global power generation. Unabated coal generation is virtually phased out by 2050; approximately 28% of installed coal-fired capacity is not equipped with CCS (219 GW) and these unabated plants are running at very low capacity factors, generating only 10 TWh in 2050.

Gas-fired power generation with CCS is also important in the 2DS, accounting for almost 8 $GtCO_2$ captured cumulatively through 2050. This represents around 15% of CO_2 captured in the power sector. In 2050, 250 GW of gas-fired power plants are equipped with CCS and provide around 4% (1 485 TWh) of global power generation. In 2050, 42% of gas-fired power generation comes from plants equipped with CCS.

Biomass plants equipped with CCS and biomass co-firing provide 5% of the cumulative CO_2 captured in the power sector through 2050. In 2050, 30 GW of dedicated biomass capacity with CCS generates 163 TWh.

2.1.3 CCS in industry

CCS is a key technology for reducing CO_2 emissions in carbon-intensive industrial processes. In the 2DS, CCS contributes 29 $GtCO_2$ of emissions reductions in the industry sector through 2050, representing around 20% of the cumulative emissions reductions achieved in the sector relative to current trends. The remaining 113 $GtCO_2$ of emissions reductions in industry, are delivered through improvements in energy and material efficiency (e.g. plastics recycling), switching to lower-carbon fuel and feedstock, and low-carbon innovative processes. The vast majority of the CO_2 is captured from three subsectors (see Figure 2.3), namely the production of chemicals and petrochemicals, iron and steel, and cement:

- *Chemical and petrochemicals:* Nearly 11 $GtCO_2$ is captured from the chemicals and petrochemicals sector through 2050 in the 2DS, representing the largest source of CO_2 captured from industrial processes. The CCS deployment considered in the 2DS is attached to the production of ammonia and methanol, as well as high-value chemicals such as ethylene, propylene and aromatics.
- *Iron and steel:* In the 2DS, 10 $GtCO_2$ is cumulatively captured from iron and steel production through 2050. This represents 19% of the total reduction in emissions from this subsector through 2050.
- *Cement:* 8 $GtCO_2$ is captured in total from the cement industry. CCS plays a particularly important role in reducing the carbon emissions in the cement sector. It provides 48% of total emissions reductions from cement production given the inherent generation of CO_2 during the calcination of limestone, the main raw material for clinker production that is the key intermediate step in the cement process.

The role of CCS in industry grows over time in the 2DS as deeper emissions cuts are needed and as other options become exhausted or less economical.

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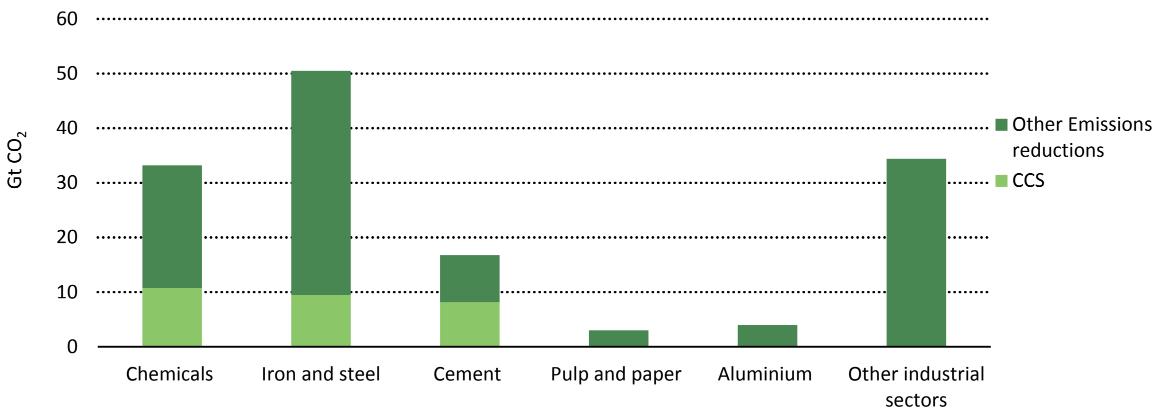
efficiency falls to around 36% as a result of the energy penalty, an additional 0.25 kWh-equivalent are required to run the capture-related installations. As a result, the carbon intensity for each kWh actually delivered to the grid is 143 gCO_2/kWh after factoring the impact of this energy penalty. The carbon intensity varies, and can even be lower, for different technologies and under other assumptions.

Figure 2.3 • Cumulative emissions reductions from CCS in industry (2DS relative to 6DS)



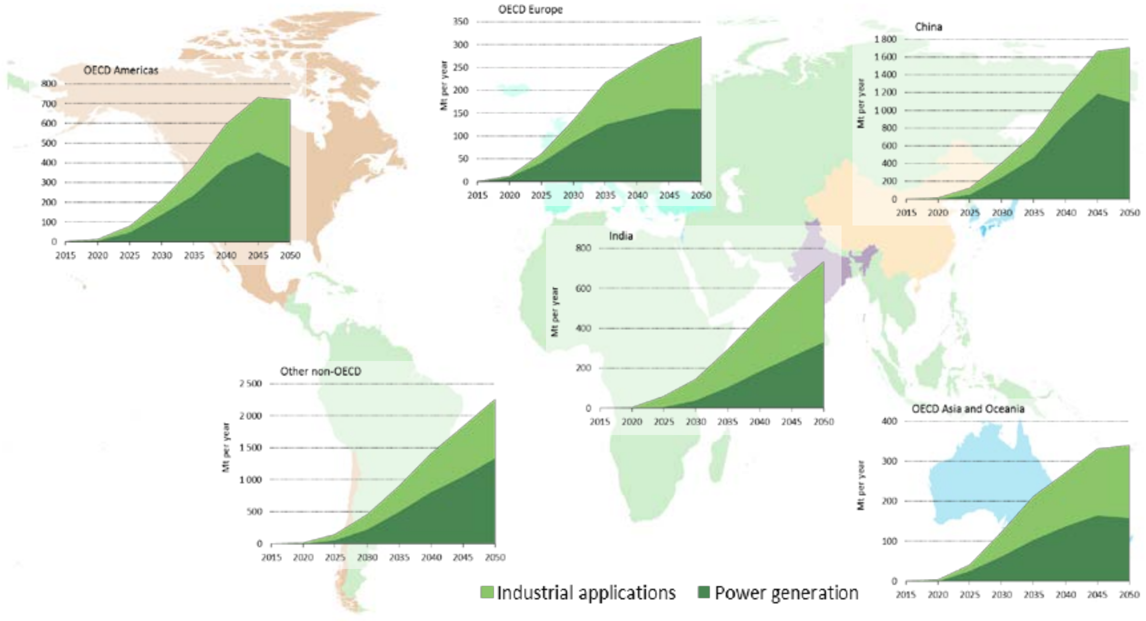
Source: Derived from IEA (2016b), *Energy Technology Perspectives 2016*.

Note: There are 97 $MtCO_2$ captured from pulp and paper production

2.1.4 CCS deployment across regions

In the 2DS, nearly 75% of CCS is deployed outside of the OECD, most notably in China which alone accounts for 28% (26 Gt) of the CO_2 captured globally through 2050 (see Figure 2.4). After China, OECD Americas is the region with the largest amount of CCS, capturing 12 $GtCO_2$ through 2050. In China, OECD Americas, OECD Europe and other non-OECD countries, CCS for power generation is dominant over the period to 2050. In OECD Asia and Oceania, the role of CCS in power and industry is roughly equal, while in India there is an emphasis on industrial deployment.

Figure 2.4 • CCS in key regions in the 2DS



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: Derived from IEA (2016b), *Energy Technology Perspectives 2016*.

In China, CCS plays a particularly important role in power generation, with 67% of CO_2 captured from power generation through 2050 compared with 33% from industry. Coal and gas-fired plants with CCS account for 13% of China's power generation in 2050. Almost all of this CCS is coal-based, and virtually all coal-fired generation comes from plants equipped with CCS. In contrast, around 13% of gas-fired power generation in China is from CCS-equipped plants in 2050.

In the United States, 67% of the CO_2 captured is from power generation. Gas-fired power generation with CCS plays a particularly important role in the electricity mix, with 80 GW of installed capacity and 98% of gas-fired power generation coming from plants equipped with CCS in 2050. 32 GW of coal-fired generation capacity with CCS is also installed while unabated coal-fired generation is phased out.

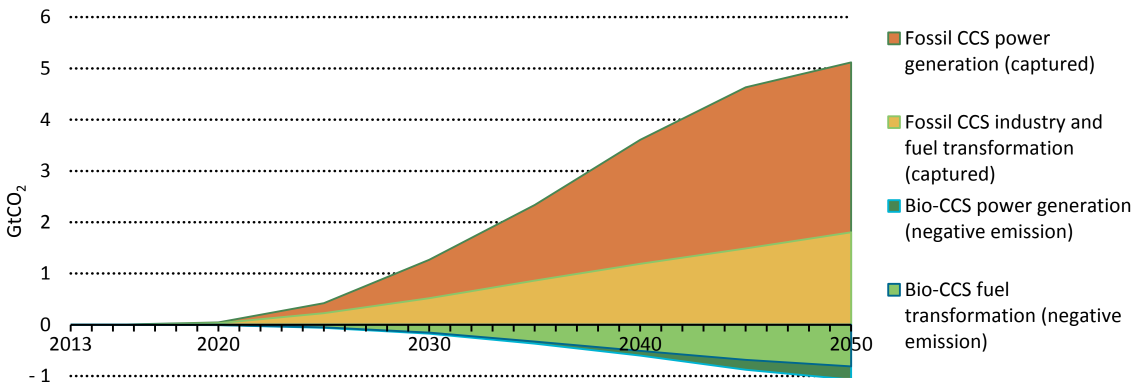
The use of CCS in industry plays a relatively larger role in India, with 60% of CO_2 captured from industrial processes through 2050. Within power generation, 63 GW or 54% of coal-fired capacity is equipped with CCS, although the remaining unabated coal generation fleet operates at very low capacity. In 2050, only 5% of gas-fired power generation capacity in India is equipped with CCS.

In Europe, roughly equal shares of CO_2 are captured in industry and power through 2050. Within the power sector, 7 GW of coal-fired power generation capacity and 19 GW of gas-fired power generation capacity is equipped with CCS in 2050. Gas-fired power plants provide 4% of total generation in Europe, and 90% of this is from plants equipped with CCS in 2050. Coal-fired power generation is minimal, providing around 1% of total generation. However all this is from CCS-equipped plants.

2.1.5 The role of negative emissions

In the 2DS, the combination of biomass with CCS, or BECCS, delivers "negative emissions" which effectively offset higher emissions elsewhere in the energy systems. BECCS account for around 2% of the cumulative emissions reductions in the 2DS, with almost 14 $GtCO_2$ captured in the period to 2050. The negative emissions delivered through BECCS in the 2DS equal 1.1 $GtCO_2$ in 2050, or 16% of the total of 6 Gt of CO_2 captured for that year (see Figure 2.5).

Figure 2.5 • "Negative emissions" in the 2DS



Source: Derived from IEA (2016b), *Energy Technology Perspectives 2016*.

Note: The chart is stylised to illustrate negative emission effect. In 2050, 6 $GtCO_2$ is captured, with 1 $GtCO_2$ of "negative emissions".

Negative emissions from BECCS arise due to the fact that biomass absorbs CO_2 as it grows and when combusted for energy the CO_2 is released back in to the atmosphere, creating a full cycle with a neutral impact on atmospheric volumes of CO_2.[18] When combined with the CO_2 capture and storage process, a portion of the CO_2 absorbed by the biomass is permanently removed from the atmosphere.[19] In comparison, when the emissions created from the combustion of fossil fuels are captured and stored, it more closely resembles a closed cycle with a slightly positive carbon balance,[20] depending on the rate of capture (see Section 1.4.1).

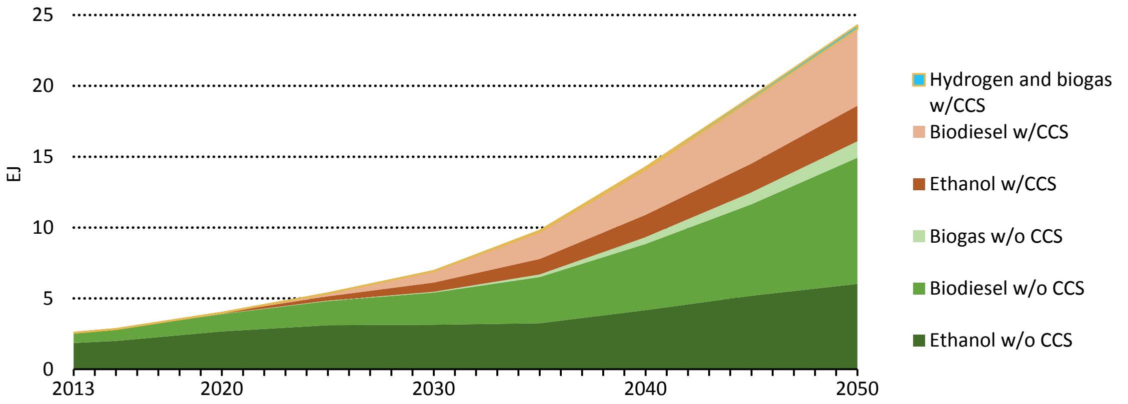
Annual negative emissions delivered through BECCS in the 2DS grow from around 0.01 $GtCO_2$ in 2020 to 1.1 $GtCO_2$ in 2050. The impact of these negative emissions is that total gross energy sector emissions in 2050 in the 2DS are 16 $GtCO_2$, but the net emissions are 1.1 Gt lower at 14.9 $GtCO_2$ (see Table 2.2). Viewed from a cumulative perspective, total gross energy sector emissions over the period through 2050 are 1 027 $GtCO_2$, but with the impact of the 14 Gt of cumulative negative emissions the net total in the 2DS is reduced to 1 013 $GtCO_2$.

Table 2.2 • Gross vs. net emissions (Gt): Impact of negative emissions in the 2DS

	2020	2035	2050	Cumulative 2015-50
Gross emissions	35.7	24.9	16.0	1 027
Negative emissions	0.0	0.4	1.1	14
Net emissions	35.7	24.5	14.9	1 013

BECCS is primarily deployed in biofuel production, which accounts for a cumulative 11 $GtCO_2$ captured until 2050 (see Figure 2.6). BECCS accounts for almost 30% of liquid and gaseous biofuel production in 2050 in the 2DS. However, a significant share of biodiesel and ethanol production is not equipped with CCS. BECCS in the power sector is rather limited for both dedicated biomass plants and biomass co-firing, providing a cumulative 3 $GtCO_2$ captured from biomass over the time horizon until 2050.

Figure 2.6 • CCS in biofuel production



Source: Derived from IEA (2016b), *Energy Technology Perspectives 2016*.

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[18] The conditions under which the biomass is grown is central to determining whether it is carbon neutral.

[19] Other technologies could generate negative emissions, for instance direct air capture of CO_2. For more on BECCS and negative emission technologies see Chapter 3.

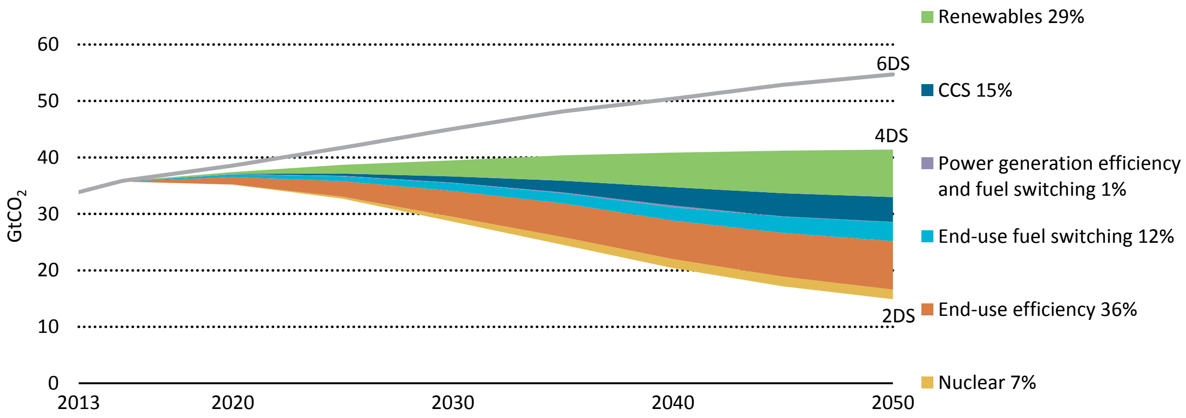
[20] Typically, only part of the emissions resulting from fuel combustion are captured. See also Section 2.4 on these associated challenges in efforts to pursue even more ambitious climate targets.

2.1.6 Bending the curve: From the 4DS to the 2DS

If all announced policies and recent pledges to limit emissions are implemented, the energy sector trajectory most closely resembles the 4DS.[21] The *ETP 2016* splits out the relative contributions of CCS and other technologies in moving to the 4DS outcome, under a cost-optimised approach,[22] and then onwards to the 2DS (see Figure 2.8). This analysis shows that a cost-optimised pathway to 4DS emissions would involve a significant amount of CO_2 capture, totalling 17 $GtCO_2$ through 2050.

The role of CCS in reducing emissions becomes relatively more important in moving closer to the 2DS for which deeper emissions reductions are needed. Significant additional effort will be required to bend the trajectory from the 4DS to the 2DS pathway, with CCS contributing 15% of the emission reductions between the 4DS and 2DS as compared to only 6% in the 4DS (see Figure 2.7). Of the total of 94 $GtCO_2$ captured in the 2DS through 2050, only 18 $GtCO_2$ is captured to move to the 4DS, while 74 $GtCO_2$ is captured in moving from the 4DS to the 2DS.

Figure 2.7 • Moving from 4DS to 2DS: An increased role for CCS



Source: IEA (2016b), *Energy Technology Perspectives 2016*.

The 18 $GtCO_2$ in the 4DS, while small relative to 2DS levels, appears large relative to the intentions reflected in the Nationally Determined Contributions (NDCs) as submitted prior to the Paris climate negotiations, which have limited reference to CCS (see Section 3.1.1). Accordingly, implementation of announced policies leading to an emissions pathway consistent with the 4DS may in practice result in relatively limited investment in CCS projects, with preference given to investments in renewables and energy efficiency. As a result, a significant portion of the 18 $GtCO_2$ in CCS capture (and related investment) provided for in the 4DS may in practice be deferred to a future time when policies are announced and adopted that align with the 2°C goal.

2.2 A low-carbon world without CCS?

As discussed in Chapter 1, policy and financial support for CCS has been relatively limited and the pace of deployment has fallen behind that of other low-emissions technologies. Yet CCS remains

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[21] The *ETP* 4DS takes into account recent pledges by countries to limit emissions and improve energy efficiency, which help limit the long-term temperature rise to below 4°C. The 4DS would still require significant changes in policy and technologies compared to a business-as-usual continuation of current trends, and will also require substantial additional cuts in emissions after 2050. Even with post-2050 action, the likely average temperature increase in 2100 under this scenario is almost 3°C. (IEA, 2016b)

[22] The modelling is done relative to the 6DS, which scenario is described above in footnote 15.

important in energy sector models to achieve the deep emissions reductions needed over the medium and long term in more ambitious climate scenarios. This section examines the implications for achieving the 2DS if CCS technologies are not available to contribute to emissions reductions, notably for the power and industry sectors.

2.2.1 CCS provides a lower-cost transformation in power

Removing CCS as a technology option for power generation would significantly increase the cost and complexity of decarbonising the sector. It would require a substantial increase in the use of renewable technologies and a virtual phasing out of all coal-fired power generation, both of which will be challenging in practice.

Under a preliminary analysis of a "no CCS for power" (NCCS) variant of the 2DS,[23] coal, gas and biomass-fired power generation with CCS is replaced primarily by renewable generation and to a limited extent by gains in nuclear generation (see Figure 2.8). In the NCCS, coal-based generation drops from 3 340 TWh in 2050 in the 2DS to 21 TWh, while the share of renewables in the electricity mix grows from 67% to 75%, an increase of 3 700 TWh. Given the lower capacity factors of variable renewables, meeting these generation targets would require an additional 1 900 GW of renewable capacity to replace the 850 GW of (predominately) fossil fuel capacity equipped with CCS. This is equivalent to around four times the total wind and solar PV capacity additions achieved in the last decade (IEA, 2015b). Achieving such high rates of renewable deployment over and above the level already contemplated in the 2DS will create significant challenges for energy planners and network managers, including the physical installation and integration of this capacity into electricity networks. It would also be considerably more expensive. Under the NCCS variant, the additional investments needed in power generation capacity alone – excluding electricity storage and network requirements – would be at least USD 3.5 trillion.[24]

The phase-out of coal generation by 2050 presents further challenges, particularly for many emerging economies that plan to build new coal-fired generation capacity with potential operating life beyond 2050. Removing the option for CCS retrofitting would increase the need for early retirement of plants in order to reduce emissions to levels consistent with climate targets.

Gas-fired power generation would continue to play a role in the NCCS variant, but would generate 400 TWh less in 2050 (an 11% decrease) compared to total gas generation (with and without CCS) in the 2DS. Gas would continue to be used even without CCS in order to provide flexibility in the system and to support the integration of the higher shares of renewable power.

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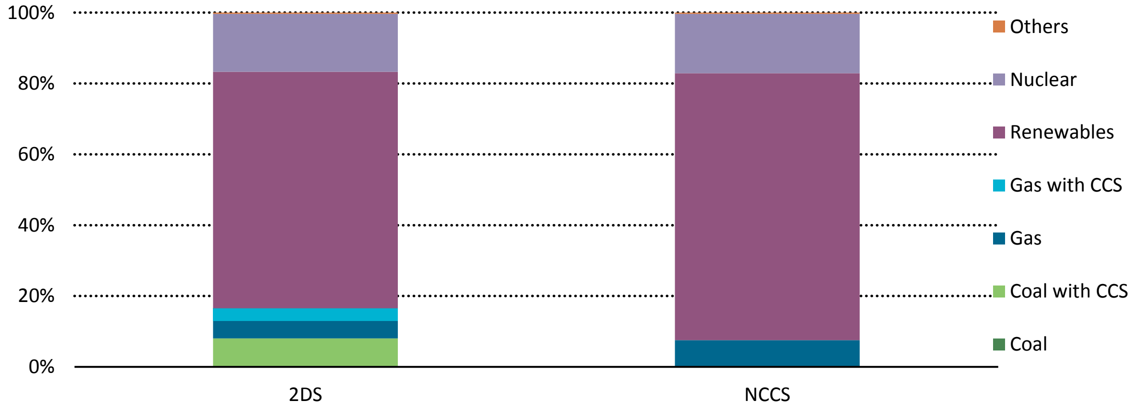
[23] The NCCS variant assumes no additional energy efficiency or any demand side measures beyond those in the 2DS.

[24] Total investment in power rises from USD 28.5 trillion (USD 2014) in the 2DS to USD 32.0 trillion (USD 2014) in the NCCS variant. The additional investment in power generation capacity is over and above the USD 2.2 trillion that would otherwise be required for CCS.

Figure 2.8 • No CCS in power: Coal virtually disappears from the generation mix



2.2.2 *Industry: Few alternatives to CCS for deep emissions reductions*

There are limited alternatives to CCS for achieving deep emissions reductions in industry. If CCS were unavailable, the 29 $GtCO_2$ captured cumulatively through 2050 in the 2DS from industrial processes would be difficult to reduce through other measures within the sector. Based on present and emerging technologies, it is unlikely that substantial reductions in CO_2 emissions could be made in these energy-intensive industrial sectors without CCS while maintaining production levels. Demand for these materials is expected to remain strong over the next several decades, notably in emerging economies where significant new infrastructure developments are projected to take place.

CCS is currently one of few technology options for reducing CO_2 emissions from processes which produce CO_2 as an inherent by-product of the chemical process involved in the manufacture of materials, such as cement and ammonia. Other carbon emission reduction measures are available in the industrial sector, such as energy efficiency improvements, the use of biomass or other low-carbon feedstocks, and the generation of heat through renewable-based power rather than the combustion of fossil fuels. However, these options are highly dependent on such factors as the availability and cost of biomass and renewable electricity. There are also limits to the technical feasibility of these options. For example, industrial processes with energy-intensive elements (e.g. cement) are less well suited to renewable-based electric heating technologies compared to those with low-temperature heat demand requirements (e.g. food and beverage).

The emissions reduction possibilities without CCS in the production of iron and steel, cement and chemicals – the largest three subsectors for CCS-related emissions reductions under the 2DS – illustrate the limits to the potential of current alternatives.

- **Iron and steel.** Carbon emissions reductions are possible in the iron and steel sector without CCS; however their potential is constrained economically and technically. Emissions from iron and steel production in the 2DS are reduced in part through energy efficiency, switching to direct reduced iron (DRI), especially gas-based DRI, and shifting to scrap-based electric arc furnaces (EAFs). However there are limits to increasing the CO_2 emissions reductions available from these options. For example, in the current 2DS, energy efficiency opportunities are largely exhausted as they are often lowest on the cost curve and in some cases may in fact reduce the cost of production (IEA, 2015a). Similarly, by 2050 there is little production with coal-based DRI remaining which could be converted to gas-based DRI, limiting the further reductions available through fuel switching. Steel production in EAFs can also significantly reduce carbon emissions, depending on the CO_2

intensity of the electricity being used, compared to the widely used blast-furnace-plus-basic-oxygen-furnace route (BF-BOF). The lowest carbon EAF processes use high levels of scrap steel rather than lowering the iron requirement. The use of scrap in the 2DS increases by around 80% from 2020 to 2050 and global production from EAF almost triples in the 2DS between 2015 and 2050, but there are limits to the availability of economical scrap steel.

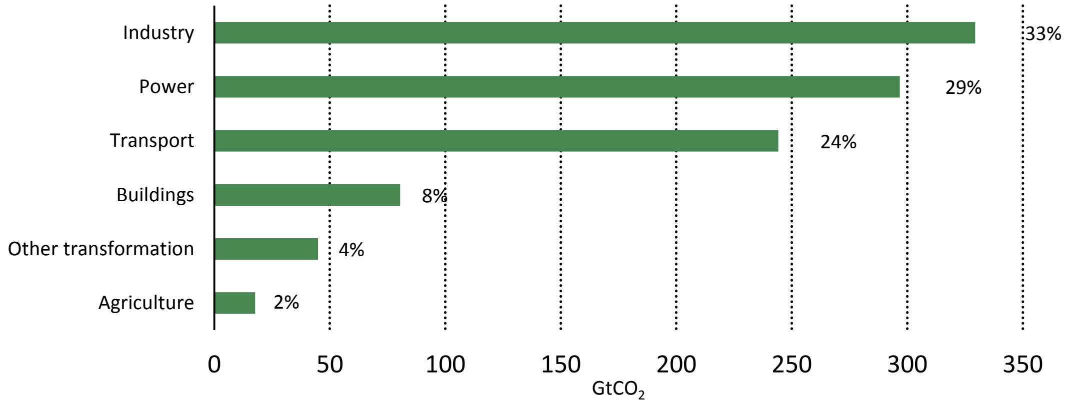
- **Cement.** Given current technological trends, it is unclear how the cumulative 8 Gt CO_2 captured from the cement sector could be reduced through other measures within the sector if CCS were unavailable. Limited carbon emissions reductions can be found through other measures including switching to low-carbon fuels, energy efficiency improvements and reducing the clinker-to-cement ratio. Clinker substitution and CCS are the only available measures for drastically reducing the process CO_2 emissions arising from the calcination of limestone in the making of clinker (the precursor of cement). The potential for clinker substitution is limited by the availability of alternative products, such as blast-furnace slag and fly ash. Compounding the challenge, fewer of these substitutes will be available in a 2DS as there is less production using blast furnaces and more electricity is generated by renewables.
- **Chemicals.** Carbon emissions from the production of chemicals and petrochemicals can be reduced through a number of other methods including energy and material efficiency measures, emerging less carbon-intensive catalytic processes and the introduction of innovative process routes based on low-carbon or renewable feedstocks. However, given the breadth of processes covered in the chemicals and petrochemicals subsector, and the relatively cost-competitive integration of carbon capture in key chemical processes (such as ammonia and methanol), it is difficult to assess the prospects for reducing emissions without CCS being available.

If CCS were not available, the 29 $GtCO_2$ of related emissions in the 2DS will likely need to be avoided in large part through emissions abatement elsewhere.

2.3 Meeting the Paris Agreement's greater ambition: Well below 2°C

The Paris Agreement goal of limiting future temperature increases to well below 2°C will require a significant increase in the pace and intensity of emissions reductions compared to a 2°C target. Energy sector emissions would need to become net zero by around 2060. The additional emissions reduction opportunities beyond those already captured in a 2DS are likely to be more challenging to identify and more expensive to implement. While a fully integrated cross-sectoral analysis of the pathways to a well-below 2°C target is beyond the scope of this publication, an analysis of the remaining emissions in the 2DS allows investigation into the potential role of CCS in further reducing these emissions to reach the Paris Agreement targets.

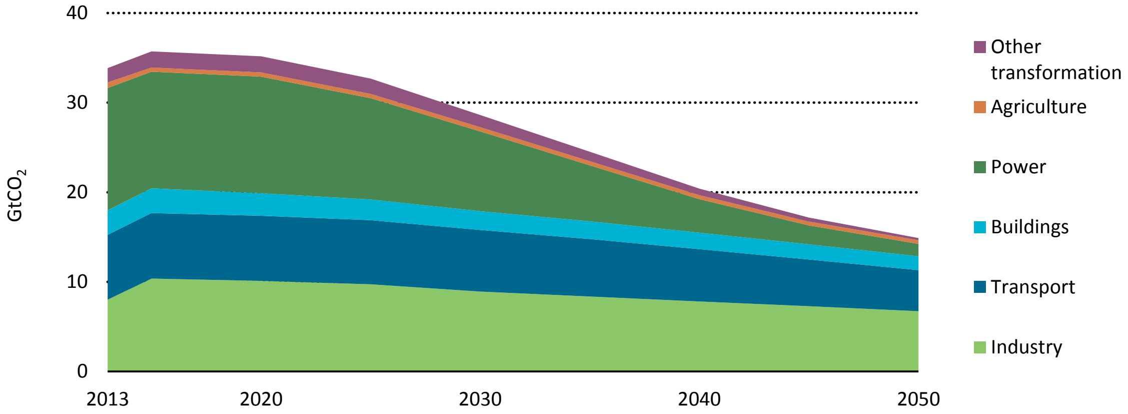
Figure 2.9 • Cumulative CO_2 emissions through 2050 (2DS): Industry, power and transport dominate



Source: Derived from IEA (2016b), *Energy Technology Perspectives 2016.*

The industry, power and transport sectors generate 86% of emissions from the energy sector under the 2DS through 2050 (see Figure 2.9). In 2050, more than two-thirds of annual CO_2 emissions in the 2DS come from the industry and transport sectors, at 6.7 $GtCO_2$ and 4.6 $GtCO_2$ respectively, with power largely decarbonised by that point (see Figure 2.10). While CCS is not available in transport, CCS applications in industry are already part of the 2DS pathway and a faster and stronger deployment could contribute to reducing cumulative emissions.

Figure 2.10 • Remaining CO_2 emissions in 2050 in the 2DS



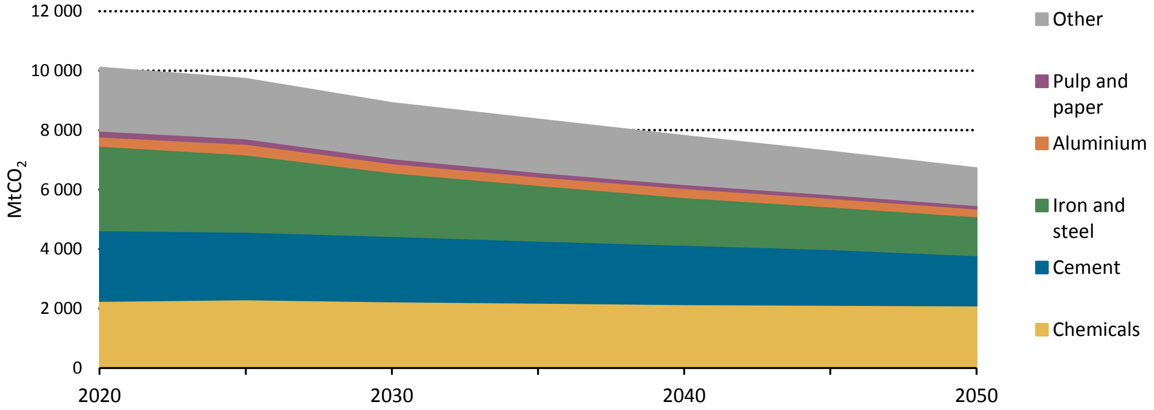
Source: Derived from IEA (2016b), *Energy Technology Perspectives 2016*.

Targeting 2DS's remaining emissions in industry

Industrial processes are the largest source of residual emissions in the 2DS, representing 45% of emissions in 2050 and 33% of aggregate emissions under the 2DS pathway over the 2015 to 2050 period. Given that the global emissions budget will be smaller for a target well below 2°C, industrial CO_2 emissions will need to fall further. This will be particularly important as there will be even fewer opportunities to offset emissions with additional measures in other sectors that will also face larger emissions constraints.

As discussed above, there are few options for deep emissions reductions in the industrial sector other than CCS. Therefore pushing emissions below a 2°C trajectory will likely require greater penetration of CCS in the sector. CCS is already widely deployed in the industrial sector in the 2DS: it is applied to 29% of iron and steel production and 41% of cement production in 2050, while 20% of annual carbon emissions from the chemicals and petrochemicals sector will be captured in that year. There is the potential for CCS to drive further reductions from the industrial sector. The focus would be on chemicals, cement and iron and steel, representing 31%, 25% and 20% of remaining industrial sector emissions respectively in 2050 (see Figure 2.11), but there are important challenges and limitations.

Figure 2.11 • Emissions remaining in the 2DS by industrial subsector



Source: Derived from IEA (2016b), *Energy Technology Perspectives 2016*.

There is the technical potential for greater CCS deployment in the chemicals subsector, given that much production is still not equipped with CCS in 2050. In the 2DS, CCS is widely deployed by 2050, with 20% of emissions from the chemicals and petrochemicals sector captured. Further CCS implementation in the chemicals and petrochemicals sector would require tapping those CCS integration options that are less economical, such as separating the CO_2 from dilute emissions streams (e.g. from on-site utilities or process heaters). The global penetration of CCS in cement manufacture is 41% in 2050 in the 2DS. Technically, CO_2 capture can be applied further in the cement subsector. There may also be the potential to use different capture technologies which could unlock further emissions reductions. As discussed, the limited availability of alternatives means further deployment of CCS is likely to be necessary in seeking deeper emissions reductions from the cement subsector. The deployment of CCS in cement manufacturing may be limited by storage constraints given that production facilities can be isolated from viable storage options.

In the 2DS, by 2050 CCS has been applied to 29% of global crude steel production, leading to a cumulative emissions reduction of 10 $GtCO_2$ to 2050. Based on the mix of iron and steel production techniques in the 2DS in 2050, a further 24% of global steel production would be technically suitable for applying CCS assuming storage was available. However, it must be noted that more ambitious emissions reduction targets would probably lead to a different production technology mix as well as the implementation of other emissions reduction options in the sector and the broader economy.

Paper production is a low-carbon process due to its inherent use of biomass-based feedstocks, and therefore there has been limited interest in deployment of CCS. CCS is not widely deployed in the pulp and paper subsector in the 2DS; only 6 $MtCO_2$ are captured in 2050, while the emissions from the subsector that year total only 11 $MtCO_2$. However, through its application to biomass-based CO_2 emissions streams, CCS in pulp and paper could provide a potential source for negative emissions to offset emissions from other sectors where deep emissions reductions are technically or economically more challenging.

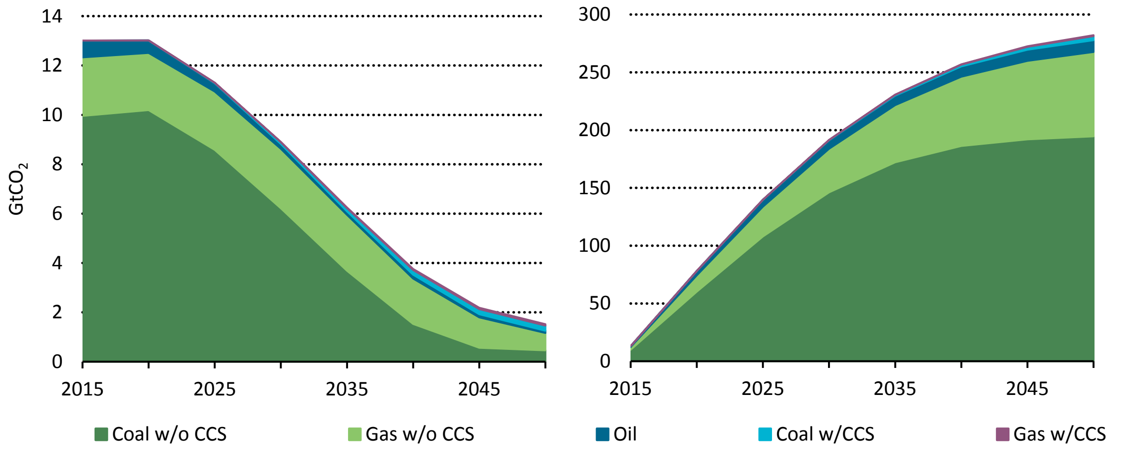
Faster CCS deployment in power

By 2050, the power sector is virtually decarbonised in the 2DS, with total emissions dropping from current levels that exceed 13 $GtCO_2$ to 1.4 $GtCO_2$ in 2050, with a carbon intensity of

40 gCO_2/kWh. This is compared with over 500 gCO_2/kWh today. In 2050, the power sector contributes only 9% of energy sector emissions in the 2DS. However, the cumulative emissions of the power sector over the period to 2050 are the second-highest after industry, accounting for nearly 30% of total cumulative emissions (see Figure 2.9).

Reducing cumulative emissions in the power sector in the time period to 2050 is therefore an important strategy for achieving a well-below 2°C target. Of the 280 $GtCO_2$ emitted by the power sector through 2050, 70% is from coal-fired power generation and around one-quarter from gas-fired generation (see Figure 2.12). One of the crucial opportunities to reduce these cumulative emissions lies in accelerating efforts to deploy CCS notably on coal-fired power generation in the period 2025 to 2035, while the expanding role for gas as a fossil fuel power source through 2050 and beyond provides a longer timeframe for continued action.

Figure 2.12 • Annual (left) and cumulative (right) CO_2 emissions of the power sector in the 2DS



Source: Derived from IEA (2016b), *Energy Technology Perspectives 2016*.
Note: Emissions from coal-fired power plants with CCS amount to 0.2 $GtCO_2$ in 2050 in the 2DS, emissions from gas-fired power plants with CCS amount to 0.1 $GtCO_2$.

By 2025, already half of the cumulative emissions of the power sector for the entire period 2015 to 2050 have been emitted. By 2035, this share increases to 82% and by 2040 to 90%. During this crucial period (2025 to 2035), more than 500 GW of new coal capacity without CCS is built in the 2DS, almost entirely in non-OECD countries. Replacing this unabated coal capacity with renewables or nuclear power yields the potential to reduce the cumulative emissions by around 40 $GtCO_2$, but could present additional challenges (as discussed in Section 2.2.1). Equipping unabated coal capacity with CCS yields a slightly lower potential of about 35 $GtCO_2$, as not all CO_2 is captured in the process. Conversion from coal to biomass yields the potential to further reduce the emissions of these plants. Some of the coal capacity already operating in 2025 will need to be retired early in order to further reduce cumulative emissions, although these retirements may be alleviated by the option of retrofitting with CCS or conversion/partial conversion of coal to biomass as fuel.

Reducing emissions from gas-fired power generation over the period to 2050 presents another important opportunity. Gas-fired generation without CCS accounts for around half of the remaining annual CO_2 emissions in 2050 (but only 5% of the global electricity generation). Increasing the rate of deployment on gas to more closely match the path of coal could help to both lower cumulative emissions in the time period to 2050 and to lower the carbon intensity of the power sector post-2050. Around 10 $GtCO_2$ of cumulative emission savings could be achieved through such an increased rate of deployment. However, equipping all gas-fired plants with CCS would not be economical or even technically feasible as several operate at low capacity to provide flexibility to the power sector.

When considering the role of CCS in power generation in a well below 2°C scenario framework, two important factors should be recognised. First, it will be necessary to ensure that the electricity system remains flexible enough to integrate an increasing share of variable renewables, which may be challenging without the flexibility provided by gas-fired power plants. As noted above, unabated gas-fired plants are used in the 2DS in 2050 to provide flexibility, however some operate at such low utilisation rates that it would make it difficult to justify the additional investment in CCS equipment. Maintaining the availability of these unabated plants to provide flexibility under scenarios where the power sector needs to be completely decarbonised would require identifying offsets elsewhere for these emissions. Alternatively, flexibility could be sought through other means, such as concentrated solar power, biogas-fired or geothermal power plants, as well as demand response, storage and grid interconnections, but these alternatives also pose deployment and network management challenges.

Second, fossil-fuel power plants equipped with CCS are unlikely to be carbon-free. The *ETP* 2DS assumes a capture rate of 85% to 95% depending on the technology.[25] Moving well below 2°C and towards 1.5°C may require the power sector to be decarbonised in the second half of the century, and consequently these residual emissions may ultimately need to be targeted. Co-firing with biomass and technological advances could present an opportunity to further reduce the emissions from CCS-equipped power generation in the long term (see Box 2.2).

Box 2.2 • Reducing the residual emissions from CCS: Co-firing biomass and further technological innovation

In the 2DS, the average carbon intensity of the power plant fleet decreases from over 500 gCO_2/kWh in 2013 to 40 gCO_2/kWh in 2050, and will need to reach net zero in the second half of the century. In a well below 2°C scenario, this decline in average carbon intensity will need to be accelerated with net zero achieved earlier.

While CCS is an effective tool to significantly reduce power sector emissions, based on current technologies, even CCS-equipped coal plants would exceed the emissions intensity of power in the 2DS in 2050. The average carbon intensity of coal plants in the 2DS decreases from around 900 gCO_2/kWh to 100 gCO_2/kWh in 2050, with almost all coal generation from CCS-equipped plants. Gas-fired power plants equipped with CCS achieve a carbon intensity of roughly 30 gCO_2/kWh in 2050. The residual emissions from CCS plants may need to be reduced further in the second half of the century as the average emissions intensity of electricity approaches zero.

Two paths to further lowering the carbon intensity of generation equipped with CCS are as follows:

1. Increasing the capture rate of CO_2 while reducing the energy penalty would reduce the emissions intensity of CCS-equipped power. Current technologies have a maximum capture rate of around 85% to 90% depending on the technology. Technological progress on increasing capture rates and lowering the energy penalty will be important to support additional emissions reductions from CCS operations.
2. Increasing the use of biomass co-firing with fossil fuel CCS plants. Preliminary *ETP* analysis finds that co-firing of biomass at coal plants (with shares of up to 10% allowed in the fuel input) can significantly reduce emissions from coal plants with CCS (hard coal and lignite). Co-firing of biogas in gas-fired CCS plants is currently not an available option in the *ETP* model, but could similarly reduce the residual emissions from these plants.

On plant level, the co-firing of biomass together with CCS could achieve carbon neutrality of the electricity produced. While various configurations would be possible, the simplest starting point to achieve this would be to apply a typical 85 to 90% capture on a post-combustion capture (PCC) plant

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[25] In practice, plant-level decisions will be driven by technology, regulatory and economic considerations, which could result in differing rates of capture. Alignment with a well-below-2°C target likely necessitates the highest possible capture rates, which can be ensured via effective policy making.

together with limited (10%) biomass co-firing. Going beyond limited shares of biomass would require changes to the plant, whereas up to 10% biomass could usually be handled with existing equipment. Under a simplified calculation, an ultra-supercritical coal-fired power plant with a net efficiency of 45% has a carbon intensity of roughly 760 gCO_2/kWh. Assuming a 90% capture rate, the carbon intensity of the produced electricity would drop to around 100 gCO_2/kWh. An additional 10% co-firing of biomass (wood pellets), would result in carbon neutrality of the plant, with higher co-firing rates leading to negative plant emissions.

On a systems level, preliminary IEA analysis shows that if up to 10% co-firing of biomass is implemented at coal-fired plants with CCS, this would on an aggregated level result in net zero emissions from coal plants with CCS globally (hard coal and lignite combined) by 2050.

3 The next 20 years: Picking up the pace

Key highlights

Twenty years of experience have provided a strong foundation for carbon capture and storage (CCS) deployment. The technology is proven in many applications and the portfolio of operating projects has grown and diversified.

The pace of CCS deployment is not consistent with a 2°C pathway; however many low-emission technologies are also off-track. Targeted financial incentives and prioritised development of CO_2 storage sites will be essential to accelerating CCS deployment to achieve the ambitions of the Paris Agreement.

Innovative approaches and a renewed focus on the key challenges can also play a role in picking up the pace of CCS deployment:

- *CCS retrofitting can provide a solution to the inherent tension between continued fossil fuel use and climate objectives, reversing the lock-in of emissions from existing coal-fired power generation assets.*
- *The development of bioenergy with CCS (BECCS) can deliver "negative emissions" which may be important to achieve a balance between emissions sources and CO_2 sinks in the second half of this century.*
- *Future clean products with significantly lower CO_2 footprints can be developed with CCS, notably for the steel, cement and chemicals industries.*
- *Conventional enhanced oil recovery (EOR) practices can be updated with an "EOR+" approach that superimposes CO_2 monitoring and verification, potentially generating significant net emission reductions notwithstanding the additional oil production.*
- *Disaggregating the CCS value chain can help to spur investment, notably by enabling new approaches to CO_2 storage business models that can make storage an attractive investment option.*

More than 20 years of CCS experience have delivered significant technology advances and the first steps of growth in the portfolio of operating projects. However, current progress is not keeping pace with the level of effort required to limit temperature increase to a target below 2°C. The challenges facing CCS are well documented, notably a lack of financial support mechanisms and a need for further development and characterisation of CO_2 storage sites. This chapter considers the urgency of the CCS deployment task and offers additional approaches which could play a role in accelerating CCS deployment.

3.1 Accelerating CCS deployment in pursuit of the Paris Agreement targets

3.1.1 CCS is more important in a post-Paris world

The importance of CCS grows with climate ambition, with more CCS deployed the greater the emissions reduction target and a particularly important role for negative emissions in scenarios approaching 1.5°C (IPCC, 2014a). The converse of this is that less ambitious climate action requires very little, if any, deployment of CCS. Indeed, the relatively slow pace of CCS deployment to date reflects, at least in part, that the world is not currently on track to keep future temperature increases to 2°C, and certainly not well below 2°C.

The Nationally Determined Contributions (NDCs) pledged in the lead-up to the Paris negotiations principally covered a period through to 2030 and were consistent in the aggregate with future temperature increases that are significantly higher than 2°C.[26] The time horizon and lower level of ambition may help to explain why CCS was mentioned in only 10 out of 162 NDCs, in contrast to 25 national governments which have indicated their commitment to CCS through membership of the Carbon Sequestration Leadership Forum (CSLF). Yet the 2DS highlights that CCS could make an important, albeit initial, contribution to reducing emissions within the NDC time horizon, with more than 8 $GtCO_2$ captured through 2030. In addition, faster deployment of CCS in the period 2025 to 2035 could play a key role in achieving a well-below 2°C target (see Section 2.3).

The Paris Agreement provides a framework for governments to set out mitigation plans that increase in ambition over time (see Box 3.1). This process will be important in strengthening policy action and refocusing attention on those technologies, such as CCS, which will be needed to achieve greater emissions reductions over the long term.

Box 3.1 • The Paris Agreement: Greater ambition and a framework for long-term action

The Paris Agreement has established more ambitious temperature targets while also setting out a framework for action that extends into the second half of the century. At the core of the Agreement is an ambitious long-term global goal defined in terms of both temperature and emissions. The rise in global average temperature is to be limited to "well below 2°C" from pre-industrial levels, and efforts are to be pursued to limit the increase to 1.5°C. The means of achieving this is by peaking global emissions "as soon as possible", and undertaking rapid reductions thereafter to "achieve a balance between anthropogenic emissions by sources and removals by sinks" in the second half of this century. The global goal builds on a previous United Nations Framework Convention on Climate Change (UNFCCC) decision at COP16 in Cancun in 2010 to commit to a maximum temperature rise of 2°C above pre-industrial levels, and to consider lowering that maximum to 1.5°C in the near future.

The accord is built around countries' NDCs. These NDCs cover a period that extends through the medium term to 2030, and a five-year review-and-revise approach that is designed to promote progression of Parties' efforts over time. Following periodic global stocktakings of collective ambition, with the first such stocktake scheduled for 2023 (and an earlier facilitative dialogue taking place in 2018), NDCs are to be communicated every five years and are to reflect each Party's "highest possible ambition", in light of different national circumstances.

The Paris Agreement also invites Parties to communicate, by 2020, "mid-century, long-term low greenhouse gas (GHG) emission development strategies". Extending the horizon to 2050 for upcoming national climate responses will be important to ensure that short- and medium-term actions are consistent with long-term strategies. The development of these strategies will likely provide opportunities to refocus attention on the important role of CCS in achieving deep emissions reductions in the future.

Source: IEA (2016e), *Energy, Climate Change and Environment: 2016 Insights*, OECD/IEA, Paris.

3.1.2 CCS is not "on track" for Paris targets, but it is not alone

Progress in deploying CCS has not matched initial expectations and is now falling short of targets inherent in the 2DS. The 2DS provides for 94 $GtCO_2$ emissions reductions from CCS cumulatively through 2050, with early deployment rates equivalent to 500 $MtCO_2$ captured in 2025 and

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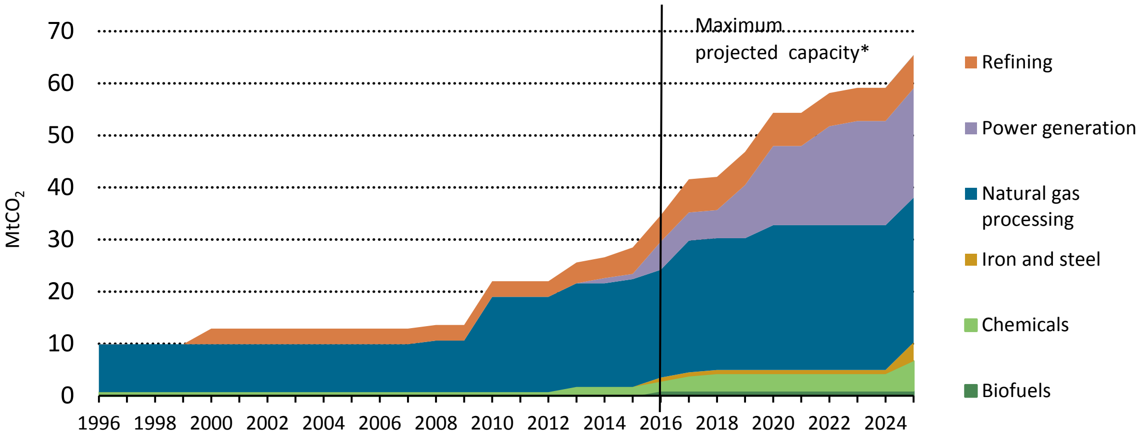
[26] The IEA has estimated that they would be consistent with a temperature increase of about 2.7°C by 2100 (IEA, 2015c), potentially increasing thereafter to above 3°C depending on emissions profiles.

1.5 $GtCO_2$ in 2030. Current progress suggests that these quantities are unlikely to be realised. If all of the large-scale CCS projects under active consideration were to proceed, the maximum capture rate would be less than 70 $MtCO_2$[27] each year in 2025 – around 15% of the 2DS figure for that year (see Figure 3.1). The prospects for increasing this are hampered by a lack of movement in the development of projects. No investment decisions on large-scale projects have been taken since 2014 and few new projects are being brought forward.

Figure 3.1 • Capture potential of projects, by sector



*This assumes all known projects, including those in early planning, will proceed.

While the rate of deployment of CCS in the 2DS can provide a useful benchmark for tracking progress, it needs to be considered in the context of the 2DS – an ambitious scenario which will require a significant strengthening of the current global policy response. The 2DS provides a least-cost long-term technology pathway, and differs from the policy decisions being made in the short term.

Many clean energy technologies are facing challenges

The fact that CCS is not on track for a 2DS pathway is not unique to CCS and reflects, in part, that the global climate response as a whole would need to be strengthened to be consistent with a 2°C target. For example, as noted above, the NDCs submitted by countries prior to the Paris negotiations would result in temperature increases closer to 3°C. The development and deployment of several important low-emission technologies are also off-track. The 2016 IEA publication, *Tracking Clean Energy Progress*, assessed that while solar PV, onshore wind and electric vehicle deployment levels are consistent with the 2DS pathway, all other technologies – including all other renewable technologies, energy efficiency in buildings, energy storage and biofuels as well as CCS – are falling behind the implied targets in the 2DS (IEA, 2016d).

An absence of climate policy support presents particular challenges for CCS as compared to other clean technologies. In contrast to renewables, nuclear, energy efficiency and various other clean energy technologies, the benefit of CCS is almost exclusively linked to emissions reduction. While, for example, renewables and nuclear energy provide electricity to customers, and energy efficiency can generate cost savings and various other benefits, CCS outputs are largely limited to the storage of CO_2 molecules. As a result, CCS is uniquely dependent on the degree of climate

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[27] Derived from GCCSI projects database. This figure assumes that all projects, including those in early planning, will proceed to a FID as planned and without significant delays.

policy ambition, which to date has not equated with the goal of limiting temperature increases to below 2°C. As policy frameworks begin to reflect an increased climate ambition (as is anticipated under the Paris Agreement), CCS is likely to receive greater attention; however, the ability of CCS to deliver in the future requires action in the very short term.

What are the implications of CCS being off-track for the 2DS?

The fact that CCS is not on track according to the near-term 2DS targets does not diminish its value and importance as a technology able to deliver deep emissions reductions in the future. Indeed, CCS can play an important role in climate change mitigation action even if it falls short of the implied 2DS target of 94 $GtCO_2$ through 2050. As described in Chapter 2, if CCS were not deployed in the power sector an additional USD 3.5 trillion in investment and almost 2 000 GW of additional renewable power capacity would be required. If the rate of use of CCS in the power sector were more moderate than under the 2DS, there would still be significant savings. For example, under a preliminary modelling exercise drawing from the *ETP*, if only half of the CCS in electricity provided for in the 2DS were in fact deployed, the savings in alternative generation capacity investments[28] through 2050 to achieve the same emissions reductions would total about USD 1 trillion. This is compared to a scenario in which no CCS was deployed in the power sector.[29] This would also reduce the challenges associated with both the significantly higher deployment of renewable generation capacity and the phasing out of coal under the "no CCS for power variant" (see Section 2.2.1).

Beyond these investment cost considerations in the power sector, CCS could also still play a major role in reducing emissions in industrial processes, where there are few alternatives (see Section 2.2.2), even in a delayed or reduced deployment scenario. Furthermore, reduced deployment would still contribute to the development of CCS as a future negative emissions source (see Section 3.3).

An alternative approach to assess CCS progress in the near future would be to ensure that the investments being made today are sufficient to permit future large-scale and accelerated CCS deployment as and when climate policy action is "ramped up". As the Intergovernmental Panel on Climate Change (IPCC) has highlighted:

> *While it is clear that some mitigation effort in the near term is crucial to preserve the option of achieving low-concentration goals, whether these goals are met in the long run depends to a greater extent on the potential for deep GHG emissions reductions several decades from now. Thus efforts to begin the transformation to lower concentrations must also be directed toward developing the technologies and institutions that will enable deep future emissions cuts rather than exclusively on meeting particular near-term goals* (IPCC, 2014b).

Given various characteristics of CCS, such as the long lead times for storage, the future availability of CCS depends on action today (see Box 3.2). Even when considered under the alternative metric enunciated by the IPCC, it is clear that current CCS development and deployment must be accelerated from its current rate of progress. In particular, the potential for

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[28] This figure is for generation capacity only; it does not include electricity storage or network costs.

[29] In this partial case, fewer additional renewables are required to replace the missing CCS investments than in the "no-CCS for power" variant. Accordingly, the incremental investment required is lower than the additional USD 3.5 trillion required under the no CCS variant. Assuming that the additional renewables in the no CCS variant are deployed on a least-cost basis, then the additional expenditure required to deploy for example only half of these renewables would be less than 50% of the total in this variant as the lower-cost renewables would be deployed first.

stagnation in global project development from around 2020 must be addressed, given the shrinking number of projects in early to mid-stages of development (see Section 1.3).

Box 3.2 • CCS – Action today for an effective solution tomorrow

CCS projects are complex integrated projects that require significant lead times to develop. Large-scale CCS projects can take as long as a decade to commission, often as a result of time frames associated with the assessment and characterisation of greenfield CO_2 storage sites. In addition, early investment is needed to secure the learning-by-doing cost reductions and to provide confidence in the future availability of large-scale CO_2 storage. This confidence in storage is also critical to informing the policy and investment decisions being made today, including in relation to the construction of new fossil fuel-based power generation which may require CCS retrofit as emissions requirements are tightened in the future. Action today is also required to retain and expand institutional and technical capacities in both industry and governments. Accelerating the deployment of CCS in line with a 2°C or well-below 2°C pathway requires substantial investment starting today.

3.1.3 Putting CCS on track: Finance, CO_2 storage and more

Numerous IEA and other studies have identified priorities and actions to stimulate investment in CCS. The IEA *Technology Roadmap: Carbon capture and storage* (2013) proposed seven key actions to put CCS on track for a 2°C target. These key actions continue to be important today (see Box 3.3). However, the need for financial support mechanisms and the development of CO_2 storage are the most critical if the Paris Agreement targets are to be met.

Financial incentives and support

Financial support mechanisms are needed to spur investment in CCS given the current lack of incentives to invest. As discussed in Section 1.5.2, support mechanisms can include mandates, direct or indirect subsidies, grants, tax credits, loan guarantees, feed-in tariffs, regulatory requirements, carbon pricing or taxes, or a combination of any of these. In the early deployment phase, mechanisms that address the additional capital and operating costs associated with CCS projects are particularly important. They can generate a positive feedback cycle, supporting technological improvements and cost reductions which lead to further investments.

CO_2 storage development

The development of CO_2 storage resources and their associated infrastructure have been identified as a key priority at both the project level and as a foundation for widespread CCS deployment. As discussed in Section 1.7.4, the confidence that is built up in CO_2 storage capacity and location will have important implications for the long-term climate and energy policy decisions being made today, including investments in fossil fuel-based power generation. While there is confidence in the adequacy of CO_2 storage resources at a global level, significant further work is required to convert this into bankable storage, where investment decisions can be made at a project level with confidence in the availability and adequacy of CO_2 storage.

Governments have a leading role to play in the early identification and characterisation of national storage resources, in much the same way that national geoscience agencies will often undertake pre-commercial exploration of energy or mineral resources. Implementation of innovative policy approaches can also encourage private investment in storage services (see Section 3.6) and act as a catalyst to promote CO_2 capture, including retrofitting, of emissions-intensive facilities in proximity of the storage resource

Stable, long-term policy frameworks

The stability of policy frameworks will be important in securing CCS investment. Fluctuations in policy support have shaken investor confidence in CCS, including recently in the United Kingdom where there is now "no discernible appetite from any project developers to participate in a further UK CCS competition" (CCSA, 2016). Furthermore, organisations which had established business units dedicated to CCS-related services, such as Schlumberger and Alstom, have significantly scaled back these efforts as the policy frameworks needed to support the establishment of a future CCS market have failed to emerge. Long-term commitment and leadership from governments is viewed by many developers and service providers as critical.

Box 3.3 • IEA CCS Roadmap: Seven key actions for CCS deployment

The IEA *Technology Roadmap for Carbon Capture and Storage* (2013) identified seven key actions for the period to 2020:

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

Source: IEA (2013), *Technology Roadmap: Carbon Capture and Storage*.

Supporting accelerated deployment: Novel approaches and renewed areas of focus

New thinking and renewed areas of focus can accelerate the pace of CCS deployment. These include:

- Fostering and maximising the opportunities for retrofitting CCS on coal-fired power to tackle today's "locked-in"[30] emissions.
- Looking at industrial CCS from the perspective of *clean products*, not only production technologies.
- Facilitating early action in negative emissions technologies through bioenergy with CCS.
- Rethinking enhanced oil recovery (EOR): a move from current ways to combining oil extraction and CO_2 storage through "EOR+".
- Reconsidering the typical CCS project models by disaggregating the CCS value chain, and targeting the development and financing of CO_2 storage infrastructure.

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[30] Emissions that will come from infrastructure that is currently in place or under construction can be thought of as "locked-in", because they cannot be avoided without stringent policy intervention to force premature retirements, costly refurbishment and retrofitting or letting capacity lie idle. They are not unavoidable, but avoiding them does not make economic sense in the current policy context (IEA, 2011).

Commentary 5 • CCS: A key part of a portfolio of technologies

Brad Page

Chief Executive Officer, Global CCS Institute

Achieving 20 years of successfully operating the world's first project to store CO_2 in a geological formation is a great accomplishment by Norway and Statoil. The Sleipner CCS facility attests to the fact that geological storage of CO_2 is a safe, secure, proven technology and commercially viable. It has blazed a trail as an early-mover project, encouraging others to follow. By the end of 2017 we expect there will be more than 20 large-scale CCS projects in operation globally. The combined CO_2 capture capacity of these projects is around 40 Mtpa, roughly the equivalent of the CO_2 emissions of Switzerland. This compares with less than ten large-scale operational projects at the beginning of this decade. Best of all, there has been a widening in the range of countries, industries and technologies represented. Large-scale applications of CCS can now be found in natural gas processing, steel making, power generation, fertiliser, hydrogen and biofuel production.

We know that CCS is already cost-competitive with other low and zero-emissions technologies on a cost per tonne of avoided CO_2 basis. Further cost reductions – capital and operating – are being identified all the time.

Since Sleipner commenced operations in 1996, one year before the famed Kyoto UNFCCC meeting, there has been much discussion and negotiation around addressing climate change. The urgency to reduce the world's greenhouse gas (GHG) emissions has continually increased. Deployment of renewables has grown very strongly over the past 20 years – starting from a small base. But this contribution has been eclipsed by the global growth in total primary energy demand, with much of this increase being met by fossil fuels.

The challenge has never been greater to achieve energy security (available, reliable and affordable energy), address energy poverty and massively lower emissions.

The 2015 Paris Agreement provides a more optimistic foundation from which the world can address this challenge. However, the time available to address the emissions problem is diminishing, while growth in energy demand continues – especially in developing countries where energy poverty remains a daily challenge for many.

There can be no doubt that continued strong investment in renewables and energy efficiency is required. But that will not be enough. Time is too short. The emissions problem is too large.

CCS is equally important to achieving energy security, defeating energy poverty and staying well below 2°C of warming. Fossil fuels will continue to be the foundation of electricity generation systems around the world for many years to come. More than 2 000 new coal-fired generators, with a total capacity of approximately 1 300 GW, are either in various stages of development planning or under construction globally. In industrial processes (such as steel making, cement manufacture and fertiliser production) there is no other technology to address the significant CO_2 emissions which account for nearly 25% of all GHG emissions. And if we do not act fast enough then negative emissions technologies will be required. Bioenergy with CCS will be key among the few available opportunities left.

Globally, emissions reduction policies have favoured rapid deployment of relatively mature, but often intermittent, low-emissions electricity generation technologies. A continuation of only this approach will not be enough in the future given the scale and breadth of the decarbonisation task.

CCS is vital to achieving a decarbonised world. It is the only technology capable of dealing with industrial process emissions. Ignoring the need for CCS in the power sector will either increase energy insecurity or prevent climate objectives from being achieved. Needing negative emissions technologies in the future looks inevitable, and CCS is again front and centre when twinned with bioenergy.

Now is the time for policy makers to support all technologies that will be necessary to achieve our energy and climate objectives. Without CCS, achieving energy and climate objectives is likely to be impossible.

3.2 Retrofitting CCS on coal-fired power – tackling today's emissions

- **CCS retrofitting provides a solution to emissions from existing and planned coal-fired power generation which recognises that much of the global fleet is unlikely to be shut down within a timeframe consistent with climate targets.**
- **More than 310 GW of coal-fired power generation in China would be suitable for CCS retrofit based on robust criteria.**
- **Implementation of "CCS-ready" requirements alongside investment in CO_2 storage development can maximise future retrofitting potential.**

3.2.1 Retrofitting CCS: A key to cutting existing emissions

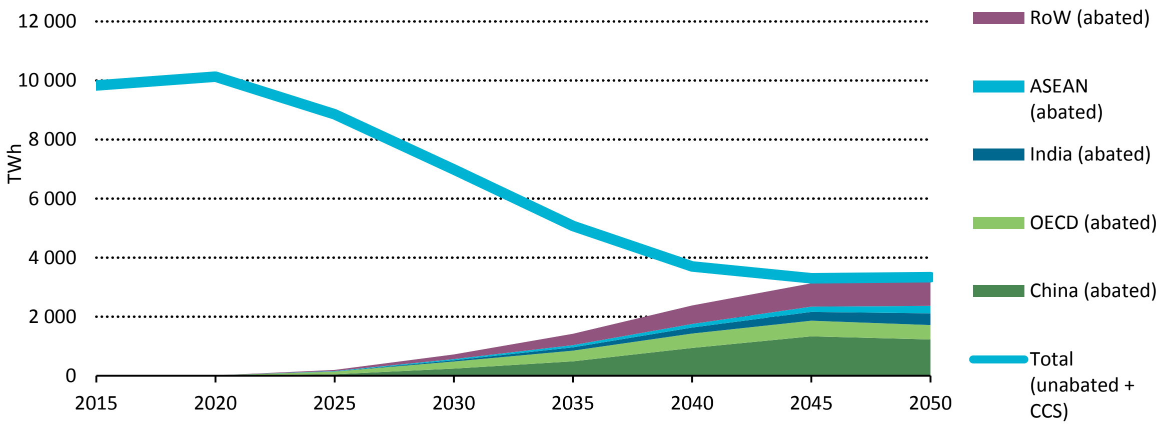
Existing coal infrastructure presents one of the most significant challenges to reducing emissions. Today's global fleet of coal-fired power stations totals around 1 950 GW and emits 9.3 $GtCO_2$. This is equivalent to almost two-thirds of the total global energy sector emissions budget in 2050 under the 2DS. A further 250 GW of new coal capacity is under construction and around 1 000 GW is in various stages of planning.

The existing coal fleet is also the youngest it has been for decades. Around 500 GW of new coal-fired generation capacity was added since 2010, most of it from developing countries (>90%). The average plant age for developing countries is around 15 years, compared with Eastern Europe and OECD at around 40 years. With plants typically having an operational life of 40 years or more, much of the current fleet in developing countries could conceivably still be operating well after 2050 (Platts, 2016).

There is a major gulf between the reality of this newly-built and planned infrastructure and what will be required to keep global temperatures below 2°C. In the 2DS, unabated coal-fired power generation (that is, without CCS) starts declining from 2020 and is virtually phased out by 2050 (see Figure 3.2 and Section 2.1.2). The range of policy options to achieve this has been the subject of previous IEA analysis, including the early retirement of coal plants and changing the dispatch order for coal-fired power (IEA, 2014b).

However, all options will have economic and social consequences. For example, the IEA *World Energy Investment Outlook* (2014c) identified that, in a 450 scenario, 165 GW of new fossil fuel capacity would need to be retired before repaying capital costs, with an unrecovered sunk cost of USD 120 billion (IEA, 2014c). With over 40% of fossil fuel power generation publicly owned, the economic impact of early retirement decisions could present challenges for many governments as shareholders.

Figure 3.2 • Unabated and abated coal-fired power generation in the IEA 2DS



Source: IEA (2016e), *Energy, Climate Change and Environment: 2016 Insights*.

While the construction of new coal power plants has slowed in many regions of the world (including in the OECD and China), coal generation still remains an important part of the electricity mix, even in those areas. Moreover, numerous countries are expanding their coal fleets (notably India and various Southeast Asian nations) or are modernising them as part of efforts to support economic growth and, specifically, to electrify large populations which have no or inadequate access to modern energy. Current investment and maintenance practices indicate that these plants can be expected to operate for two decades or more.

The option to retrofit CCS to existing coal-fired power plants can therefore be a valuable solution to avoid the long-term "lock-in" of emissions from these facilities. This also applies to other emissions-intensive installations, including gas-powered plants[31] and in industry.

3.2.2 Key aspects of CCS retrofitting

A coal-fired power plant equipped with CCS can be a source of low-carbon electricity that has the advantages of thermal generation plants: high availability all year, responsive to changes in supply and demand, and value-added for indigenous resources. CCS can reduce the emissions from a state-of-the-art hard-coal power plant from around 800 gCO_2/kWh to around 100 gCO_2/kWh if 90% of the emissions are captured and stored. Hence emissions from a CCS-retrofitted coal plant are equivalent to just over a quarter of that of a combined-cycle gas turbine (CCGT) plant.

Access to suitable storage sites is a prerequisite for any retrofit to be undertaken. This entails a high level of certainty about the suitability of an identified storage site before a retrofit project can begin.

Once confidence in storage is established, retrofitting CO_2 capture to a coal-fired power plant can be achieved by adding a capture unit that separates CO_2 from the flue gases before they are released to the atmosphere. The capture rate can be varied during design and operation of the retrofit operation. A retrofit can be applied to the whole facility; conversely, it can also be cost-

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[31] A modern CCGT typically emits 360 gCO_2/kWh (IEA, 2016e). While lower than unabated coal technologies, the carbon intensity of gas exceeds the weighted average for the power sector in the 2DS before 2030 (see discussion of carbon intensity of gas relative to the 2DS benchmarks in Chapter 2 of IEA, 2016e). The impact of CCS in reducing the carbon intensity of CCGT is discussed above in Box 2.2.

effective to only partially retrofit a coal-fired power plant, for example if the target is to reduce emissions to a level equivalent to that of a natural gas-fired CCGT (National Energy Technology Laboratory, 2015; Zhai, Ou and Rubin, 2015). Current efforts at retrofitting power plants provide important lessons (see Box 3.4).

Box 3.4 • Practical experience with retrofitting coal-fired power plants

Two large-scale projects are retrofitting CO_2 capture to coal-fired power plants.

Boundary Dam

Boundary Dam Unit 3 is a lignite-fired generating unit in Saskatchewan, Canada that was retrofitted with post-combustion capture technologies between 2011 and 2014. Unit 3, with an original net generating capacity of 139 MW, was built in 1969 and scheduled for closure in 2013, after almost 45 years in service. The retrofit involved adding an amine-based CO_2 capture plant to remove 90% to 95% of the CO_2 from the flue gas, compress it and inject it into a pipeline to an EOR operation 66 km away. After allowing for the energy requirements of the capture plant, net generating capacity for the retrofitted Unit 3 has been reduced to 120 MW, but the refurbishment has extended its life by at least 30 years.

Petra Nova – Parish project

Due to begin operation in early 2017, the Petra Nova Parish CO_2 capture project in Texas, United States is under construction. The project is retrofitting post-combustion amine-based CO_2 capture to a 240 MW slipstream of a 610 MW unit located at NRG Energy's Parish sub-bituminous coal-fired power station. This capture unit is designed to capture 1.4 $MtCO_2$ per year at a capture rate of up to 90%. The captured CO_2 will be compressed and transported via a 130 km pipeline to the West Ranch oil field, where it is to be injected for EOR at a depth of 1 km to 2 km. Steam and power for the capture unit will be provided by a 75 MW gas-fired cogeneration unit that came online in 2013 (NRG, 2014). As a result, the retrofit will not result in a derating, or reduction in the power rating, of the existing asset because steam and power from the base plant will not be redirected for CO_2 capture.

Costs and benefits

Adding CO_2 capture to a power plant entails both capital costs and operational costs. The capital costs relate to the building of the specific capture equipment and may be associated with upgrades to the power plant that are undertaken simultaneously (for example, upgrading the boiler or turbine). Different plants can have very different retrofit costs even when considering their use of the same technology. In the best conditions, equipping a power plant with CCS only requires investment in the equipment for CO_2 capture, transport and storage and not in the power plant itself. In other situations, the power plant may be upgraded at the same time as CCS retrofit, delivering several additional decades of life to the plant. Assuming the eventual imposition of carbon emissions constraints, a CCS retrofit can avoid the need to write-off otherwise productive generating capacity, or otherwise limit its use, and be economically competitive with investment in alternative low-carbon generation capacity. In addition to the capture-related capital costs, developing the CO_2 storage site will require significant capital in cases where existing storage resources are not available.

Adding CCS to a power plant incurs an operational cost penalty due to the reduction of efficiency caused by the energy requirements of CO_2 capture. CO_2 capture requires additional energy which translates into fuel use and attendant additional costs for the power plant operator. The efficiency penalty depends on the type of CO_2 capture technology used. For current, state-of-the-art designs, it is usually considered to be a reduction in the order of nine percentage points.[32]

There are also operational costs associated with transport and storage. In general, the costs of CO_2 transport and storage have a much lower impact on the costs of electricity than CO_2 capture. However, the costs of CO_2 storage rise considerably if the CO_2 needs to be transported over long distances, difficult terrain or offshore.

3.2.3 Retrofitting China's coal plants with CCS: A major opportunity

Retrofitting CCS on existing coal-fired power stations in China represents a major opportunity for significant emissions reductions. China currently has around 900 GW of installed coal-fired power capacity, representing more than 45% of global coal-fired capacity, and has nearly 200 GW under construction. China's existing coal-fired power plants represent potential emissions of 85 $GtCO_2$ if they continue to operate at current load factors for the remainder of their lives, even if smaller units are retired early (IEA, 2016c). Despite such massive emissions, the Chinese coal-fired power fleet is on average one of the world's youngest and most efficient, with more than two-thirds of its capacity built since 2005.

Through its NDC under the UNFCCC framework, China has committed to peaking CO_2 emissions by 2030. The enduring emissions from China's coal-fired power plants present a challenge to efforts to reduce GHG emissions beyond any peak. Retrofitting existing coal-fired power stations with CCS can be an important part of the solution. Coal use is also being shaped by policies to control local pollutants, which can encourage power plant upgrades. Retrofitting plants with CCS as part of these upgrades can help to add a climate mitigation benefit to a pollution control action.

As noted, access to CO_2 storage is a critically important criterion for retrofitting CCS on any power station. Proximity to a suitable storage site plays an important role in determining costs, and plants with high CO_2 transport and storage costs generally do not feature among the best candidates for CCS retrofitting in China. IEA analysis (2016c) suggests that 385 GW of China's coal-fired plant emissions would find suitable storage capacity within a 250 km radius (see Figure 3.3); longer CO_2 transport distances can still be attractive in some cases.

Other suitability criteria relate to the attributes of the coal-fired plant itself. These include plant age, size, load factor and local or regional pollution control measures, which can be used to determine whether a plant is likely to be a candidate for retrofitting.[33]

According to IEA analysis (IEA, 2016c), in total some 310 GW of existing coal-fired power capacity in China meets these criteria for being suitable for a retrofit. This number is likely to increase, as new efficient plants are being commissioned over the next few years. Plant size is of particular importance in China, where many smaller plants are likely to be retired before CCS retrofitting is widely deployed.

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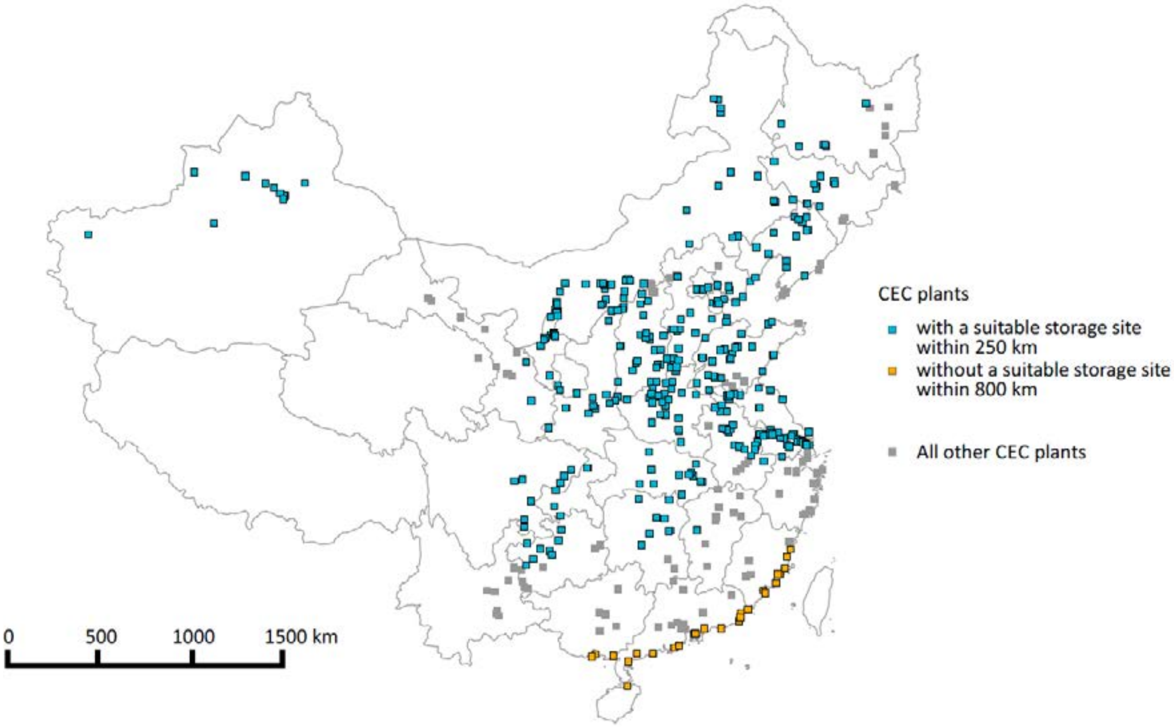
[32] For example, a plant operating at 43% efficiency without CCS would operate at the equivalent of 34% with CCS, given the need to use part of the energy generated to operate the capture equipment.

[33] Plant criteria for this analysis were: (*i*) plant age: ≤40 years in 2035; (*ii*) plant size: ≥600 MW or ≥300 MW in clusters of plant that could capture 10 Mtpa CO_2; (*iii*) load factor: ≥50%; (*iv*) proximity to storage: ≤800km; and (*v*) plant not located in provinces that have announced a coal phase-out.

Figure 3.3 • China's coal-fired power plants and their proximity to suitable CO_2 storage areas

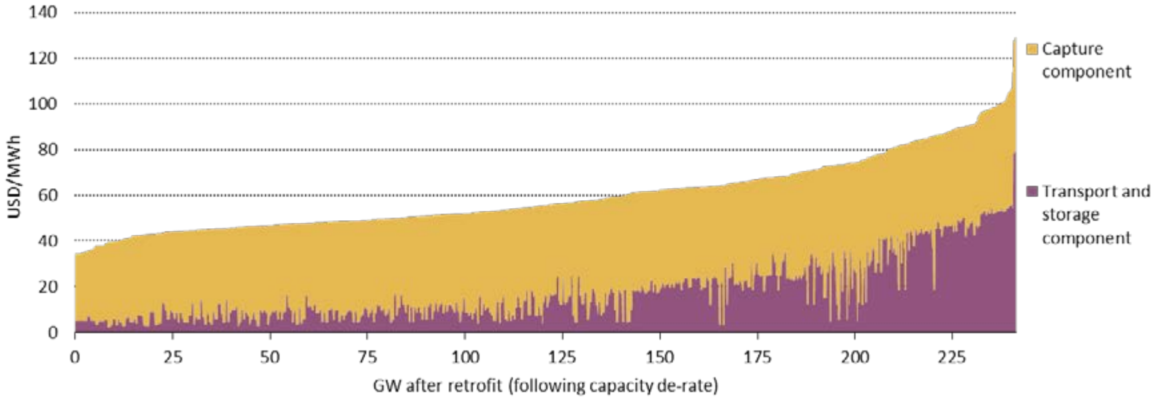


This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: IEA (2016), *Ready for CCS retrofit: The potential for equipping China's existing coal fleet with carbon capture and storage*.

Cost-related factors which influence a plant's relative attractiveness as a candidate for retrofitting with CCS include cooling type, efficiency, steam turbine design and pollution controls. These factors, including the costs of CO_2 transport and storage, can then be used to rank candidate plants according to their cost premium for generating electricity with low emissions. The costs of retrofitting are likely to vary significantly. Under a preliminary analysis of the 310 GW of plant capacity deemed suitable for retrofitting in China, additional costs of power generation after retrofitting are estimated to vary between USD 34 and USD 129/MWh (see Figure 3.4). Some 100 GW of this existing capacity is estimated to generate additional power generation costs of less than USD 50/MWh, indicating that a significant retrofit opportunity exists within a reasonable cost range.

Figure 3.4 • CCS in China: Additional electricity production costs after retrofitting



Source: IEA (2016), *Ready for CCS retrofit: The potential for equipping China's existing coal fleet with carbon capture and storage*.

3.2.4 Strategy and policy: How to drive retrofitting forward?

Facilitating retrofits will require the appropriate policies and incentives to be in place. Various steps can be taken by government and industry in many countries to ensure that retrofit of CCS is an available and attractive option in the coming decades. Three particular areas are highlighted:

- **CO_2 storage development is critical**. Suitability of a coal-fired unit for retrofitting with CCS is not just about whether and how to fit CO_2 capture equipment. Factors such as the proximity to suitable CO_2 storage can have a major impact on the feasibility and cost of retrofitting. As the development of CO_2 storage sites can have long lead times, it is important for governments and industry to increase their efforts to locate suitable storage sites.
- **New plants must be built CCS-ready to maximise future retrofit opportunity**. A new coal-fired unit that is designed to be CCS-ready must demonstrate much more than a technical suitability for the addition of post-combustion CO_2 capture (IEA and CSLF, 2010). For example, governments should ensure that new plants are located sufficiently near to prospective storage areas and that operators plan for a future retrofit during the construction phase.
- **Stakeholders must continue technology innovation and cost reduction**. There are opportunities for cost reduction in all parts of the value chain of a CCS retrofit, especially in the capital and operational costs of post-combustion CO_2 capture (IEA, 2015a). Much of this cost reduction can come from the experience that firms will gain from building and operating large-scale projects using CCS technologies.

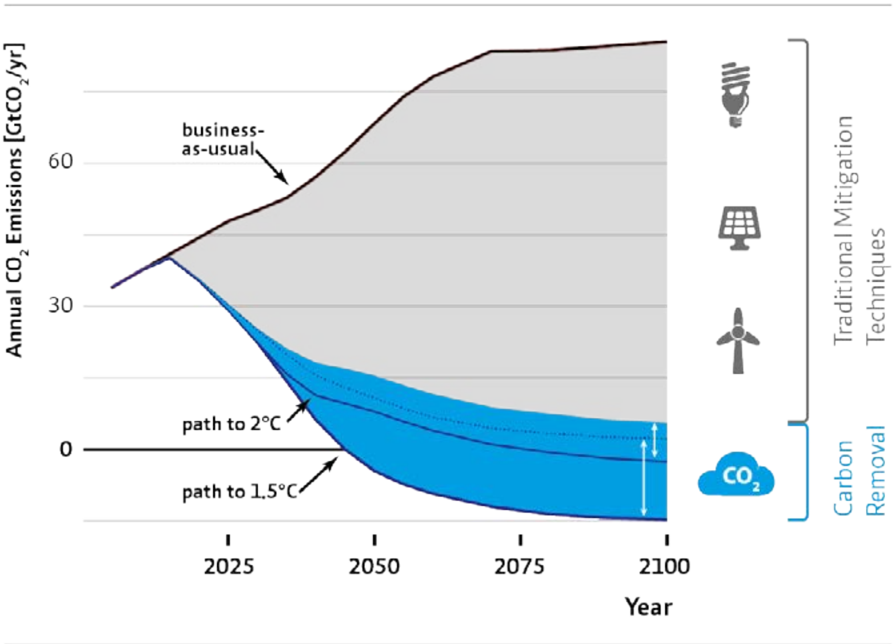
3.3 Activating negative emissions: The role of BECCS

- **The heightened ambition of the Paris Agreement increases the importance of negative emission sources. Bioenergy with CCS (BECCS) is the most mature negative emissions technology option.**
- **BECCS is a reality today, with four projects operating in the United States, Canada and the Netherlands. However, significant challenges must be overcome to expand the scale of BECCS. This includes ensuring the sustainable management of biomass sources and investment in CO_2 transport systems which can service often widely dispersed and smaller-scale BECCS plants.**
- **Early opportunities for BECCS deployment are already available and can provide an important pathway to understanding the future potential of these technologies.**

Achieving the ambitions of the Paris Agreement will require more than just an acceleration of efforts to reduce emissions; according to the IPCC it may also require the deployment of technologies to actually remove carbon from the atmosphere. This important role for "negative emissions" is also highlighted in analysis, including by the Mercator Research Institute on Global Commons and Climate Change (MCC) and the International Institute for Applied Systems Analysis (IIASA), that point to the need for overall emissions to be negative during the second half of the century (see Figure 3.5). CCS in combination with bioenergy (BECCS) is an important option for delivering these "negative emissions".

The large-scale deployment of BECCS will take its first steps in 2017, with the Illinois Industrial CCS Project that involves capture from an ethanol plant expected to commence capturing and storing up to one million tonnes of CO_2 ($MtCO_2$) per year. However, the future potential of BECCS technologies is uncertain and will ultimately depend on the availability of sustainable biomass supply and the development of a CO_2 transport network, including to service smaller-scale BECCS sites. Improvements in CCS technologies and the expansion of storage infrastructure will also be important.

Figure 3.5 • The role of "negative emissions" in achieving the Paris Agreement targets



© MCC (Mercator Research Institute on Global Commons and Climate Change) www.mcc-berlin.net.
Source: Minx, J.C. and S. Fuss (2016), "These charts show what the Paris climate agreement is up against".

3.3.1 BECCS: Critical for achieving well below 2°C?

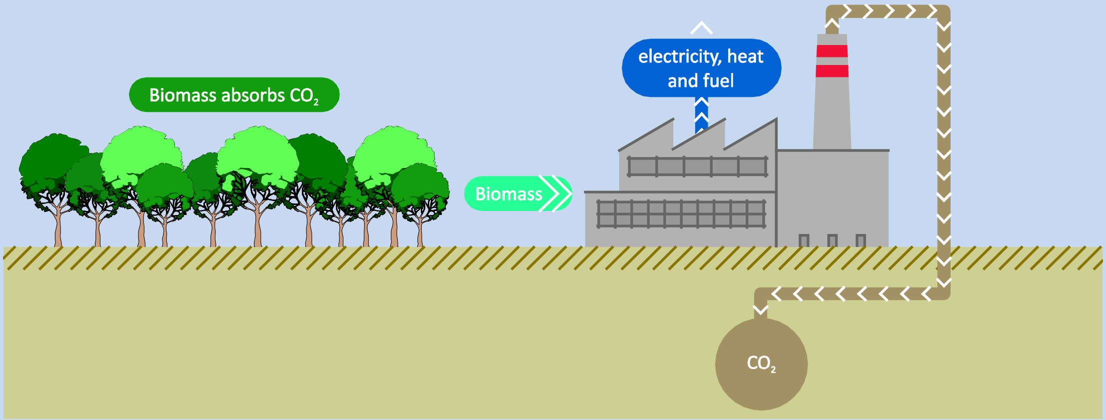
The IPCC 5th Assessment Report (AR5) highlighted that many climate models could not achieve atmospheric concentration levels of about 450 ppm CO_2-eq by 2100[34] "under limited availability of key technologies, such as bioenergy, CCS, and their combination" (IPCC, 2014a). In the majority of the scenarios examined by the IPCC that aim for concentration goals consistent with limiting future temperature increases to between 1.5°C and 2°C, BECCS "forms an essential component of the response strategy". The AR5 also highlighted that BECCS was deployed in greater quantities and earlier in time the more stringent the goal, potentially representing 100% of bioenergy in 2050 (IPCC, 2014a).

BECCS has the important capacity to generate "negative emissions" (see Box 3.5). While the use of renewables avoids the creation of CO_2 in the first place, and most CCS acts to avoid emissions by sequestering anthropogenic CO_2 created from electricity generation or industrial processes, BECCS actually removes CO_2 from the atmosphere, including anthropogenic CO_2. Negative emissions arise due to the fact that biomass absorbs CO_2 as it grows and when combusted for energy the CO_2 is released back into the atmosphere creating a full cycle with a neutral impact on atmospheric volumes of CO_2. When combined with the CO_2 capture and storage process, the CO_2 absorbed by the biomass is permanently removed from the atmosphere.

Box 3.5 • How BECCS generates negative emissions

BECCS is defined as carbon capture and storage in which the feedstock is biomass. This includes energy production processes or other industrial processes with CO_2-rich process streams originating from biomass feedstocks. Possible applications of BECCS include: dedicated or co-firing of biomass in power plant; combined heat and power (CHP); pulp and paper mills; lime kilns; ethanol plants; biogas refineries; and biomass gasification plants.

BECCS enables **negative emissions** because CO_2 sequestered during the growth of biomass is not released after the biomass is combusted or refined to produce biofuel. The CO_2 captured and stored underground outweighs the emissions related to producing the biomass, including those from land use change and transformation into the final product (IEA, 2015c). The net result is the permanent removal of CO_2 from the atmosphere, or negative emissions.



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[34] This is equivalent to a 70% chance of limiting future temperature increases to 2°C or below

This significant role for BECCS in ambitious climate scenarios derives from two factors: first, the negative emissions generated from BECCS can compensate for residual emissions in sectors where direct mitigation is difficult or more expensive, for example in aviation and some industrial sectors. Second, and perhaps more significantly, the deployment of BECCS and its negative emissions impact can counterbalance near-term carbon budget "overshoot" while still keeping more ambitious climate targets within reach. Under various analyses, BECCS (as well as other negative emissions technologies) can effectively expand global carbon budgets in the medium term and allow more time for the transition to net zero emissions, with less mitigation in the near term – the overshoot – followed by more profound emissions reductions later in the century (Kemper, 2015). Without BECCS, various scenarios point to the need for faster and more aggressive direct mitigation efforts being required. The availability of negative emissions technologies was therefore identified by the IPCC as being critical "in the context of the timing of emissions reductions" (IPCC, 2014b).

The prospect of an overshoot in carbon budgets increases exponentially the more ambitious the target. The Carbon Brief (2016) has assessed that the remaining carbon budget consistent with a 50% chance of limiting future temperature increases to 2°C by 2100 and is equivalent to 27.8 years of current emissions. For a 50% chance of achieving a 1.5 degree target, the figure is 8.9 years. The NDCs as pledged ahead of COP21 would put the world on a pathway closer to 3°C (IEA, 2015c), with significant potential for carbon budget overshoot as compared to the Paris Agreement target of well below 2°C. Without the availability of negative emissions technologies in the future, the risk that more ambitious climate targets could soon be out of reach cannot be excluded.

3.3.2 *BECCS is slowly becoming a reality*

The early deployment of BECCS has commenced, albeit on a small scale. Currently four BECCS projects are in operation in Canada, the Netherlands and the United States (see Table 3.1). These projects have an ethanol plant as their source of CO_2, with the ethanol production process producing a high-purity stream of CO_2 and with the CO_2 capture technology already commercially proven. Three of the operating projects use the CO_2 for EOR and are all capturing on a relatively small scale, at between 0.1 and 0.3 $MtCO_2$/year.

Table 3.1 • Operating BECCS projects

Project name	Country	Operation date	Source of CO_2	CO_2 capture capacity (Mtpa)	Primary storage type
Operating					
Arkalon	USA	2009/10	Ethanol plant	0.29	EOR
Bonanza	USA	2011	Ethanol plant	0.15	EOR
RCI[a]/OCAP/ROAD	The Netherlands	2011	Refinery/ ethanol plant	0.3/ 0.1	Dedicated storage planned[b]
Husky Energy	Canada	2012	Ethanol plant	0.1	EOR
Completed					
Illinois Basin Decatur Project (IPBD)	USA	2011-14	Ethanol plant	0.3	Dedicated

[a] The BECCS activities are part of a larger cluster project led by the Rotterdam Climate Initiative (RCI), including the Organic Carbon Dioxide for Assimilation of Plants (OCAP) project and the Rotterdam Opslag en Afvang Demonstratieproject (ROAD)

[b] CO_2 is currently being sold to nearby greenhouses but with a plan for dedicated storage as part of the scaled-up ROAD project

Source: Kemper, J. (2015) "Biomass and carbon dioxide capture and storage: A review".

The most significant operating BECCS project to date has been the Illinois Basin Decatur Project (IBDP) in Decatur, Illinois, which was operational between 2011 and 2014. The project captured CO_2 emissions from the distillation of corn into bioethanol, and has stored it in a sandstone formation. The project successfully stored 1 Mt of CO_2 (MIT, 2016).

From 2017, the project will be scaled up to capture and store 1 $MtCO_2$/year, under the Illinois Industrial CCS Project (IICCSP). The project has received USD 140 million in capital support from the US Department of Energy and will also be able to access CO_2 storage credits of USD 20/tCO_2. The relatively modest level of support (compared, for example, to power generation applications of CCS) highlights that, in the right circumstances, ethanol production with CCS is an example of a relatively low-cost CCS application. The favourable economics of the project are in part due to the earlier investment in geological storage characterisation, which was undertaken as part of the pilot project, as well as the fact that the CO_2 will be stored under the plant site (Herzog, 2016). Aspects of the IICCSP BECCS model have the potential to be replicated in other areas of the United States, with the bioethanol mandate currently supporting production of 50 billion litres of ethanol each year.

A further eight BECCS projects are in the identify/evaluate stage of development – four in Sweden, and one each in the Brazil, France, the United Kingdom and the United States (Kemper, 2015). The White Rose project in the United Kingdom would have had the capacity to co-fire biomass with coal; however the project is not expected to proceed following the cancellation of the UK CCS Commercialisation Programme.

3.3.3 How large is the negative emissions potential of BECCS?

Quantifying the future role of BECCS and negative emissions technologies with any accuracy is complex, reflecting considerable uncertainty around future land use policy, the availability of sustainable biomass supply, future technology costs and CO_2 storage availability. Global estimates of the technical potential of BECCS vary accordingly, from around 3 Gt CO_2/year to more than 10 Gt CO_2/year (IEAGHG, 2011b). To put this into context, afforestation and reduced deforestation also have an estimated global potential of up to 10 Gt CO_2/year in negative emissions (IPCC, 2014b).

As discussed in Chapter 2, in the 2DS almost 14 Gt CO_2 is captured from BECCS applications in the period through 2050, accounting for around 2% of cumulative emissions reductions. The rate of BECCS-related CO_2 capture grows from virtually nil to 1 Gt per year in 2050, with the vast majority of this associated with biofuel production processes which produce relatively pure CO_2 streams (see Section 2.1.5). In parallel, by 2050 biomass (including waste) becomes the largest primary energy source in the 2DS, at around 140 exajoules (EJ). The availability of CCS is likely to be a major determinant of how and where this bioenergy is used after 2050. The IPCC found that, without CCS, bioenergy is used predominately as a liquid fuel while the availability of CCS sees a shift in its use towards power generation to maximise negative emissions (IPCC, 2005).

3.3.4 The key challenges of deploying of BECCS at scale

A number of technical, economic and social issues will need to be resolved if deployment of BECCS at the scale envisaged in many long-term climate models is to be realised (see Table 3.2). Principal among these is the sustainable supply of biomass. The increased use of bioenergy could create competition with existing uses of biomass, including for food and feed, forest products, or competition for land. This competition could create upward pressure on agricultural and forestry commodity prices and thus affect food security. In some cases bioenergy may also lead to direct and indirect land use changes which result in the release of GHG emissions, more intensive land use, pressure on water resources and loss of biodiversity (IEA, 2012b).

From a CCS perspective, the challenges of BECCS deployment are broadly similar to other industrial CCS applications. Economies of scale in plant size will be crucial to improving the economic viability of projects, particularly in power generation. The availability of CO_2 transport and storage infrastructure is also likely to be an important precursor to BECCS investment. The transport process will be particularly important since many BECCS capture sources are anticipated to be small and diffuse, in contrast, for example to fossil fuel power plants. The variability in flue-stream gases and the presence of impurities can create additional complications for CO_2 capture from BECCS power plants, with further testing at large-scale required. Some of the public perception issues associated with "conventional" CCS may actually be improved with recognition of a role for CCS beyond fossil fuels, although opposition to growth in the use of bioenergy itself may ultimately counter this.

Table 3.2 • Challenges for large-scale deployment of bioenergy and CCS

Bioenergy-related factors	CCS-related factors
▪ Sustainability of biomass ▪ Land use changes ▪ Land availability ▪ Water requirements ▪ Fertiliser requirements ▪ Health and social impacts ▪ Impact of climate change on crop yields ▪ Food security/competition ▪ Competition for biomass ▪ Lifecycle emissions – measurement and uncertainty ▪ Biomass transport costs ▪ Public perception	▪ Capture cost ▪ Economies of scale ▪ Energy requirements ▪ Transport infrastructure availability ▪ Geological storage availability ▪ Technical and integration risks ▪ Public perception

A further challenge for BECCS deployment relates to the lack of accounting for "negative emissions" in some regional carbon policy frameworks.[35] For example, the EU ETS allows for consideration of geologically stored fossil carbon but treats biomass conversion as neutral, even with CO_2 capture, and so there is no incentive to generate negative emissions from BECCS (Kemper, 2015). Yet studies suggest that BECCS could play a major role in emissions reductions in Europe, removing 800 $MtCO_2$ from the atmosphere every year by 2050 – around 50% of the current EU power-sector emissions (ZEP and EBPT, 2012). In contrast, the UNFCCC Clean Development Mechanism (CDM) does recognise CCS, including BECCS, and the accounting methodology allows for negative emissions, although this has never been applied. It will be important for future carbon policy frameworks to adequately recognise and reward investment in negative emission technologies such as BECCS.

While BECCS faces various challenges, this is also the case for other prospective negative emissions technologies (see Box 3.6). These alternatives include increased direct air capture (DAC), ocean liming and biochar. BECCS likely presents certain advantages over some of these alternative technologies.

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[35] For a more comprehensive discussion of these issues, refer to Kemper (2015).

Box 3.6 • Alternative negative emissions technologies

BECCS is not the only technology capable of delivering negative emissions. Negative emission technology options which would also rely on access to geological CO_2 storage include DAC and ocean liming. However these technologies are less mature and their economic potential is likely to be significantly smaller than BECCS (Caldecott, Lomax and Workman, 2015). Concern around the environmental impacts of ocean liming is also likely to be a barrier to its deployment. Approaches which do not rely on CCS to deliver negative emissions include afforestation and reduced deforestation, agricultural land management and biochar. The future potential of these options is also highly uncertain and dependent on land use policy and patterns. Afforestation and agricultural land management may also be vulnerable to the effects of climate change, including water scarcity, and do not provide permanent CO_2 storage (i.e. over thousands of years) in the same way that geological storage does (IPCC, 2014b).

3.3.5 Capturing the future potential of BECCS: The need for action today

The IPCC analysis suggests that the availability of negative emissions technologies, and particularly BECCS, will be a critical determinant of the timing and scale of emissions reductions needed if long-term climate targets are to be met. If the availability of BECCS is limited, the option to counter near-term carbon budget overshoot will be constrained and more aggressive emissions reduction action will be required in the early part of the century. Greater confidence in the future role of BECCS will therefore be important to inform today's climate policy response.

As a starting point, the challenges associated with sustainable biomass supply will need to be addressed, including through continued research and development in next generation biomass feedstock. This could also be complemented by the establishment of internationally-agreed technical standards and sustainability criteria (IEA, 2012b).

Increasing the level of practical experience with both small and large-scale BECCS projects will also be important. Targeted policy and financial support for early deployment of BECCS should be considered in parallel with that for conventional CCS, and coupled with appropriate recognition of negative emissions in accounting frameworks. The IICCSP in the United States has highlighted the fact that lower-cost opportunities for BECCS deployment are available, and cultivating these could deliver significant value from an emissions reduction perspective.

As with other industrial applications of CCS, the availability of CO_2 transport and storage infrastructure networks could be a key to addressing the economies-of-scale challenges of BECCS applications which involve smaller quantities of CO_2, such as dedicated power generation plants. The use of a disaggregated approach to CCS that relies on hubs and clusters, in particular a shared transport system, could help in this regard (see discussion in Section 3.6). Co-firing of biomass with coal or gas in power generation with CCS could also help to resolve some of these scale issues while contributing to net-zero fossil fuel power generation (see Box 2.2).

3.3.6 Refocusing attention on BECCS

The negative emissions potential of BECCS has now been recognised for many years, including by the IPCC, yet progress with deployment has remained fairly stagnant. The heightened ambition of the Paris Agreement and the 2018 IPCC Special Report should be an opportunity to refocus policy attention on the need for early action on this important technology option.

3.4 CCS: Enabling clean products

- **Key industrial products such as steel, cement and chemicals have a high CO_2 footprint per tonne of product and contribute to significant emissions globally. Demand for these materials is likely to be sustained and even grow through to 2050, making it imperative to reduce the emissions intensity of production.**
- **The embodied emissions of various industrial products can be reduced substantially by applying CCS to industrial processes and manufacturing.**
- **Various push and pull mechanisms could be used to create a market for "clean products". These mechanisms include policy incentives on the supply side, actions to support consumer demand, and regulations targeting the carbon content of products.**

3.4.1 The potential to reduce emissions: Changing how key industrial products are made

The global demand for industrial products such as crude steel, cement and various chemicals and petrochemicals is expected to increase over the coming decades. Under the IEA 2DS, the demand for these products is expected to continue to rise, particularly in developing economies seeking to further their economic development and raise living standards. In 2DS the demand for steel reaches 1.75 Gt in 2020 and 2.25 Gt in 2050 and that of cement 4.3 Gt and 4.5 Gt respectively.

Chemicals, steel and cement all have significant carbon footprints which can be reduced through CCS. On average globally 1.7 tCO_2 are directly released for every tonne of steel produced, with significant differences between production methods and countries. For every tonne of cement, approximately 550 kg of CO_2 is emitted. In the 2DS, emissions from the production of basic materials and commodities (such as steel, cement and chemicals) and from other industrial activity will remain significant. In 2030, they represent over 30% of energy-related emissions in the 2DS, and become the largest source of remaining emissions in 2050, contributing 45% of total emissions. Roughly half of these remaining emissions will come from the production of steel and cement. Given that the demand for these products is likely to be sustained and even grow to 2050 (as described above), it will be necessary to reduce the emissions intensity of production processes. Opportunities to achieve this include energy efficiency improvements, switching to low-carbon fuel or feedstock, shifting to less carbon–intensive process routes or the use of innovative processes. However CCS will be critical to achieving deep emissions reductions in the industrial sector, ultimately enabling the production of a variety of "clean products",[36] with a lower CO_2 footprint**.**

Under the 2DS, the aggregated direct CO_2 intensity of crude steel production declines from 1.7 tCO_2 per tonne to 0.59 tCO_2 by 2050 and cement declines from 0.55 tCO_2 per tonne of cement to 0.37 tCO_2 of direct emissions (see Figure 3.6). CCS plays a key role in achieving this reduction in CO_2 emissions intensity levels. As discussed in Chapter 2 of this publication, in a well-below 2°C world, there would be a need to go beyond these levels of emissions reduction from industrial sectors.

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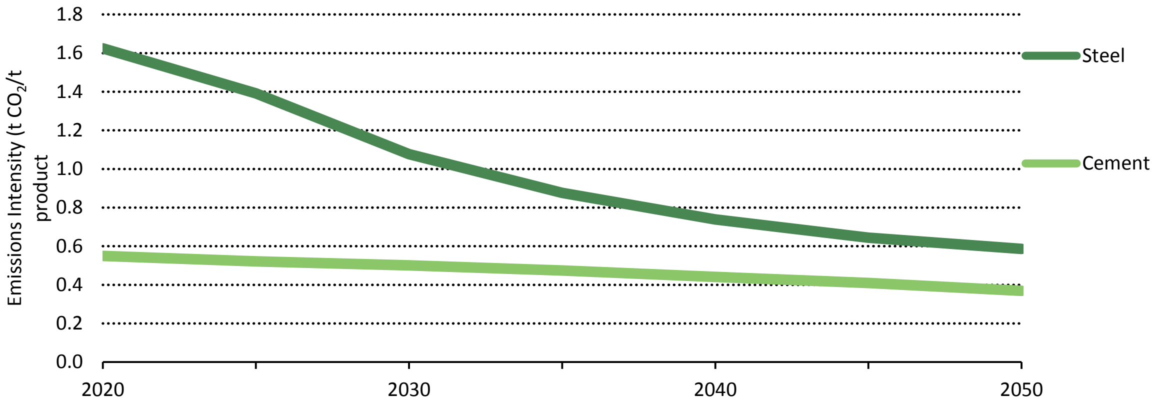
[36] The emphasis in this section is mostly on products in the industrial sense, as key materials used in industry, for construction of buildings, etc. While this section does not deal much with "end-consumer products", there is a relevant linkage to choices made by individual consumers especially as regards houses and apartments, for which low-emission cement or steel could be used.

Figure 3.6 • Emissions intensity of steel and cement production in the 2DS (tCO_2/t product)



Source: Derived from IEA (2016b), *Energy Technology Perspectives 2016*.

3.4.2 CCS enabling clean products

Reducing emissions in the production of key crude materials effectively lowers the CO_2 footprint of a range of downstream products. As described in Chapter 2, an industrial production site may have several point sources of CO_2 emissions to which CO_2 capture can be applied. Some widely used industrial processes involve the release of CO_2 as an inherent by-product of the chemical conversions at the heart of the process. For example, the calcination of limestone in cement kilns and the reduction of iron ore in blast furnaces both release CO_2 which can only be reduced through CO_2 capture. Many producers use fossil fuels to generate heat or power. In some cases, the combustion of fossil fuels can be replaced by low-carbon energy sources such as biomass or renewables, and in some cases, producers could choose to apply CO_2 to fossil fuel-based or renewables-based emissions. CCS can be applied to a number of industries:

- **Iron and steel**: The application of CCS to various parts of the iron and steel-making process can reduce emissions per tonne of steel by 45% to 60%. The cost and emissions impact of applying CO_2 capture will depend on the process route and which elements of the process have CO_2 capture applied to them.
- **Cement**: The emissions from the production of cement can be reduced by 60% to 70% through CCS (IEAGHG, 2008). This could increase the cost of producing cement by 36% to 42% for oxy-fuel capture and 68% to 105% for post-combustion capture (IEAGHG, 2013c). A reduction in the emissions of the cement could substantially reduce the embodied emissions in a building or house, with a relatively minor impact on the cost of the total construction.
- **Fertilisers**: Ammonia is the basis for nearly all synthetic fertilisers globally. With population growth, economic development and increasing competition for land use there will be increasing demand for productivity increases in food production. Presently, most ammonia is derived from hydrogen from fossil fuels and inherent in the hydrogen production process is the stripping out of CO_2. With CCS applied, the emissions from ammonia production could be reduced by 65% to 70%.
- **Plastics etc**: Ethylene is a building block for a wide variety of consumer products including plastics, polymers and detergents. Ethylene is produced from cracking hydrocarbons, usually through steam. CO_2 is produced both through the generation of heat and from the cracking of the hydrocarbons.

The application of CCS will increase the costs of producing basic materials, substantially in some cases. While some industrial applications could be first movers in CCS, in most cases CCS application would require policy or regulatory measures that either necessitate CCS or which create a market for "clean products".

3.4.3 Creating a market for clean products: Push and pull levers

While CCS offers a way to reduce the carbon footprint of various industrial products, today producers are unlikely to choose to apply CCS voluntarily, given its impact on their costs and competitiveness. Demand for clean industrial products could be generated by both push and pull measures, using regulatory push for cleaner production and demand-led pull levers for lower emissions products. A combination of regulation, incentive mechanisms and consumer demand for clean products could provide a framework to support the large capital investments involved in CCS, and help to manage the impact on competitiveness for plants that reduce emissions.

Regulatory and policy measures

Policy and regulation can "push" producers to apply CCS. Regulation or standards for the emissions intensity of products can drive the adoption of CCS in emissions-intensive industries; but will likely need to be complemented with measures to protect the competitiveness of the industry. There are numerous options for regulation, notably setting a cap on the emissions intensity of a given material. Requiring emissions intensities to be below a certain point can indirectly encourage the adoption of CCS. Such standards can drive CCS in a given country or jurisdiction, but if not implemented in a similar way in other countries they will lead to issues of competitiveness.

Public policy practices can also be used to create a market for clean products through demand "pull levers". Government procurement policies can drive government spending towards lower emission products by including emissions intensity as a selection criterion in the bidding process. Doing this in co-ordination with similar procurement policies across other large consumers would help to create a broad market for lower-emissions products, possibly sufficient to incentivise the necessary capital investment.

For regulation to be effective in supporting lower-emissions products from industry, it will need to address these competitiveness issues. It will also need to provide industry companies and investors with the certainty and foresight sufficient to support the necessary capital investments.

Incentive policies for industrial CCS

Policy incentive can be applied to industrial sectors to encourage cleaner production, including with CCS. These are likely to require sector-specific application due to the particular technical and market characteristics of the industrial sectors and the impacts on their competitiveness. Several incentive mechanisms could be envisaged for industrial sectors, such as:

- investment tax credits offering a fiscal incentive linked to CCS investment
- production tax credits offering a fiscal incentive according to production with CCS
- CO_2 purchase commitments, whereby governments commit to purchasing CO_2 from the producers, while the products themselves continue to be sold in the product markets.

Other incentive mechanisms and their combination can also be considered.[37]

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[37] See IEA 2014a for a more detailed discussion on various incentive mechanisms.

In addition to the incentives given to producers, incentives that encourage demand for clean products can also be considered. For example, as users of products, the construction industry sector could be incentivised through fiscal or other policy measures to purchase lower-emissions cement and steel products.

Consumer-led demand

The deployment of CCS on industrial processes can also be catalysed through demand "pull" measures that support increased demand from consumers themselves for clean products. The increased cost of CCS can be significant as a proportion of the cost of raw materials, however once carried through to final consumer products, such as an apartment in a new housing block, the price impact may be relatively minor. At present there is no differentiation between products in key sectors on the basis of embodied emissions, and therefore there is little or no opportunity to recoup the added production and investment costs arising from the application of CCS.

The increase in costs can be partially addressed by demand-led pull, with consumers preferring clean products and accordingly willing to pay more, at least partly offsetting the cost of CCS. Demand for clean products could be driven in different ways such as through mandatory labelling schemes or greater public awareness of the CO_2 intensities of different materials. Hence a "clean product" designation could differentiate products with lower embodied emissions, allowing more of the costs of CCS to be passed on to the consumer. Such schemes would be analogous to consumers choosing to pay a premium for green electricity, for example. While there is little experience on such schemes for industrial products, significant consumer-driven demand has been created for various environmentally-friendly or ethically-sourced consumer products (Isley et al., 2016).

It is clear that an approach based solely on consumers willing to pay more for clean products would not be enough to drive CCS into industrial applications. The solution might lie in a concept of "layered incentives", whereby the additional cost of CCS is covered "throughout the chain". In such a system, incentives could be provided on three levels: a level of incentive for the producer of industrial products (for example, a steel or cement manufacturer), an incentive for the industrial customer (such as the construction industry using cement and steel) and via the end-user (the customer).

3.5 Enhanced oil recovery: From old ways to EOR+

- **EOR+ can achieve significant net reductions in CO_2 emissions. Using more CO_2 to extract oil from reservoirs delivers a potential to permanently store large quantities of CO_2 – significantly beyond any CO_2 resulting from the additional oil production.**
- **With today's technologies, EOR+ can be undertaken immediately to ensure permanent storage of CO_2. A key addition is to include adequate monitoring, reporting and verification measures to current EOR practices.**
- **As carbon markets mature and expand, EOR+ can be an interesting way for the oil industry to combine revenue from additional oil extraction with CO_2 storage. Combining oil production and CO_2 injection, and ensuring permanent storage of CO_2 in the process, can result in a win-win situation for both business and the climate.**

Co-exploiting the injection of CO_2 into oil reservoirs to enhance oil recovery (CO_2-EOR) has been an important business driver for several CO_2 capture projects over the past decades. It can offer further opportunities as the largest single use of CO_2, both today and in the foreseeable future. The resulting CO_2 storage could create a win-win situation and achieve a business model that could generate additional revenue for the operator from oil production and CO_2 storage. In addition, it would create significant net CO_2 emissions reductions. Transforming practices to support climate change objectives in addition to oil extraction, that is moving from simple EOR to "EOR+", is entirely possible with existing technologies. This will require additional measurement, monitoring and verification (MMV) beyond current EOR practices, as well as other actions designed to increase the robustness of CO_2 storage such as well and field abandonment processes. However, to achieve significant emissions reduction benefits, a second point is critically important: more CO_2 must be injected per barrel of additional oil. This will require an additional economic driver.

3.5.1 Adding the "+" to EOR: Ensuring CO_2 storage through MMV practices

EOR+ involves extending today's traditional EOR practice to include actions directed at providing for the storage of CO_2 that are consistent with the emissions reductions requirement of climate change mitigation action (see Box 3.7). It is possible to apply the measures needed to add this climate-related CO_2 function with existing technologies and practices, although additional actions are required:

- **Additional site characterisation and risk assessment** is required to collect information on overlying caprock and geological formations, as well as abandoned wellbores, to assess the potential for leakage of CO_2 from the reservoir.
- **Additional measurement of venting and fugitive emissions** is needed from surface processing equipment.
- **Monitoring and enhanced field surveillance** must be aimed at identifying and, if necessary, estimating leakage rates from the site to assess whether the reservoir behaves as anticipated.
- **Changes to abandonment processes** must be made that help guarantee long-term containment of injected CO_2, such as plugging and removal of the uppermost components of wells so they can withstand the corrosive effects of CO_2-water mixtures.

Ensuring that operators take these steps to manage oil fields for both oil recovery and CO_2 storage would require a policy push from governments. This could be done in various ways, including a sufficient carbon price to incentivise EOR operators to take on the additional actions for EOR+ (such as increased CO_2 injection and implementation of related MMV processes), or a mandate requiring oil field operators to demonstrate permanent storage.

Box 3.7 • How does EOR+ differ from today's conventional EOR practices?

Today's CO_2-EOR is an oil production enhancement technique, aimed solely at increasing the production of oil from existing fields. "Storing" the utilised CO_2 happens incidentally, and is typically not verified. Furthermore, as CO_2 constitutes a cost for the operator, the quantities injected are naturally minimised, and recycling of CO_2 is maximised. Conventional EOR has been practiced for over 50 years, primarily in North America. Most CO_2-EOR projects today use naturally occurring CO_2 extracted for EOR purposes – a practice not in any way beneficial to the climate.

In contrast to conventional practices, the concept of EOR+ aims to co-exploit oil production and geologic CO_2 storage. EOR+ differs from conventional EOR in three key areas:

1. The CO_2 must be anthropogenic;
2. Under EOR+, operators undertake a number of key additional activities to ensure long-term retention of CO_2 from the atmosphere: 1) site characterisation; 2) measurement of fugitive emissions from the EOR+ operations site; 3) monitoring and verification of the field itself; and 4) field abandonment practices aimed at ensuring long-term storage. Such activities can be undertaken with existing technologies; and

3. Operators increase the volume of CO_2 used per additional barrel of oil produced.

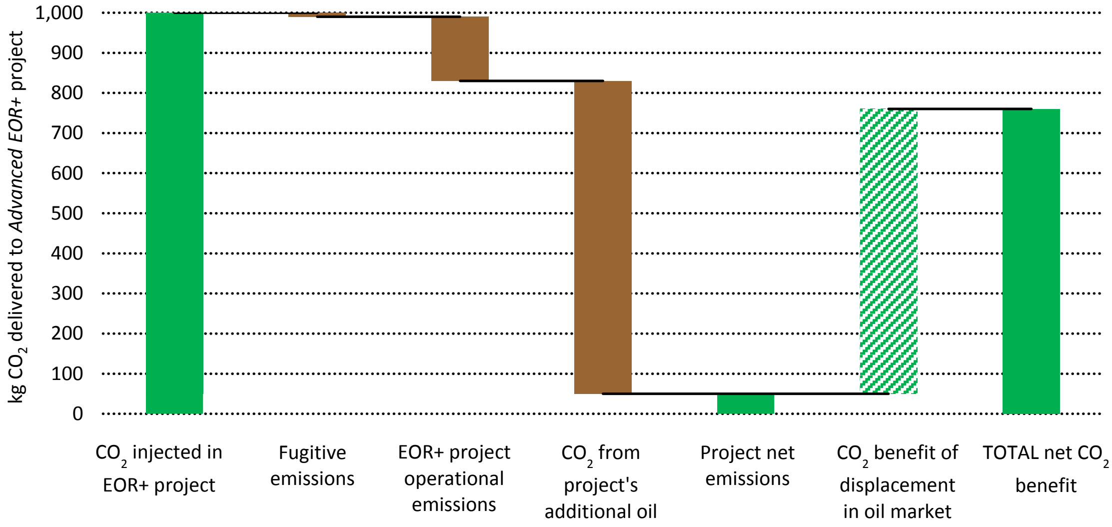
Today, no major EOR operation can be classified as being EOR+ (although the Weyburn EOR project did previously include an MMV programme until 2012 – see discussion in Section 1.3). Incentivising EOR+ requires either regulatory mandates, or a significantly higher emissions penalty, part of which could be paid as service fee to the EOR+ operator.

3.5.2 EOR+ offers significant potential for net reduced emissions

EOR+ practices have the potential to achieve a significant net reduction in CO_2 emissions, notwithstanding the emissions from the resulting oil production. While one tonne of CO_2 injected in the oil field is not equal to one tonne stored, using EOR+ practices can generate a net emissions benefit. This involves an evaluation of: (i) emissions at the level of the CO_2-EOR project itself (e.g. related to the EOR+ field production activities); (ii) the emissions resulting from the additional oil produced from the EOR+ field as a result of CO_2 injection; and (iii) the displacement of other types of oil with oil from the EOR+ field.

The key to achieving net reductions is the increase in volumes of CO_2 injected per additional barrel produced. Under conventional EOR practices, CO_2 is a cost that operators try to minimise; accordingly, operators look to minimise the amount of CO_2 used to produce an additional barrel of oil, typically about 0.3 t CO_2 per additional barrel. Under an EOR+ model, operators are incentivised to inject higher levels of CO_2, for example up to 0.6 t CO_2 per barrel in the "Advanced EOR+" model.[38] Such doubling of the volume of CO_2 injected per barrel would make significant net emission reductions possible.

Figure 3.7 • Net emissions reductions using "Advanced EOR+"



According to a preliminary IEA analysis which considers displacement of other types of oil, Advanced EOR+ practices can generate a significant emissions reduction benefit (see Figure 3.7). As conventional crude oil is displaced by oil from EOR+,[39] for every tonne of CO_2 injected as part

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[38] For further discussion, see IEA 2015a.

[39] In order for oil produced through EOR+ to be competitive, a barrel recovered through EOR+ must have a lower cost than that produced from competing options (e.g. unconventional resources, deep water, etc.). IEA analysis of future oil supply curves can shed light to how much of EOR+ oil substitutes other oils, and how much it adds to global oil demand. Oil produced with EOR+, in a cost-effective manner, would not simply lead to incremental oil demand in a global market, but would mostly

of the Advanced EOR+ operation, 0.73 tonnes can effectively be avoided. On an oil production basis, this equates to 440kg CO_2 per barrel produced through Advanced EOR+. Although generating an emissions benefit from an oil production activity may appear counter-intuitive, the positive impact largely results from the displacement of oil produced without any CO_2 storage by oil that involves CO_2 storage through EOR+ practices.

Understanding the net CO_2 emissions benefit of EOR+ on both project level and globally is a complex task. The net benefit depends largely on the included elements (“project boundaries”) and a determination of the amount of oil displacement (which requires an analysis of global market dynamics). Further analysis of the dynamics of EOR+ merits consideration, given the potential for this approach to generate net emissions reductions while building on the profitable EOR business model. However, as the preliminary IEA analysis discussed above indicates, EOR+ may potentially generate a significant emissions reduction benefit.

From a global perspective, there is a substantial opportunity for CO_2 storage through EOR+. According to IEA analysis (2015a), the technical potential of EOR+ practices to store CO_2 in suitable oil fields worldwide ranges from about 60 Gt CO_2 with current practices to potentially 360 Gt CO_2 globally if CO_2 injection rates are maximised. Even the lower potential of 60 Gt represents two-thirds of the total CO_2 storage needed to keep the world on the 2DS trajectory.

3.5.3 EOR+: A possible win-win-win proposition

EOR+ can thus provide various advantages that generate a win-win-win solution. The first win is that under future carbon pricing mechanisms, EOR+ can generate revenue for oil field operators, who would be paid not only for the increased oil production, but also for storing the utilised CO_2. A second win is that EOR+ can generate a beneficial outcome for climate change mitigation efforts by allowing for net lowered emissions when the displacement of other more CO_2-intensive oil is considered. The third win is that it can help to stimulate early investment in CCS, including in CO_2 capture and transport infrastructure which can benefit future CCS projects. Countries and regions with EOR projects and/or known future potential for EOR could stimulate CCS investment and innovation by setting the necessary policy framework, through incentives or mandates, to drive EOR+ practices.

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substitute other oil production. Under preliminary IEA analysis, some 20% of the cumulative oil production realised via EOR+ would be additional production; the vast majority, 80%, would effectively substitute other oil production, which would be displaced from the market. For a fuller discussion see Chapter 3 of IEA (2015d).

Commentary 6 • Financing CCS

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While we have seen a number of notable large-scale CCS developments recently achieving or approaching commercial operation (Kemper, Boundary Dam and Al Reyadah, the Masdar/Emirates Steel JV), we have yet to see a commercial bank financing in CCS. In fact, most projects to date have been financed with a combination of grant funding, various forms of incentive payments and shareholder equity. This is not to say that project finance debt has not been considered; a number of potential projects in North America and Europe have investigated the project financing potential of CCS, most recently the White Rose oxy-combustion power project through the UK CCS commercialisation competition, but none have reached financial close. Why is this, apart from the obvious lack of large-scale projects reaching a financial investment decision (FID)?

Based on experience from a number of large-scale CCS project developments, a number of common themes pose very significant challenges for bankability, include the following:

Risk allocation: Current large-scale CCS projects, particularly in the power sector, have yet to establish a risk allocation that could be considered bankable by the commercial banking community. The risk profile of capture, transport and storage elements of the CCS chain are very different, with challenging interface issues leading to a level of "project-on-project" risk that has so far proven difficult to sell into the debt market or in some cases to equity providers. Equally, large-scale CCUS projects have also yet to demonstrate a risk allocation that enables commercial debt to be raised on acceptable terms.

Technology: While the underlying technology deployed in CCS has been to a large extent proven at smaller or pilot scale, there is currently a lack of precedent for large scale commercial operation, particularly in an integrated system with power plant or other chemical processes. Where large-scale projects have been developed the perception of the finance community is that these projects have generally been late in construction, significantly over budget and, to a certain extent, problematic to commission and operate on a stable basis. Uncertainty in cost, time and performance (and potentially a "white elephant" risk) lead to the conclusion that financing fully operational rather than construction projects is a better prospect, absent full completion guarantees from strong sponsors.

Commercial structure: Unlike the power and large-scale infrastructure markets, there is currently no established commercial contract structure (template) for CCS. While this is linked to the point on risk allocation to a certain extent, the commercial structure from engineering, procurement and construction (EPC) to offtake also needs to support the project economics on which debt availability and debt sizing are based. The lack of consistent CCS development has hampered the development of "standardised" templates and precedent that the finance community likes to see. If we look at the growth of debt financing for gas-fired power and more recently for offshore wind power, one factor in the rapid expansion of debt liquidity and improving financing terms has been the consistent deal flow of similar projects and the emergence of a common financing approach.

Capital structure: Large-scale CCS projects are expensive and complex. Where debt could potentially be available, gearing (funding from lenders rather than shareholders) is usually limited due to the immaturity of the sector. This is not uncommon in a new sector as demonstrated by offshore wind power where gearing on early transactions was around 50%, but is now moving towards 75% as the sector matures. However, whereas the scale of capital required for early offshore wind projects was relatively modest, CCS projects are significantly larger, meaning that 50% gearing translates into a very large equity cheque, potentially billions. When added to other guarantees on construction, etc., the total liabilities not only stretch available debt market liquidity, but also call into question how equity is funded. This is typically where grant funding can help to close what can be a significant funding gap on early projects.

Policy clarity and consistency: Last but by no means least, policy confidence is essential to securing long-term financing, particularly where project economics may be dependent on grant funding and/or ongoing incentive payments. While there has been some evident financial support for CCS, this has been sporadic and subject to changing economic or political priorities. This was starkly illustrated by the UK Government termination of the CCS Commercialisation Competition immediately prior to final bids from the shortlisted projects. The apparent failure of CCS to make it into the core energy policy in any meaningful way is more damaging to the prospects of financing large-scale projects. This, combined with the cost and complexity of the larger projects, leaves the finance community questioning whether the sector will develop in a financeable form – from a policy perspective the impression is that CCS is in the "too difficult" box. Despite progress, the continually diminishing pipeline of large-scale projects as a result of a succession of projects failing to get to FID reinforces this impression.

Based on experience of evaluating bankability of the CCS sector and a number of specific large-scale projects over the past seven years, there is reason to be optimistic about the ability to raise commercial debt for large-scale CCS if a solution can be found for the not insignificant challenges of any first-of-a-kind technology. The significant work done with financial institutions for the White Rose project supports this optimism and suggests that there are potentially workable/bankable risk allocation and commercial arrangements available if all parties at the table take a pragmatic approach. Cost reduction can only come with experience and volume, and increasing debt liquidity has a part to play in this. However, the essential first step is to translate the recognition of the potential of CCS into a tangible place in national and international clean energy policy.

3.6 Disaggregating CCS – spurring storage and other parts of the CCS value chain

- **A CCS project involves three distinct interdependent components – capture, transport and storage – with different operational, commercial and risk profiles that create obstacles for developers and financiers.**
- **A disaggregated approach, using hubs and clusters for example, could help to foster the development of distinct business models better adapted to the distinct characteristics of the differing capture, transport and storage components.**
- **If CCS deployment targets are to be achieved, a significant amount of financial resources will need to be sourced by energy companies and other CO_2 emitters from bank debt and the capital markets; developing more "bankable" project structures that can attract financing will be needed.**
- **Separating out the CO_2 storage business in particular could reduce financing barriers, especially if the storage activity is recast under a regulatory or business model which uses an annualised payment for actual storage.**
- **A significant amount of CCS investment under the 2DS is likely to be made by state-owned enterprises (SOEs) (including, notably in China, but also elsewhere) which often face incentive frameworks and opportunities to access financing (including from public sector banks) that differ from their private sector counterparts. More analysis is needed to understand how to incentivise these companies. Shenhua Group's project in Inner Mongolia, SaskPower's Boundary Dam, and Statoil's Sleipner are all projects sponsored by SOEs.**

More than 20 years of project experience has highlighted that single full-chain CCS projects can face significant integration challenges which can act as a barrier to reaching operation. Conversely, several of the projects which have been successful have used existing transport and storage options. Exploring models that separate out (i.e., disaggregate) the three components, based notably on common user transport and storage infrastructure alongside incentives for capture, could provide an effective additional way to galvanise CCS deployment.

3.6.1 The complexity of a stand-alone full-chain project model

The component parts of the CCS chain, CO_2 capture, transport and storage, are distinct processes which are challenging to integrate, particularly within a stand-alone project structure (see Figure 3.8). This presents challenges for project sponsors, and even greater concerns for potential financiers. The following points characterise some of the complex issues that have to be managed as part of the equity and debt mobilisation process.

- **Different capabilities involving different market actors and risk cultures**. Different capabilities are required along the CCS chain often with distinct market actors with different strengths and risk cultures. Emitters of CO_2 range from power generation to heavy industry such as steel and cement to gas extraction and processing companies. Transport and storage operators are required to have different competencies and tend to come from the oil and gas market. So, aside from a situation where the emitter is in the petroleum sector, few companies are well-equipped to deal with the three distinct activities inherent in CO_2 capture, transport and storage.
- **Development times**. The three components of the CCS project chain also present different development timing. Long lead times are often needed for storage sites and transportation systems. The risk of finding available storage is a significant hurdle for the development and timing of the capture facility. The initial screening, the characterisation of selected sites and ultimately the permitting can be expensive and time-consuming.
- **Inter-dependence and cross default**[40] is a related area of concern. For example, construction problems at any level of the chain could lead to delays, additional costs and, in the worst case, cross default. Significant construction guarantees at both levels could be required, increasing costs. As noted in a recent review of the United Kingdom's CCS Commercialisation Programme, the likelihood and consequence of cross default by either the capture operator or the transport or storage operator proved to be a major challenge to both debt and equity investors in all parts of the CCS chain (CCSA, 2016).
- **Performance and volume risk**. Investors will be wary of how performance and volume risk is treated. For example, the capture of CO_2 may not be the core competency of the emitter and there will likely be a learning curve for performance. This could reflect on the production volume of CO_2 and the risk of its delivery to the actor managing storage. Conversely, the emitter is also subject to the availability of the storage site.
- **Remuneration**. A complicated remuneration system will need to be agreed between the different actors which will need to incentivise performance and take into account delays and underperformance. For example, the emitter will need a funding mechanism to cover the capture investment and operating costs (including any parasitic load). In addition, the CO_2 emissions-related payment obligation may often fall to the emitter (e.g. under a carbon tax or emissions trading scheme); these payments will need to remunerate investment in the transportation and storage stages of the project.[41]
- **Emitter counterparty credit risk**. As a corollary, the transport and storage functions will be subject to the emitter's credit risk.

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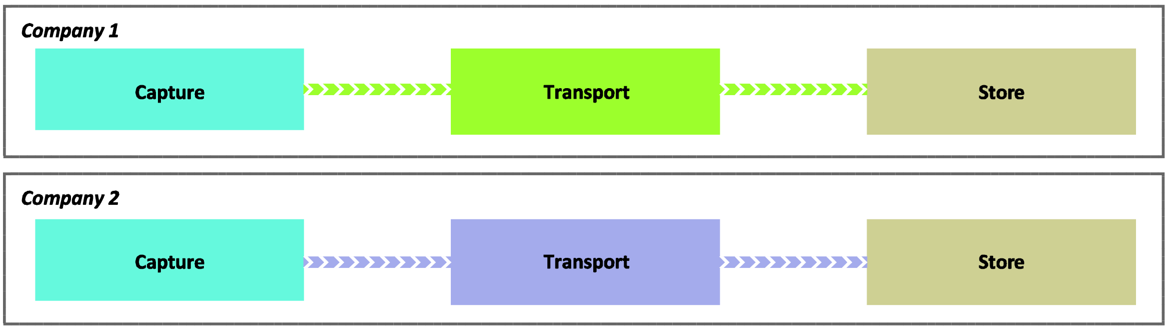
[40] Cross default refers to an entity in the project value chain (for example, the CO_2 storage provider) defaulting under its obligations, which has a subsequent material impact on other entities within the chain.

[41] Where a single company (most likely a petroleum company) assumes responsibility for all three components, these dynamics are not eliminated, but rather become an internal corporate discussion between different business lines.

Figure 3.8 • A stand-alone CCS project model



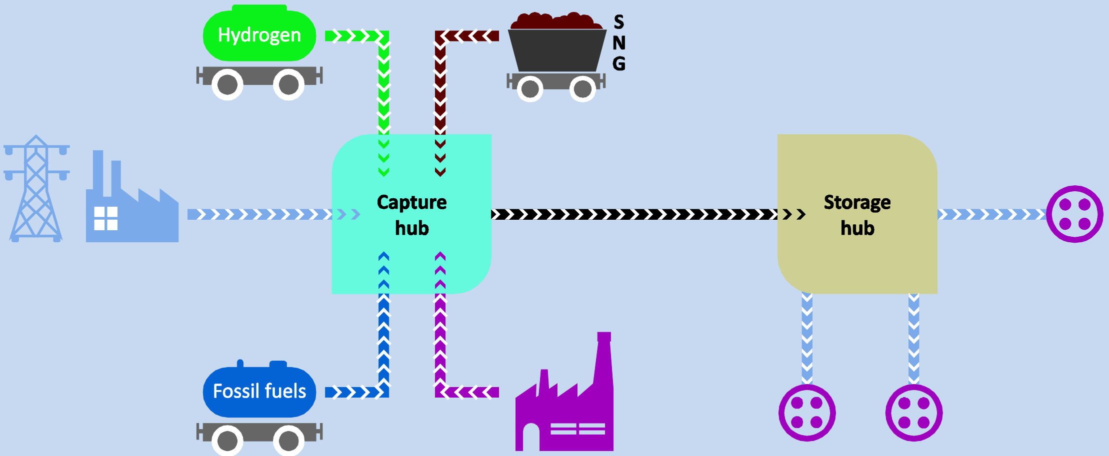
3.6.2 Disaggregated thinking and "hubs and clusters" – a way to simplify?

While intuitively perhaps a "step backwards", disaggregating the capture, transport and storage components of the CCS value chain might help in certain cases to simplify various aspects of CCS project organisation and financing. Establishing transport networks and storage resources which are commercially separate from capture projects could reduce the challenges associated with a stand-alone integrated model and make CCS an easier commercial proposition overall. Sponsors could focus on the distinct part of the CCS value chain where they are expert or which they are otherwise better equipped to fund, to evaluate and to manage the attendant risks. A disaggregated approach would likely see the eventual development of separate storage resources and transport networks which high-emission sources could readily access.

For emitters, a disaggregated approach can allow for several emissions sources, including smaller ones, together to sponsor and access common transport and storage facilities under what has been described as a "hubs and cluster" approach (see Box 3.8). From the perspective of transport and storage infrastructure operators, this approach can enable them to source CO_2 from a variety of capture points. Transport and storage infrastructure networks could be developed by targeting areas with a concentration of emissions sources, rather than relying on a single, large source.

Box 3.8 • Hubs and clusters

CCS hubs and clusters can help to support the development of needed storage and transport infrastructure. Many industrial plants and CCS projects are likely to operate only at a relatively small scale, and hence it may be uneconomic for them to individually invest in the full CCS value chain, particularly in transport and storage infrastructure. However, if several smaller CO_2 sources were combined, it could well become economic to invest in joint collection, transport and storage systems, i.e. hubs and clusters (see figure below). In this clustered approach, several smaller emitters, for example in industry or smaller power plants, share joint infrastructure. A hubs and clusters approach can help reduce costs and risks for any individual emitter and can also enable smaller emitters to financially support needed CCS infrastructure through joint action. In this way, it can make CCS more available to them as a low-emissions tool.



Source: Adapted from GCCSI (2016e), *Global Status of CCS: Special Report, Understanding Industrial CCS Hubs and Clusters.*

The stand-alone integrated project model has been successfully used on several occasions for CCS project development. The disaggregated approach is an additional model which can operate independently of or in tandem with stand-alone projects. There are also possible synergies between the two approaches as a stand-alone project can, for example, be used to anchor the development of a hubs-and-clusters network.

3.6.3 Disaggregating storage while promoting CO_2 capture

A disaggregated approach to storage could help attract potential storage investors and operators by creating a simpler storage-dedicated business model. This model would be based on a focused activity, namely storing CO_2 for which operators would receive payment, either from government or CO_2 emitters. Development of storage as a priority was identified in the 2013 IEA CCS Roadmap as one of the seven key actions for CCS deployment. The knowledge that adequate storage exists is fundamental to investment decisions in CO_2 capture. The development of storage as a business in its own right, with dedicated and independent incentives for storage development, could provide a catalyst for widespread CCS deployment.

A storage-centric approach using a commercial structure for storage services delivery

A variety of approaches could be developed to promote a storage-specific business. Three key elements are: (i) focusing operations on CO_2 injection and storage to help to simplify performance risk management; (ii) establishing a secure, predictable and adequate revenue stream; and (iii) potentially addressing the contingent liability concerns faced by storage operators under various regulatory and business models (see Box 3.9).

Box 3.9 • The "chilling" impact of contingent liabilities associated with future leakage

One of the challenges of mobilising investment in storage sites is the issue of long-term liability for CO_2 retention under many regulatory frameworks. These frameworks are typified by the following legal/commercial structure:

- The CO_2 emitter avoids a payment (for example, under a carbon tax or an emissions trading scheme) by capturing and storing the CO_2, thereby preventing it from entering the atmosphere. While the financial benefit is typically obtained in the first year (namely the year in which the CO_2 benefit is generated, by not emitting it into the atmosphere), it is contingent on the CO_2 remaining stored.
- In the unlikely event that any of the CO_2 is released later as a result of seepage or leakage, then in addition to the adverse impact on climate change mitigation efforts at a national and global level (referred to in this report as "climate-related leakage risk" – see discussion above in Section 1.5.3), the emitter or storage company (depending on the allocation of responsibility) faces a financial liability since it was not able to fully perform the storage upon which the initial financial benefit was predicated.

This contingent financial liability may often need to be recognised from the very beginning. It presents several "chilling" aspects, notably because the contingent liability extends decades into the future, and also because the financial penalty associated with future leakage is difficult to predict and may be significantly higher in the future if carbon prices increase. This presents a barrier to attracting investment into the storage business and to generating financing.

One possible approach is to develop a model based on a commercial storage delivery services and regulatory structure akin to electricity delivery under a power purchase agreement. Under this model, the storage providers are paid on a yearly basis for storage provided (similar to payments under a power purchase agreement), rather than being paid in advance with an outstanding liability in the case of leakage. One key aspect of the commercial structure is that rather than a liability-based arrangement, the storage company would only be paid each year for each unit of CO_2 actually stored.[42] This structure could be further enhanced by removing the delivery risk faced by the storage provider by providing it with a "ship-or-pay" type contract based on available capacity. Under this contract structure, the storage operator receives its annual payments provided it is able to store the CO_2, irrespective of delivery failure as a result of either emitter or transporter action; the ship-or-pay option would likely increase the bankability of the storage investment (see Box 3.10).

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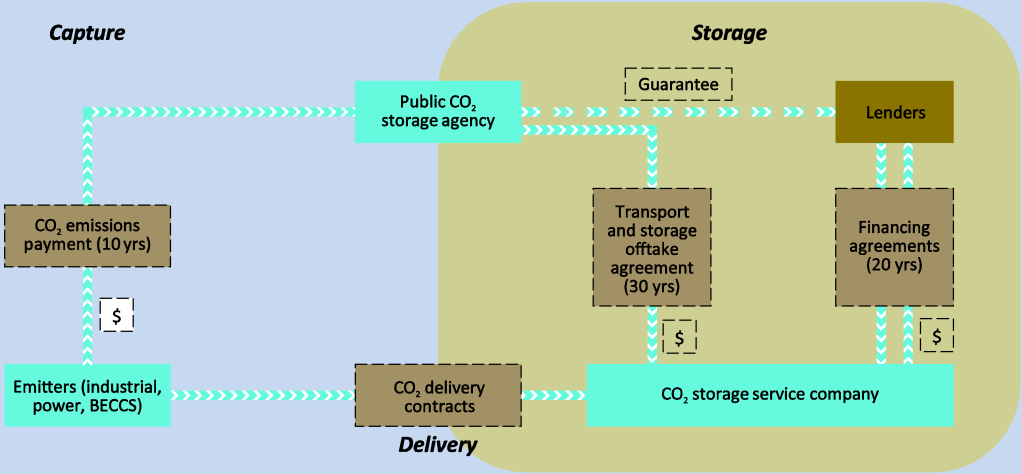
[42] If it is shown that (certain) volumes of CO_2 are not retained in the reservoir, the storage operator would forego income (in the same manner that an independent power producer is not paid if it fails to make the capacity of kWh available in a particular year).

Box 3.10 • A possible storage service delivery model

One among many possible alternative structures for a storage delivery model is as follows:

1. "Upstream", the emitter would pay the PSA as it emits (for example, under a 10-year contract). The payments would cover storage costs (with the emitter bearing capture costs, potentially with the support of the government during an initial period). The emitter would enter into a CO_2 delivery agreement with the storage operator.
2. The PSA, or alternatively the emitter, would contract for transport services; in the former case, the emitter's payments to the PSA would also cover transport costs (in the diagram below, the transporter has not been depicted for simplicity).
3. The PSA would enter into a long-term storage contract with a private sector storage service provider, the aim of which would be to develop, finance, maintain and operate the storage site. Under the terms of the contract (for example, 30 to 40 years), the storage provider would be paid an annual unit fee for each tonne of CO_2 stored in a given year (or for which capacity was available, but unused because it did not receive the CO_2 because of emitter or transporter failure to perform). If certain volumes of CO_2 stored in the reservoir leak in a subsequent year, the storage operator would forego income in that subsequent year.
4. Given the creditworthiness of the PSA, the storage service company should be able to raise financing from lenders (for example, potentially up to 20 years) provided that it can provide comfort on its performance risk, namely its ability to keep a sufficient amount of the delivered CO_2 stored.



The government could play an important catalytic role under this structure by creating a national public agency whose role is to promote the creation of CO_2 storage sites. This public storage agency (PSA) could, for example, be an intermediary between emitters and storage companies, work to promote the expansion of storage sites and service provision, or provide the "ship-or-pay" payments to the storage company (potentially funded by payments from the emitter).[43] Moreover, consistent with the principle of allocating risks to the party best able to manage them, the government might also bear the mitigation responsibility to take measures to compensate for any actual CO_2 leakages (the "climate-related leakage risk" presented in Section 1.5 for which it

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[43] Intermediating payments from the emitter to the storage company could provide a cash flow benefit to the government that receives emission fees during the shorter emissions period and only pays for the storage payments over a longer period. See Box 3.10.

has already been paid by the emitter) given that it has access to a variety of compensation tools beyond the individual project (for example, requiring increased use of renewables).

The storage-centric approach: Easier to finance?

The above-described storage delivery service model could enable the financing of storage sites by creating a known secure cash flow (from the PSA) and building confidence in long-term CCS policy and strategy. At the same time it would significantly reduce the storage entity's exposure to the emitter's credit and performance risks.

- **Improving bankability.** The development of storage would be promoted by a single government entity (under a form of public-private partnership or a concession-type agreement using a "ship or pay" commercial structure) that provides the storage company – and by extension potential financiers – with comfort of payment upon its performance, whether or not the emitter or transporter breaches their obligations. These mechanisms are well known to the financial community in power or infrastructure sector concession agreements. The strong presence of the government and its rating would help improve financing terms and conditions.
- **Confidence in long-term CCS policy.** Investors are highly sensitive to the stability of policy. Significant long-term government support for storage through the storage offtake agreement would send the right signals to market participants of the role of CCS in a low-carbon environment.
- **Reducing credit, performance, volume and cross-default risk.** The storage provider would be insulated from the emitter's credit, performance, volume and cross-default risk as its remuneration would be based on a service-type fee related to the provision of a storage service. This approach should offer a more acceptable risk profile for the storage provider and should be more interesting to financiers.
- **Long-term risk of leakage still needs to be addressed.** Regardless of a funding model based on storage performance, the long-term risks associated with leakage are inherent to CCS and will still need to be addressed. While the government arguably is better placed to assume "climate-related leakage risk" (with the operator facing lost revenues), the storage operator would need to retain responsibility for local environmental impacts, as well as health and safety (see discussion in Section 1.5.3). After closure of the storage operation, a mechanism for a handover to government for long-term stewardship would be required in any case.

How the storage-centric approach can also support investment in capture

There are a number of aspects to developing a storage-centric approach for CCS that could support investment in CO_2 capture. These include the following.

- **Confidence in the availability of storage.** One of the main concerns of investors and financiers in CO_2 capture is the availability of storage. It will be extremely challenging for any investment decision in capture to be made until the availability of storage has been confirmed. The provision of strategic storage sites in advance addresses this problem and therefore can help to remove one of the most important barriers to CCS development. In addition to incentives to develop CO_2 capture, having a guaranteed CO_2 storage solution at a known price provides a critical cost element for capture projects seeking financing.
- **Removing physical storage risk.** Under the proposed structure, the emitter would not be taking any physical storage risk (which passes to the storage provider and the government). The emitter's risk is therefore significantly reduced to its own operating and

availability risks. As such, a financial investment decision in a capture plant can be made in the knowledge that the storage risk has been essentially removed. Increasing prospects for capture investment in turn will support investment in transport and storage.

- **Reducing storage counterparty credit risk.** As described above, separating storage from capture and transport under the coverage of the PSA will significantly reduce the exposure of the storage operator to the emitter's and transporter's credit risk. At the same time, this also helps to reduce the financial riskiness of the storage activities, thereby reducing the storage company counterparty risk faced by emitters and transporters.
- **Diversifying risk through market expansion.** Moreover, using the disaggregated hubs and clusters approach increases the number of market actors in the project on the storage, transport and capture side. This can serve to diversify the credit and performance risks faced by all parties. Although a stand-alone integrated project with a creditworthy company managing each of the capture, transport and storage components, or even a single company managing the entire chain, can potentially provide a very robust credit and performance structure (for example, in the case of an established petroleum company), expanding the market to include more actors will likely help to increase investment and financing in CCS, in particular in the industry and power sectors.

3.6.4 State owned enterprises: Special opportunities and challenges

To date, state-owned enterprises (SOEs) have been major players in the execution of CCS projects. This includes SOEs that operate in different businesses and in a wide range of commercial and regulatory contexts, including largely liberalised market conditions (such as Norway's Statoil), as well as SOEs that operate in more regulated and centrally controlled market environments (such as China's power companies, the China Huaneng Group and the Shenhua Group). Even the recent Boundary Dam project, which is notable in many ways as the first CCS project at scale in the power sector, is arguably also noteworthy because it is owned and operated by SaskPower, a Crown Corporation owned by the Province of Saskatchewan. As described in Section 1.3.5, almost one-third of the projects in operation or under construction are owned, or majority owned, by state-owned enterprises, and 12 of the 18 large-scale projects in earlier stages of development are led by SOEs.

Many of the discussions about CCS business models, and also about appropriate regulatory frameworks, are based on the involvement of companies responding to traditional private sector incentives. However, many of the required CCS investments in the 2DS will likely need to be made by SOEs which often face a different incentives framework. For example, under the 2DS, 250 GW of coal in China is equipped with CCS in 2050; about 95% of the coal-fired power plants in China belong to companies that are owned or controlled by the government (including, as is the case for Boundary Dam, owned by a provincial government).

Incentivising SOEs can, at times, involve different levers than for traditional private sector companies. Governments can wield their public shareholder power through various means, including shareholder directives, targeted financial support in their capacity as shareholder, informal and formal discussions with SOE management, and exercising their discretion in the selection of management (see Box 3.11).

Moreover, SOEs are often financed through other public sector banks under targeted terms and conditions. This is the case, for example, in China (Hervé-Mignucci et al., 2015). National development banks in many countries today play, and are expected to continue to play, an important role in financing low-carbon investments (for example Brazil's *Banco nacional do desenvolvimento*); while these financiers often undertake a traditional bankability credit review, they can at times differ from one made by a private commercial lender. For example, public sector performance risks might be viewed differently by a national public bank than by a foreign lender. The ability of potential SOE project sponsors to access public development bank financing for their CCS project presents a different funding avenue with its own dynamics. Accordingly, an SOE might need a project structuring and risk mitigation approach and funding mobilisation strategy that differs from those used by a private sector sponsor mobilising.

Box 3.11 • Promoting SOE action in the CCS effort

Governments, as sole or primary shareholders of SOEs, can control or otherwise influence decisions taken by these companies to support of CCS deployment through a number of direct and indirect channels:

- Adopting and implementing clear, consistent and predictable policy directives to influence investments, notably in CCS or, indirectly, by restricting the carbon intensity of generation. These policies can be supported with informal dialogue to reinforce policy messages.
- Exercising authority to appoint (and change) senior management, which can provide an important means to influence SOE action (balanced with the need to avoid excessive political interference).
- Leveraging cadre evaluation systems to encourage actions by mid-level management and other operations parts of the company.
- Influencing investment patterns in specific energy technologies as a supplier/facilitator of funding for SOEs (including funding through state-owned financial institutions).
- Providing both formal and informal signals to SOEs, which are more likely than private enterprises to follow government signalling because of their shareholding structure (e.g. encouraging greater SOE engagement in CCS technological development).

See the discussion on public shareholder measures to influence SOE action in Chapter 6 of *Energy, Climate Change and Environment: 2016 Insights* (IEA, 2016e)

3.6.5 Disaggregating CCS: An important option

Developing a policy framework and business approach based on a disaggregation of capture, transport and storage can offer new ways to drive the deployment of CCS further in addition to the current single stand-alone integrated project approach. Separating out the three components will allow for more targeted and effective policy and regulation, and can encourage greater investment across the three distinct parts of the CCS value chain, particularly CO_2 storage.

A storage-centric approach presented above that relies on a “ship or pay” commercial structure from a PSA could provide a bankable structure to attract financing for the development of storage. In addition, the provision of targeted storage infrastructure solutions would provide assurance to all investors in capture that appropriate storage is available at a known price. A storage-centric approach could accelerate the deployment of CCS and would be particularly relevant to the promotion of CCS in industry, which is often highly dependent on the availability of third-party transport and storage infrastructure.

The requirements for mobilising investment and financing for CCS projects sponsored by SOEs may differ. Further analysis is needed to determine what are the “right” conditions to promote CCS investments by SOEs, in China and other countries.

4 Conclusions

CCS has moved forward significantly over the past 20 years, with important advances in technology and project experience. The publication outlines some key lessons over this time:

- Significant progress has been made but policy support commensurate with the potential role of CCS in meeting climate goals is needed.
- Long-term commitment and stability in policy frameworks is critical.
- Early opportunities for CCS deployment exist, but must be cultivated. Commercial CCS projects are already operating where a combination of economic, regional and project-specific factors as well as government policies have been aligned.
- There is no CCS without the "S" and investment in CO_2 storage must be a priority. Access to geological storage is potentially the most significant impediment to widespread CCS deployment.
- The role of CCS goes well beyond a "clean coal technology". The experience of the last 20 years has highlighted the diversity of CCS applications and particularly its essential role in addressing emissions from industrial processes.
- The availability of CCS in the future depends on investment today. An expanded project pipeline is needed to allow for more new projects to become operational in 2020 and beyond.
- Community engagement is essential. Successful deployment of CCS will involve improved efforts to ensure that local communities and the general public understand the technology.

The challenges facing CCS are well known and must now be addressed with a renewed sense of urgency if global climate goals are to be met. Targeted policies which provide a financial incentive for investment will be essential in the near term. New approaches and thinking can also help to drive CCS forward.

- Governments and industry should exploit CCS retrofitting opportunities. CCS has the unique capacity to reverse the "lock-in" of emissions from existing infrastructure.
- Governments should instigate a move from EOR to EOR+. With relatively small adjustments, enhanced oil recovery can generate net emissions reductions and yield verifiable storage of CO_2.
- CCS can significantly reduce the CO_2 footprint of primary building and other products such as steel, cement and chemicals. Governments should take steps to create markets for clean products with a low CO_2 content.
- Early deployment of BECCS is needed to promote better understanding of the potential for "negative emissions" in the future, recognising that many climate models rely on BECCS to achieve targets of 2°C or below.
- Differentiated business models for CO_2 capture, transport and storage could address some of the challenges faced by integrated projects. Industry and governments should explore novel ways of financing CCS projects, for example through a storage-centric model.

CCS will be essential in delivering the ambitions of the Paris Agreement and limiting future temperature increases to well below 2°C. After 20 years of progress, the technology has been proven in many applications and should now form an important and integral part of global energy and climate strategies. The pace and intensity with which governments act to strengthen policies to meet the Paris Agreement targets will play a critical role in determining what the next 20 years of CCS will deliver.

Further reading

- ADB (Asian Development Bank) (2015), *Roadmap for CCS Demonstration and Deployment for* the People's Republic of China, Asian Development Bank, Manila.
- Bennett, S.J., D.J. Schroeder and S.T. McCoy (2014), "Towards a framework for discussing and assessing CO_2 utilisation in a climate context", *Energy Procedia*, Vol. 63, Elsevier, Amsterdam, pp. 7976-7992.
- British Geological Survey (2008), *Best Practice for the Storage of CO_2 in Saline Aquifers,* British Geological Survey, Nottingham.
- CCSA (Carbon Capture and Storage Association) (2016), *Lessons and Evidence Derived from the UK CCS Programmes, 2008 – 2015*, Carbon Capture and Storage Association, London.
- Cook, P. (2012), *Clean Energy, Climate and Carbon*, Commonwealth Scientific and Industrial Research Organisation Publishing, Collingwood.
- Deloitte (2015), *The Future of the Global Power Sector – Preparing for Emerging Opportunities and Threats*, Deloitte Global Services Limited, London.
- Gale et al. (eds) (2015), Special Issue commemorating the 10th year anniversary of the publication of the Intergovernmental Panel on Climate Change Special Report on CO_2 Capture and Storage, *International Journal of Greenhouse Gas Control,* Volume 40, September 2015, Elsevier, Amsterdam.
- Global CCS Institute (GCCSI) (2016), *Global Status of CCS 2016*, Global CCS Institute, Melbourne.
- GCCSI and Société Générale (2014), *Targeted report: financing large scale integrated CCS demonstration projects*, Global CCS Institute, Melbourne.
- Herzog, H. (2016), *Lessons Learned from CCS Demonstration and Large Pilot Projects; An MIT Energy Initiative Working Paper*, May 2016, Massachusetts Institute of Technology, Cambridge, Mass., https://sequestration.mit.edu/bibliography/CCS%20Demos.pdf
- Hitchon, B. (2012), *Best Practices for Validating CO_2 Geological Storage: Observations and Guidance from the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project*, Geoscience Publishing, Alberta, www.geosciencepublishing.ca/.
- IEA (International Energy Agency) (2013), *Technology Roadmap: Carbon Capture and Storage*, OECD/IEA, Paris.
- IEA (2008), *Energy Technology Analysis: CO_2 Capture and Storage A Key Carbon Abatement Option*, OECD/IEA, Paris.
- IEAGHG (IEA Greenhouse Gas R&D Programme) (2015), *Integrated Carbon Capture and Storage Project at Saskpower's Boundary Dam Power Station*, IEAGHG, Cheltenham.
- IEAGHG (2011), *Potential for Biomass and Carbon Dioxide Capture and Storage*, IEAGHG, Cheltenham.
- IEAGHG and Petroleum Research Technology Centre and (2004), *IEAGHG Weyburn CO_2 Monitoring and Storage Project – Summary Report 2000-2004*, IEAGHG, Cheltenham.

- IPCC (Intergovernmental Panel on Climate Change) (2005), *Special Report on Carbon Dioxide Capture and Storage*, IPCC, Cambridge University Press, New York.
- KAPSARC (King Abdullah Petroleum Studies and Research Center) (2012), *Carbon Capture and Storage Technologies, Policies, Economics and Implementation*, King Abdullah Petroleum Studies, ARC, CRC Press, Meppel.
- Granger Morgan, M. and S.T. McCoy (2012), *Carbon Capture and Sequestration, Removing the Legal and Regulatory Barriers*, RFF Press, New York.
- NETL (National Energy Technology Laboratory) (2014), *Carbon Storage – Technology Program*, National Energy Technology Laboratory, United States Department of Energy.
- Pale Blue Dot and Axis Well Technology (2016), *Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource: A Summary of Results from the Strategic UK* CO_2 *Storage Appraisal Project*, www.eti.co.uk/wp-content/uploads/2016/04/D16-10113ETIS-WP6-Report-Publishable-Summary.pdf.
- Shell (2015), *Peterhead CCS Project - FEED Lessons Learned Report*, Shell UK Limited, London.

References

BNEF (Bloomberg New Energy Finance) (2016), Clean Energy Investment Trends, BNEF, London

Caldecott, B., G. Lomax and M. Workman (2015), *Stranded Carbon Assets and Negative Emissions Technologies* Working Paper*,* Stranded Assets Programme, University of Oxford, www.smithschool.ox.ac.uk/research-programmes/stranded-assets/Stranded%20Carbon%20Assets%20and%20NETs%20-%2006.02.15.pdf.

Carbon Brief (2016), "Analysis: Only five years left before 1.5°C budget is blown", www.carbonbrief.org/analysis-only-five-years-left-before-one-point-five-c-budget-is-blown (accessed 12 September 2016).

CCSA (Carbon Capture and Storage Association) (2016), *Lessons and evidence derived from the UK CCS Programmes, 2008 – 2015*, Carbon Capture and Storage Association, London.

CO_2 Solutions (2016), "CO_2 Solutions Announces Commercial Agreement for Carbon Capture Unit", Press Release, 16 August 2016, www.co2solutions.com/uploads/file/635e296dac35bd0cf7ebc7dcbea429164b1f835f.pdf.

Dixon, T., S.T. McCoy and I. Havercroft (2015), "Legal and Regulatory Developments on CCS", *International Journal of Greenhouse Gas Control,* Vol. 40, Elsevier, Amsterdam, pp. 431-448.

Dooley, J. J., R. T. Dahowski and C.L. Davidson (2010), *CO_2-driven Enhanced Oil Recovery as a Stepping Stone to What?*, Pacific Northwest National Laboratory, United States Department of Energy.

European Commission (2011), *Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide Guidance Document 3, Criteria for Transfer of Responsibility to the Competent Authority*, European Commission, Brussels.

Feenstra, C.F.J., T. Mikunda and S. Brunsting (2010), *What happened in Barendrecht? Case study on the planned onshore carbon dioxide storage in Barendrecht, the Netherlands*, Energy Research Centre of the Netherlands, www.globalccsinstitute.com/sites/www.globalccsinstitute.com/files/publications/8172/barendrecht-ccs-project-case-study.pdf.

Gale, J. et al. (2015), "Special issue commemorating the 10th year anniversary of the publication of the Intergovernmental Panel on Climate Change Special Report on CO_2 Capture and Storage", *International Journal of Greenhouse Gas Control,* Vol. 40, Elsevier, Amsterdam, pages 1-458.

Garnett, A.J, C.R Greig, and M. Oettinger (2012), *ZeroGen IGCC with CCS: A Case History*, University of Queensland, Brisbane, https://energy.uq.edu.au/files/1084/ZeroGen.pdf.

GCCSI (Global CCS Institute) (2016a), "Enid Fertilizer CO_2-EOR Project", www.globalccsinstitute.com/projects/enid-fertilizer-co2-eor-project (accessed 25 August 2016).

GCCSI (2016b), "Snøhvit CO_2 Storage Project", www.globalccsinstitute.com/projects/snøhvit-co2-storage-project (accessed 25 August 2016).

GCCSI (2016c), "Notable projects database", www.globalccsinstitute.com/projects/notable-projects (accessed 1 October 2016).

GCCSI (2016d), *Global storage portfolio: A global assessment of the geological CO_2 storage resource potential*, Global CCS Institute, Melbourne.

GCCSI (2016e), *Global Status of CCS: Special Report, Understanding Industrial CCS Hubs and Clusters*, Global CCS Institute, Melbourne.

GCCSI and Société Générale (2014), *Targeted report: financing large scale integrated CCS demonstration projects*, Global CCS Institute, Melbourne.

GCCSI (2010), *The Global Status of CCS 2010*, Global CCS Institute, Canberra.

Greig, C. et al. (2016), *Energy Security and Prosperity in Australia – A Roadmap for CCS*, University of Queensland, Brisbane.

Hervé-Mignucci, M, et al.(2015) "Slowing the Growth of Coal Power in China: the role of Finance in State-Owned Enterprises", Climate Policy Initiative, December 2015.

Herzog, H. (2016), *Lessons Learned from CCS Demonstration and Large Pilot Projects; An MIT Energy Initiative Working Paper*, Massachusetts Institute of Technology, Cambridge, Mass.

Idem, R. et al. (2015), "Practical experience in post-combustion CO_2 capture using reactive solvents in large pilot and demonstration plants", *International Journal of Greenhouse Gas Control*, Vol. 40, Elsevier, Amsterdam, pp. 6-25.

IEA (International Energy Agency) (2016a) *Reducing Emissions in Fossil-Fired Generation - Indonesia, Malaysia and Viet Nam*, OECD/IEA, Paris.

IEA (2016b), *Energy Technology Perspectives 2016*, OECD/IEA, Paris.

IEA (2016c), *Ready for CCS retrofit: The potential for equipping China's existing coal fleet with carbon capture and storage*, OECD/IEA, Paris.

IEA (2016d), "Tracking Clean Energy Progress" in *Energy Technology Perspectives 2016*, OECD/IEA, Paris.

IEA (2016e), *Energy, Climate Change and Environment, 2016 Insights*, OECD/IEA, Paris.

IEA (2015a), *Energy Technology Perspectives 2015*, OECD/IEA, Paris.

IEA (2015b), *World Energy Outlook 2015*, OECD/IEA, Paris.

IEA (2015c), *World Energy Outlook Special Report: Energy and Climate Change*, OECD/IEA, Paris.

IEA (2015d), *Storing CO_2 through Enhanced Oil Recovery*, OECD/IEA, Paris.

IEA (2014a), *CCS 2014 – What lies in store for CCS?* OECD/IEA, Paris.

IEA (2014b), *Energy, Climate Change and Environment, 2014 Insights*, OECD/IEA, Paris.

IEA (2014c), *World Energy Investment Outlook Special Report*, OECD/IEA, Paris.

IEA (2013), *Technology Roadmap: Carbon capture and storage*, OECD/IEA, Paris.

IEA (2012a), *Energy Technology Perspectives 2012*, OECD/IEA, Paris

IEA (2012b), *Technology Roadmap: Bioenergy for Heat and Power*, OECD/IEA, Paris.

IEA (2011), *World Energy Outlook 2011*, OECD/IEA, Paris.

IEA/Carbon Sequestration Leadership Forum (CSLF) (2010), *IEA/CSLF Report to the Muskoka 2010 G8 Summit, Progress and Next Steps*, OECD/IEA, Paris.

IEAGHG (IEA Greenhouse Gas R&D Programme) (2015), *Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam* Power Station, 2015/06, IEAGHG, Cheltenham.

IEAGHG (2013a), *CO_2 Pipeline Infrastructure*, 2013/18, IEAGHG, Cheltenham.

IEAGHG (2013b), *The Process of Developing a CO_2 Test Injection: Experience To Date And Best Practice*, 2013/13, IEAGHG, Cheltenham.

IEAGHG (2013c), Deployment of CCS in the cement industry, 2013/19, IEAGHG, Cheltenham.

IEAGHG (2011a), *Global Storage Resources Gap Analysis for Policy Makers*, 2011/10, IEAGHG, Cheltenham.

IEAGHG (2011b), *Potential for Biomass and Carbon Dioxide Capture and Storage*, 2011/06, IEAGHG, Cheltenham.

IEAGHG (2008), *CO_2 Capture in the Cement Industry*, 2008/3, IEAGHG, Cheltenham.

IPCC (Intergovernmental Panel on Climate Change) (2014a), *Climate Change 2014: Mitigation of Climate Change Summary for Policymakers: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* IPCC, Cambridge University Press, Cambridge, United Kingdom and New York.

IPCC (2014b), Assessing Transformation Pathways, Chapter 6, in *Climate Change 2014: Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* IPCC, Cambridge University Press, Cambridge, United Kingdom and New York.

IPCC (2005), *Special Report on Carbon Dioxide Capture and Storage*, IPCC, Cambridge University Press, New York.

IPCC (1995), *IPCC Second Assessment, Climate Change 1995*, IPCC, Cambridge University Press, Cambridge, United Kingdom and New York.

Isley, S.C. et al. (2016), "Online purchasing creates opportunities to lower the life cycle carbon footprints of consumer products*", Proceedings of the National Academy of Sciences of the United States of America,* www.pnas.org/content/113/35/9780.abstract.

Jansen, D. et al. (2015), "Pre-combustion CO_2 capture"*, International Journal of Greenhouse Gas Control*, Vol. 40, Elsevier, Amsterdam, pp. 167-187.

Japan CCS Co. (2016), "Progress of the Tamakomai CCS Demonstration Project", Presentation to the combined meeting of the IEAGHG Modelling and Monitoring Networks, 7 July 2016.

Jones, D.G. et al. (2015), "Developments since 2005 in understanding potential environmental impacts of CO_2 leakage from geological storage", *International Journal of Greenhouse Gas Control*, Vol. 40, Elsevier, Amsterdam, pp. 350–377.

Kemper, J. (2015) "Biomass and carbon dioxide capture and storage: A review", *International Journal of Greenhouse Gas Control*, Vol. 40, Elsevier, Amsterdam, pp. 401-430.

Minx, J.C., and S. Fuss (2016), "These charts show what the Paris climate agreement is up against", *The World Post*, 15 August 2016.

MIT (Massachusetts Institute of Technology) (2016), "Illinois Industrial Carbon Capture and Storage Fact Sheet: Carbon Dioxide Capture and Storage Project", MIT, Cambridge, MA, https://sequestration.mit.edu/tools/projects/illinois_industrial_ccs.html (accessed 12 September 2016).

National Audit Office (United Kingdom) (2016), *Briefing for the House of Commons Environmental Audit Committee, Sustainability in the spending review*, July 2016, London.

NETL (National Energy Technology Laboratory) (2015), *Cost and performance baseline for fossil energy plants supplement: sensitivity to CO_2 capture rate in coal-fired power plants*, DOE/NETL-2015/1720, NNETL, Pittsburgh.

NRG (2014), WA Parish Carbon Capture and Enhanced Oil Recovery Project. Presentation at Clean Coal Day in Japan 2014 International Symposium, 9 September 2014 www.jcoal.or.jp/coaldb/shiryo/material/2_Session%202_speech%202_US%20NRG.pdf (accessed 3 October 2016)

Parker, M.E. et al. (2011), "CO_2 management at ExxonMobil's LaBarge field, Wyoming, USA", 10th International Conference on Greenhouse Gas Control Technologies, *Energy Procedia*, Vol 4, pp. 5455-5470.

Platts (2016), World Electric Power Plant database, April 2016.

Ringrose, P. S. et al. (2013), "The In Salah CO_2 Storage Project: Lessons Learned and Knowledge Transfer", Proceedings of the 11th International Conference on Greenhouse Gas Control Technologies, *Energy Procedia*, Vol. 37, pp. 6226-6236.

Rochelle, G.T. (2009), "Amine Scrubbing for CO_2 Capture", *Science*, Vol. 325, Issue 5948, pp. 1652-1654.

Rogelj, J. et al. (2015), "Energy system transformations for limiting end-of-century warming to below 1.5°C", *Nature Climate Change*, published online 21 May 2015

Rubin, E. S., J. E Davison and Howard J. Herzog (2015), "The cost of CO_2 capture and storage", *International Journal of Greenhouse Gas Control,* Vol. 40, Elsevier, Amsterdam, pp. 378–400.

SaskPower (2016a), "Boundary Dam Carbon Capture Project",www.saskpowerccs.com/ccs-projects/boundary-dam-carbon-capture-project (accessed on 24 August 2016).

SaskPower (2016b), "BD3 Status Update: July 2016", www.saskpower.com/about-us/blog/bd3-status-update-july-2016/ (accessed 8 September 2016).

SBC Energy Institute (2016), Low Carbon Energy Technologies Fact Book Update: *Carbon Capture and Storage at a Crossroads, May 2016*, SBC Energy Institute, The Hague.

Shell Canada (2016a), "Quest carbon capture and storage project reaches significant one-year milestone", www.shell.ca/can/en_ca/media/news-and-media-releases/news-releases-2016/shell_s-quest-carbon-capture-and-storage-project-reaches-signifi.html (accessed 5 October 2016)

Shell Canada (2016b), "Quest Carbon Capture and Storage Project", www.shell.ca/can/en_ca/about-us/projects-and-sites/quest-carbon-capture-and-storage-project.html (accessed 15 September 2016).

Stanger, R. et al. (2015), "Oxyfuel combustion for CO_2 capture in power plants", *International Journal of Greenhouse Gas Control* Vol. 40, Elsevier, Amsterdam, pp. 55-125.

Statoil (2016), "Sleipner West", www.statoil.com/en/TechnologyInnovation/NewEnergy/Co2CaptureStorage/Pages/SleipnerVest.aspx (accessed on 24 August 2016).

Urbina, I. (2016), "Piles of dirty secrets behind a modern 'clean coal' project", *New York Times*, 5 July 2016 www.nytimes.com/2016/07/05/science/kemper-coal-mississippi.html?_r=0.

ZEP (European Technology Platform for Zero Emission Fossil Fuel Power Plants) and EBTP (European Biofuels Technology Platform) (2012), *Biomass with CO_2 Capture and Storage: The way forward for Europe*, ZEP/EBTP, Brussels.

Zhai, H., Y. Ou and E. Rubin (2015) "Opportunities for Decarbonizing Existing U.S. Coal-Fired Power Plants via CO_2 Capture, Utilization and Storage", *Environmental Science and Technology*, Vol. 49, American Chemical Society, Washington, DC, pp. 7571-7579.

Acronyms, abbreviations and units of measure

Acronyms and abbreviations

2DS	2-Degree Scenario (IEA)
4DS	4-Degree Scenario (IEA)
6DS	6-Degree Scenario (IEA)
ADB	Asian Development Bank
AR4	IPCC Fourth Assessment report
AR5	IPCC Fifth Assessment Report
ARRA	American Recovery and Reinvestment Act
AUD	Australian Dollar
BECCS	bioenergy-CCS
BF-BOF	blast furnace plus basic oxygen furnace
CAD	Canadian dollar
CCGT	combined-cycle gas turbine
CCOP	Coordinating Committee for Geoscience Programmes in East & Southeast Asia
CCS	carbon capture and storage
CCSA	Carbon Capture and Storage Association (UK)
CCUS	carbon capture, use and storage
CDM	Clean Development Mechanism
CHP	combined heat and power
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
CO2CRC	Cooperative Research Centre for Greenhouse Gas Technologies (Australia)
CO_2-EOR	carbon dioxide for enhanced oil recovery
COP	Conference of the Parties (UNFCCC)
CSLF	Carbon Sequestration Leadership Forum
DAC	direct air capture
DRI	direct reduced iron
EAF	electric arc furnaces
EOR	enhanced oil recovery
ETP	*Energy Technology Perspectives* (IEA)
EU	European Union
FEED	front-end engineering and design
FID	final investment decision
FOAK	first-of-a-kind
GCCSI	Global CCS Institute
GHG	greenhouse gas
H_2	hydrogen
H_2O	water
IBDP	Illinois Basin Decatur Project
IICCSP	Illinois Industrial CCS Project
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
LCOE	levelised cost of electricity
LNG	liquefied natural gas
MEA	monoethanolamine

MHI	Mitsubishi Heavy Industries
MMV	measurement, monitoring and verification
NACCSA	North American Carbon Capture & Storage Association
NCCC	National Carbon Capture Centre (US)
NDC	Nationally Determined Contribution
NETL	National Energy Technology Laboratory (US)
OECD	Organisation for Economic Co-operation and Development
PCC	post-combustion capture
PV	photovoltaic
RCSP	Regional Carbon Sequestration Partnership (US)
R&D	research and development
SOE	state-owned enterprises
SRCCS	Special Report on CCS (IPCC)
TCM	Technology Centre Mongstad
TCP	Technology Collaboration Programme (IEA)
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USD	United States dollar
WEO	*World Energy Outlook* (IEA)
ZEP	European Technology Platform for Zero Emission Fossil Fuel Power Plants

Units of measure

°C	degrees centigrade
/d	per day
EJ	exajoule
g	gramme
gCO_2	grammes of CO_2
GJ	gigajoule
Gt	gigatonne
$GtCO_2$	gigatonnes of carbon dioxide
GW	gigawatt
kWh	kilowatt-hour
Mt	million tonnes (megatonne)
$MtCO_2$	million tonnes (megatonne) of carbon dioxide
Mtpa	million tonnes (megatonne) per annum
MW	megawatt
MWh	megawatt-hour
PM	particulate matter
ppm	parts per million
t	tonne
TWh	terawatt-hour
/yr	per year

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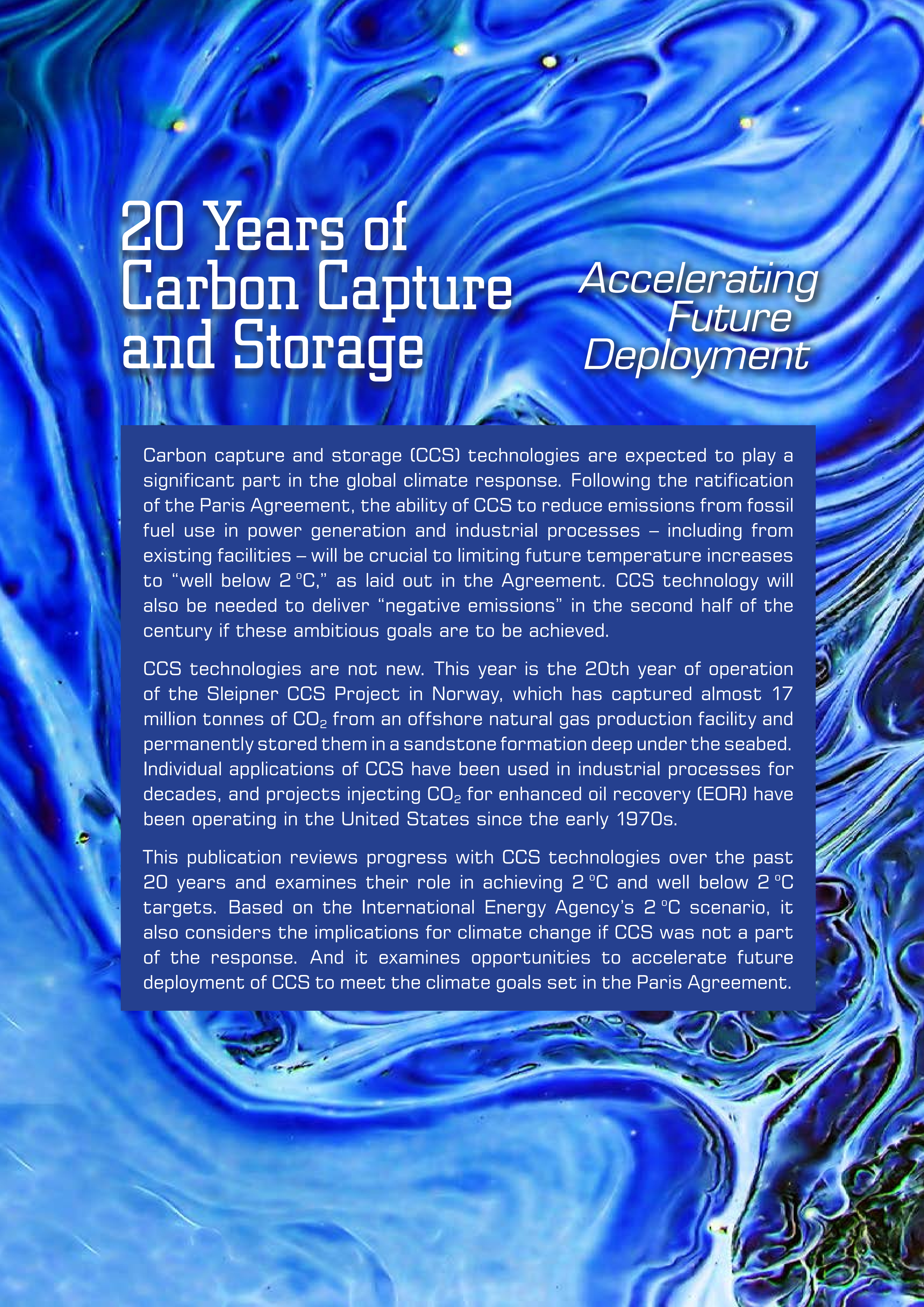

20 Years of Carbon Capture and Storage

Accelerating Future Deployment

Carbon capture and storage (CCS) technologies are expected to play a significant part in the global climate response. Following the ratification of the Paris Agreement, the ability of CCS to reduce emissions from fossil fuel use in power generation and industrial processes – including from existing facilities – will be crucial to limiting future temperature increases to “well below 2 °C,” as laid out in the Agreement. CCS technology will also be needed to deliver “negative emissions” in the second half of the century if these ambitious goals are to be achieved.

CCS technologies are not new. This year is the 20th year of operation of the Sleipner CCS Project in Norway, which has captured almost 17 million tonnes of CO_2 from an offshore natural gas production facility and permanently stored them in a sandstone formation deep under the seabed. Individual applications of CCS have been used in industrial processes for decades, and projects injecting CO_2 for enhanced oil recovery (EOR) have been operating in the United States since the early 1970s.

This publication reviews progress with CCS technologies over the past 20 years and examines their role in achieving 2 °C and well below 2 °C targets. Based on the International Energy Agency’s 2 °C scenario, it also considers the implications for climate change if CCS was not a part of the response. And it examines opportunities to accelerate future deployment of CCS to meet the climate goals set in the Paris Agreement.