GLOBAL CCS INSTITUTE

THE GLOBAL STATUS OF CCS | 2016

SUMMARY REPORT

"TIME TO ACCELERATE" – FOREWORD BY GLOBAL CCS INSTITUTE CHIEF EXECUTIVE OFFICER, BRAD PAGE

For carbon capture and storage (CCS), 2016 has been characterised by a number of significant successes but also brings into stark contrast some serious challenges.

The Paris Agreement lays a sound foundation on which the world can build its climate change mitigation actions. We know that the targets volunteered by countries at the Paris Conference of Parties (COP) are insufficient to limit the temperature increase to 'well below' 2°C, let alone approaching 1.5°C. Much more must be done, and most importantly, CCS will need to be more actively pursued by many countries.

The Institute has identified 38 large-scale CCS projects around the world, of which we anticipate that more than 20 will be operational by the end of 2017. These projects are testament to the safety, reliability, adaptability, and cost-efficiency of CCS.

As I write this, two significant projects have been launched in 2016 – the Abu Dhabi CCS Project, Phase 1 being the Emirates Steel Industries CCS Project, the world's first large-scale application of CCS to iron and steel production; and Japan's Tomakomai CCS Demonstration Project, with CO_2 capture at a hydrogen production facility and near-shore storage.

Three more major large-scale CCS projects are poised to commence operations across the United States:

- The world's largest post-combustion capture project at a power station (the Petra Nova Carbon Capture Project in Texas);
- The world's first large-scale bio-CCS project (the Illinois Industrial Carbon Capture and Storage Project); and
- The world's first CCS project at a commercial-scale coal gasification power facility (the Kemper County Energy Facility in Mississippi).

There are other large-scale projects in Canada, Europe, South America, Australia and parts of Asia and the Middle East, and a considerable number of pilot and demonstration projects around the world.

Encouraging as this is, it is not enough. And by a long way. The current level of CCS deployment does not go anywhere near what is required from CCS to meet the Paris 'well below' 2°C climate target.

The Intergovernmental Panel on Climate Change (IPCC) *Fifth Assessment Report Summary for Policymakers* found that most climate model runs could not meet emissions reduction targets without CCS. Crucially, without CCS, the cost of mitigation would more than double – rising by an average of 138 per cent.

The International Energy Agency (IEA) has found that the world needs to capture and store almost 4,000 million tonnes per annum (Mtpa) of CO_2 in 2040 to meet a 2°C scenario. It is likely to be much more for 1.5°C.

Current carbon capture capacity for projects in operation or under construction sits at approximately 40 Mtpa.

The numbers speak for themselves. It means that there is a lot of ground to make up.

This is not to say that significant headway has not been made over the last few years. But, tried and tested as CCS is, it is not accelerating at the pace needed to satisfy the ambitions of the Paris Agreement.

Ultimately, CCS will only be widely deployed when a supportive business case can be made. This is not predominantly a question of cost as CCS is already cost-competitive with many other technologies, on a CO_2 avoided basis. However, it does not attract anywhere near the same level of support as most other clean energy technologies. Unless CCS is afforded 'policy parity' – equitable consideration, recognition and support with other low-carbon technologies – then achieving the Paris Agreement objectives is in serious doubt.

The Global CCS Institute will consequently be working even more actively to advocate the case for economic and regulatory instruments and incentive mechanisms that improve CCS uptake.

In the decade since the 2005 IPCC Special Report on *Carbon Dioxide Capture and Storage*, CCS has been recognised as a major climate change mitigation option and it has been included amongst all major global greenhouse gas reduction scenarios.

The IEA and the IPCC have both identified its intrinsic place in achieving climate outcomes.

We sit at a crossroads. The projects materialising now are the result of government policy initiatives developed towards the end of the last decade.

The next wave of CCS projects depends on what happens now, in the next decade, and the recognition and resolve that all parties can bring.

In this spirit, I commend this report to you and hope you will join us in accelerating the pace of CCS deployment so we can achieve the world's imperative climate outcomes.

BRAD PAGE
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FOREWORD BY CAMERON HEPBURN

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The international agreement on climate change adopted in Paris in December 2015 represents a historic milestone in multilateral climate diplomacy. Two critical components of the Paris Agreement are: (a) limiting the temperature increase to 'well below' 2°C and pursuing 'efforts' to limit such increase to 1.5°C, and (b) achieving a balance between 'sources and removal by sinks' – or net-zero emissions – in the second half of this century. The Paris Agreement sends an unprecedented signal that governments in developed and developing nations understand the scale of the challenge and the necessary speed of the response. Their corresponding commitments suggest greater political willingness to address the challenge and to support the technologies that can scale up to reduce net emissions to zero.

There are reasons for optimism. As is now well-known, impressive technical progress has been made in clean energy technologies such as renewables (especially solar), electric vehicles and energy storage. Progress continues, with ever-deeper reductions in unit capital costs as the market grows and market penetration increases for these solutions. However, these technologies are currently a small proportion of the global energy system and their deployment needs to be massively accelerated if the unanimously agreed goals of the Paris Agreement are to be met.

Even if such a rapid deployment of these technologies is realised, it is very unlikely that this will be sufficient to halt temperature rises to within 2°C, let alone 1.5°C. Our research at the University of Oxford shows that even the emissions from existing power sector assets, if operated to the end of their normal economic life, will exceed the cumulative emissions budget consistent with halting global average temperature rise to 1.5°C. By the end of 2017, the emissions signature from installed power plants implies a greater than 50 per cent probability of exceeding 2°C, unless power plants are either prematurely retired (economically stranded) or carbon capture and storage (CCS) is retrofitted. In short, it is virtually impossible that deploying renewables and nuclear alone can reduce net emissions to zero before the temperature increase reaches 2°C, never mind 1.5°C. Additional effort is required to develop techniques to capture and securely store carbon.

Furthermore, the achievement of net-zero emissions across the entire global economy this century appears economically impossible without negative emissions technologies, such as bio-energy coupled with CCS (BECCS) or other carbon dioxide removal (CDR) technologies. Continued emissions from industrial and agricultural production processes seem very likely for the foreseeable future. To eventually reach a balance between emissions sources and carbon sinks, negative emissions technologies and processes will be important. Renewable energy technologies alone cannot supply the necessary carbon sinks to balance the residual sources and reach net-zero emissions.

Progress on carbon capture technologies is therefore critical to limit cumulative greenhouse gas emissions and to halt global temperature rises to between 1.5°C and 2°C. Negative emissions technologies will be required to deliver net-zero emissions sometime between 2050 and 2100, indicated as essential by the Fifth Assessment Report (AR-5) of the Intergovernmental Panel on Climate Change in order to stabilise the rise in global temperature at 2°C or lower.

Such truths, inconvenient or otherwise, remain truths even if carbon capture technologies are not always afforded a favourable impression by the popular press and some environmental groups. These impressions may stem from understandable opposition to any continued use of fossil energy, but the modern economy has been built upon the foundations of a fossil energy system that will remain vital for our prosperity for decades into the future. Make no mistake, the continued use of fossil fuels will be dependent on the ability of technologies to capture the corresponding greenhouse gas emissions, along with other technologies to greatly reduce damaging local pollutants. Without these advances, fossil fuels can have no place in the economy of a stabilised climate.

In this context, the annual *Global Status of CCS* report provides a very important resource for policymakers and businesses to rapidly get up to speed on the developments and progress of CCS. The core conclusion I take from this report is that, although there are important developments in both theoretical and applied knowledge, with some valuable practical wins, the current rate of progress on CCS is simply too slow.

This conclusion follows from the severity of the risks from climate change, the fact that renewables and nuclear alone are unlikely to reduce emissions fast enough, and the fact that residual process emissions need to be offset for the requirement of net-zero emissions to be achieved. Progress on CCS is much more important than current climate policy suggests it is – a more systematic, substantial and sustained push to stimulate its further development and roll-out, including on carbon pricing, is an appropriate response to the Paris Agreement.

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Image: Laurence Tubiana, COP 21/CMP 11 Presidency; UNFCCC Executive Secretary Christiana Figueres; UN Secretary-General Ban Ki-moon; COP 21/CMP 11 President Laurent Fabius, Foreign Minister, France; and President François Hollande, France, celebrate the adoption of the Paris Agreement. Photo by IISD/ENB | Kiara Worth (http://www.iisd.ca/climate/cop21/enb/images/12dec/3K1A5493.jpg)

INTERNATIONAL CLIMATE DISCUSSIONS AND CCS

The Paris Agreement, which focuses on climate mitigation actions after 2020, represents a clear and indisputable commitment from the world's political leaders to transition to a low-carbon economy. It provides a benchmark by which to gauge society's collective efforts and progress. If the ambitions of the Paris Agreement are to be achieved, CCS must enter into the mainstream of climate mitigation actions to be undertaken by governments and by business.

The approach adopted for the post-2020 climate agreement is fundamentally different to that of the pre-2020 agreement under the Kyoto Protocol. A more 'bottom-up' approach, allowing for greater national level determination of future climate actions, was developed and agreed by the Parties at COP 21 in Paris in December 2015.

This new approach is expected to secure a greater level of climate action than previous arrangements. It took just ten months for the Paris Agreement to legally commence or 'enter into force'. In contrast, its sister agreement, the Kyoto Protocol, took eight years to reach that milestone.

The Paris Agreement provides cause for optimism that the future investment environment required to accelerate the widespread deployment of CCS will eventuate – but much needs to be done in the next five years.

The Agreement articulates the scale of the challenge and the necessary speed of response, and CCS must be in the mainstream of that response

The Agreement defines a number of climate goals:

- A short-term goal is to reach peak emissions as soon as possible.
- A longer term goal is to limit average global warming to well below 2 degrees Celsius (2°C) above pre-industrial times, and an aspiration to limit warming to 1.5°C.
- In the second half of this century, a balance between emissions sources and sinks (often referred to as net-zero emissions) will be needed.

The level of global emissions reduction that must be delivered to meet these goals positions CCS as a critically important mitigation technology.

It is not possible to envisage least-cost emissions reduction scenarios, consistent with the Paris Agreement, that do not include broad deployment of CCS.

Global modelling efforts by the IPCC and the IEA highlight the importance of CCS in delivering a 2°C climate goal.

The IPCC *Climate Change 2014: Synthesis Report Summary for Policymakers* highlights that, without CCS, the cost of achieving 450 parts per million (ppm) carbon dioxide equivalent (CO_2eq) by 2100 could be 138 per cent more costly (compared to scenarios that include CCS), and that only a minority of climate model runs could successfully produce a 450 ppm scenario in the absence of CCS.[1]

IEA projections indicate that a least-cost pathway to achieving a 2°C scenario would require the capture and storage of almost 4,000 million tonnes of carbon dioxide (CO_2) per annum in 2040;[2] this is almost 100 times the annual CO_2 capture capacity expected to be in operation by the end of 2017.

1 IPCC, 2014. *Climate Change 2014: Synthesis Report Summary for Policymakers.* Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC. Geneva. Switzerland.
2 IEA, 2016. *Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems.* Paris. OECD/IEA.

Emissions reduction pledges provide a solid foundation to build upon, but accelerated deployment of CCS is necessary if the Paris Agreement ambitions are to be realised

The Paris Agreement's Nationally Determined Contributions (NDCs) process allows for transparent assessment of national mitigation outcomes, and enhancements if necessary. The Agreement provides opportunities for nations to revise their NDCs, and for the establishment of credible, cost-effective and predictable national climate and energy policies.

These are necessary elements to give confidence to investors to support capital-intensive, long-lived, low-carbon technologies such as CCS.

The Intended NDCs (INDCs) submitted prior to COP 21 in Paris expressed emission reduction pledges between 2020 and (up to) 2030. Submitted INDCs, if implemented fully, lead to a substantial slowing in the growth in emissions; however, they fall short of what is necessary to achieve the ambitions of the Paris Agreement.

IEA analysis, released prior to COP 21, notes that submitted INDCs:[3]

> ***"…fall short of the major course correction required to achieve the agreed climate goal.*** *If climate ambition is not raised progressively, it is estimated that the path set by the INDCs would be consistent with an average global temperature increase of around 2.7 degrees Celsius (°C) by 2100, falling short of limiting the increase to no more than 2°C. The INDCs must therefore be viewed as an important base upon which to build ambition."*

Achieving a 2°C goal (let alone 'well below' 2°C) is very challenging. Limiting the long-term rise in average global temperature to 2°C involves a substantial reduction in CO_2 emissions from present levels (not just a slowing in the growth of emissions). The Paris Agreement is a critical evolutionary step ('an important base') along the road to addressing climate change.

The global community will need to ratchet up mitigation action beyond 2030 (and preferably in the lead-up to 2030) or face an even bigger challenge later.

The 'INDC shortfall' highlights the importance of ensuring the role of CCS is recognised by all stakeholders as a 'mainstream' necessary technology in the long-term transformation of the energy sector.

In the absence of significant further mitigation actions, climate models indicate that the 450 ppm atmospheric concentration threshold will likely be exceeded. This implies greater reliance in the post-2050 period on net-negative emissions (and especially those generated from bio-energy coupled with CCS (BECCS)) to help reclaim the carbon budget.

Net-negative technologies face considerable hurdles to large-scale deployment. In the case of BECCS, key issues include whether there will be enough sustainable biomass available and the need to much better understand interactions between water, energy, agriculture and climate systems.

CCS technologies must be a strong priority for development (and research) given the likelihood of a carbon budget overshoot, particularly for a 'well below' 2°C target.

CCS must be afforded 'policy parity' in clean energy dialogues as reliance on renewables and energy efficiency alone cannot deliver climate outcomes consistent with the Paris Agreement

There appears a general preoccupation with the promotion of renewables and energy efficiency in international clean energy dialogues. Carbon capture and storage must take a greater part in these discussions than hitherto. This is especially the case in the United Nation's (UN's) clean energy flagship initiative, Sustainable Energy For All (SE4ALL), where there is no formal platform to discuss fossil fuel-based mitigation.

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[3] IEA, 2015. *Energy and Climate Change: World Energy Outlook Special Briefing for COP21*. Paris. OECD/IEA.

Renewables and energy efficiency alone cannot achieve the reduction in CO_2 emissions required to meet the Paris Agreement climate goals, given the embedded fossil-fuel base in the power sector and little scope for substitution of fossil energy use in the industrial sector.

- Adding to the emissions potential from existing coal-fired power stations, over 2,000 coal-fired stations are either under construction or in various stages of development planning around the world.[4]
- Industry (non-power) accounts for around one-quarter of global CO_2 emissions; CCS is the only option available to significantly reduce direct emissions from many industrial processes. Renewable technologies are not mitigation substitutes for CCS in many industrial sectors.
- In many regions, there has been a 'push for gas' to reduce emissions growth in the power sector. To achieve the 'well below' 2°C climate goal, CCS will also need to be applied to gas-fired power stations.

The United Nations Framework Convention on Climate Change (UNFCCC) processes would benefit greatly from hosting a second Technical Expert Process workshop on CCS. The last Technical Expert Process workshop on CCS was two years ago in October 2014.

Further workshops will assist Parties to better understand the mitigation potential of CCS, enhance the urgency of its deployment, and showcase the significant progress in CCS technologies in the past decade in reducing cost and providing for secure and effective storage.

Wider reception of these 'understandings' within the broader UN processes is especially important in light of the expected upcoming findings of the IPCC's Special Report on 1.5°C (to be published in 2018) and its Sixth Assessment Report cycle (to be finalised in 2021).[5]

Establishing the pre-conditions for widespread deployment of CCS throughout the next decade and beyond is a process that must gather momentum in the next five years.

The extent to which CCS is included in future NDCs could well serve as a proxy for the seriousness of global efforts to pursue the Paris Agreement climate goals at least cost.

Ultimately, widespread deployment of CCS will depend on the extent to which governments afford it 'policy parity' – namely, the provision of an equitable level of consideration, recognition and support for CCS alongside other low-carbon technologies.

Complacency in providing sufficient support for the deployment of CCS will substantially reduce the ability of world economies to limit global emissions to levels consistent with the climate goals of the Paris Agreement.

PROJECTS, POLICY AND MARKETS

The Institute has identified 38 large-scale CCS projects around the world, either in operation, under construction or in various stages of development planning. The global CCS effort extends well beyond the portfolio of large-scale CCS projects. The number of pilot and demonstration-scale projects and CCS initiatives that have made, or are making, a significant contribution to the understanding of CCS technologies can be counted in the hundreds.[6]

This combination of large and smaller scale projects is evidence of the breadth of global interest in CCS, with projects in Australia, Brazil, Canada, China, France, Germany, Japan, the Netherlands, Norway, Saudi Arabia, South Korea, Spain, the United Arab Emirates, the United Kingdom and the United States (to name a few countries from what is a more exhaustive list).

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4 Sourced from July 2016 data from CoalSwarm, Global Coal Plant Tracker: Proposed Coal Plants by Country (Units)

5 The COP 21 in Paris formally invited the IPCC to undertake a special report on the impacts of limiting global warming to 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. The IPCC accepted this invitation at its 43rd session in April 2016, and agreed that its Sixth Assessment Report (AR-6) would explicitly consider 1.5°C to 2°C scenarios (in addition to further considering the key findings arising from the special report on 1.5°C warming).

6 A comprehensive listing of large-scale, pilot and demonstration-scale CCS projects (as well as other project and program activities) and definitions of such is contained in the Institute's Projects database.

The growth in the portfolio of operating projects is continuing and a number of notable project milestones were achieved in 2016 (see below), further reinforcing that CCS technology is proven and capable of preventing large quantities of CO_2 from entering the atmosphere and securely and effectively storing the CO_2.

At the time of launch of this *Global Status of CCS: 2016* report, there were 15 large-scale CCS projects in operation around the world, with a CO_2 capture capacity of close to 30 million tonnes per annum (Mtpa). A further three large-scale projects, all in the US, are poised to become operational, bringing the number of operational projects to 18 by early 2017 (with a CO_2 capture capacity of 35 Mtpa). As projects in Australia and Canada come on-line during 2017, the number of large-scale operational CCS projects is expected to increase to 21 by the end of 2017, with a CO_2 capture capacity of approximately 40 Mtpa. This compares with less than 10 operational large-scale CCS projects in 2010.

Key CCS projects in the industrial sector launched in 2016

Two significant projects were launched in 2016 (as of time of writing) – one large-scale project and one demonstration-scale project. Both projects are in the industrial sector:

- A key large-scale CCS project development was the launch on 5 November of the Abu Dhabi CCS Project, Phase 1 being the Emirates Steel Industries (ESI) CCS Project. This project represents the world's first application of CCS to iron and steel production. It involves the capture of approximately 0.8 Mtpa of CO_2 from the direct reduced iron (DRI) process used at the ESI plant in Abu Dhabi and its use for enhanced oil recovery (EOR).
- Japan has embarked on an active program of pilot and demonstration CCS projects. The most notable development in 2016 was the commencement of CO_2 injection in April at the Tomakomai CCS Demonstration Project. The capture system (using emissions from a hydrogen production facility at Tomakomai port) is processing CO_2 at a rate of at least 100,000 tonnes per annum; this CO_2 is then injected into near-shore deep geologic formations.

Imminent launches of CCS projects in both the power and industrial sectors

Three large-scale CCS projects are considered very close (possibly a matter of weeks) to being operational, having achieved significant plant construction and commissioning milestones. All three projects are in the US; they include two key projects in (coal-fired) power generation and one in the industrial sector.

- The Kemper County Energy Facility in Mississippi (CO_2 capture capacity of approximately 3 Mtpa) is expected to be operational by the end of 2016. This landmark project will be the first commercial-scale deployment of the TRIG™ coal gasification process developed jointly by Southern Company and KBR in partnership with the United States Department of Energy (US DOE).
- The Petra Nova Carbon Capture Project in Texas (CO_2 capture capacity of approximately 1.4 Mtpa) is expected to be operational either by the end of 2016 or at the beginning of 2017. When fully operational, this project will be the world's largest post-combustion capture project at a power station.

  The Kemper County and Petra Nova projects follow on from the world's first large-scale CCS project in the power sector in Saskatchewan, Canada, at the Boundary Dam Unit 3 plant (CO_2 capture capacity of approximately 1 Mtpa), launched in October 2014.
- The Illinois Industrial Carbon Capture and Storage Project (CO_2 capture capacity of approximately 1 Mtpa) is expected to begin operations early in 2017. This project will be the world's first large-scale BECCS project, as well as the first CCS project in the US to inject CO_2 into a deep saline formation at a scale of 1 Mtpa.

More Projects expected to progress into operation during 2017

Commissioning of the Gorgon Project, offshore Western Australia, is also progressing, with the first LNG delivery made in 2016. The Gorgon Carbon Dioxide Injection Project, which the Institute anticipates will begin operations late in the first half of 2017, is the largest in the world to inject CO_2 into a deep saline formation (being capable of injecting up to 4 Mtpa of CO_2). This milestone would bring the number of large-scale operational CCS projects to 19 by the middle of 2017. Two additional large-scale CCS projects in Alberta, Canada, associated with the Alberta Carbon Trunk Line (ACTL) development, are expected to be operational by the end of 2017, bringing the number of operational large-scale CCS projects to 21 at that time.

Strong expectations for key projects to progress into construction or enter advanced planning

Positive signals are emerging on key projects progressing through development planning:

- In China, there are strong indications that the Yanchang Integrated Carbon Capture and Storage Demonstration Project will progress into the Execute (or construction) stage in the near future (possibly before the end of 2016). Between 0.4 and 0.5 Mtpa of CO_2 would be captured from gasification facilities at chemical plants in Shaanxi Province, with the CO_2 used for EOR.
- In the Netherlands, the ROAD project (CO_2 capture capacity of approximately 1 Mtpa) is proposing a new initial storage site. Revised storage and transport permitting is underway, suggesting a willingness on the part of the project proponents to move the project forward into construction in 2017.
- The Norwegian budget for 2017, released in early October 2016, contained grant monies of 360 million Norwegian Krone (approximately US$45 million) for the continued planning of a full-chain CCS project. While contracts for the financing of these advanced planning studies need to be completed, this is a very positive signal for CCS in Norway.

Operational milestones highlight that CCS works

A number of large and demonstration-scale projects across the world have achieved significant milestones in the past year (Figure 1):

- Twenty years of successful operation for the Sleipner CO_2 Storage Project (located off the Norwegian coast), with over 16 million tonnes of CO_2 injected since the project commenced operations in 1996.

  When added to the more than three million tonnes of CO_2 injected by the Snøhvit CO_2 Storage Project (also offshore Norway) since 2008, the combined CO_2 injection volume into geological formations for these two pioneer projects is approximately 20 million tonnes.
- In Brazil, Petrobras announced that, as of December 2015, the Santos Basin Pre-Salt Oil Field CCS Project (located approximately 300 kilometres off the coast of Rio de Janeiro in ultra-deep water) had injected three million tonnes of CO_2 into the producing reservoirs.
- The Air Products Steam Methane Reformer EOR Project in Texas had captured three million tonnes of CO_2 from hydrogen production facilities as of end June 2016 (and used for EOR).
- The Boundary Dam Carbon Capture and Storage Project had captured one million tonnes of CO_2 from its Unit 3 power generation facility as of July 2016 (and used mainly for EOR).
- The Quest project in Alberta, Canada, had successfully captured (from a hydrogen-processing plant) and stored more than one million tonnes of CO_2 into a deep saline formation as of September 2016.
- In October 2016, the US DOE Office of Fossil Energy website highlighted that over 13 million tonnes of CO_2 has been injected in the US as part of the DOE's Clean Coal Research, Development, and Demonstration Programs.
- The Jilin Oil Field EOR Demonstration Project in China began CO_2-EOR injection testing ten years ago, and reached one million tonnes of CO_2 injected in 2016.

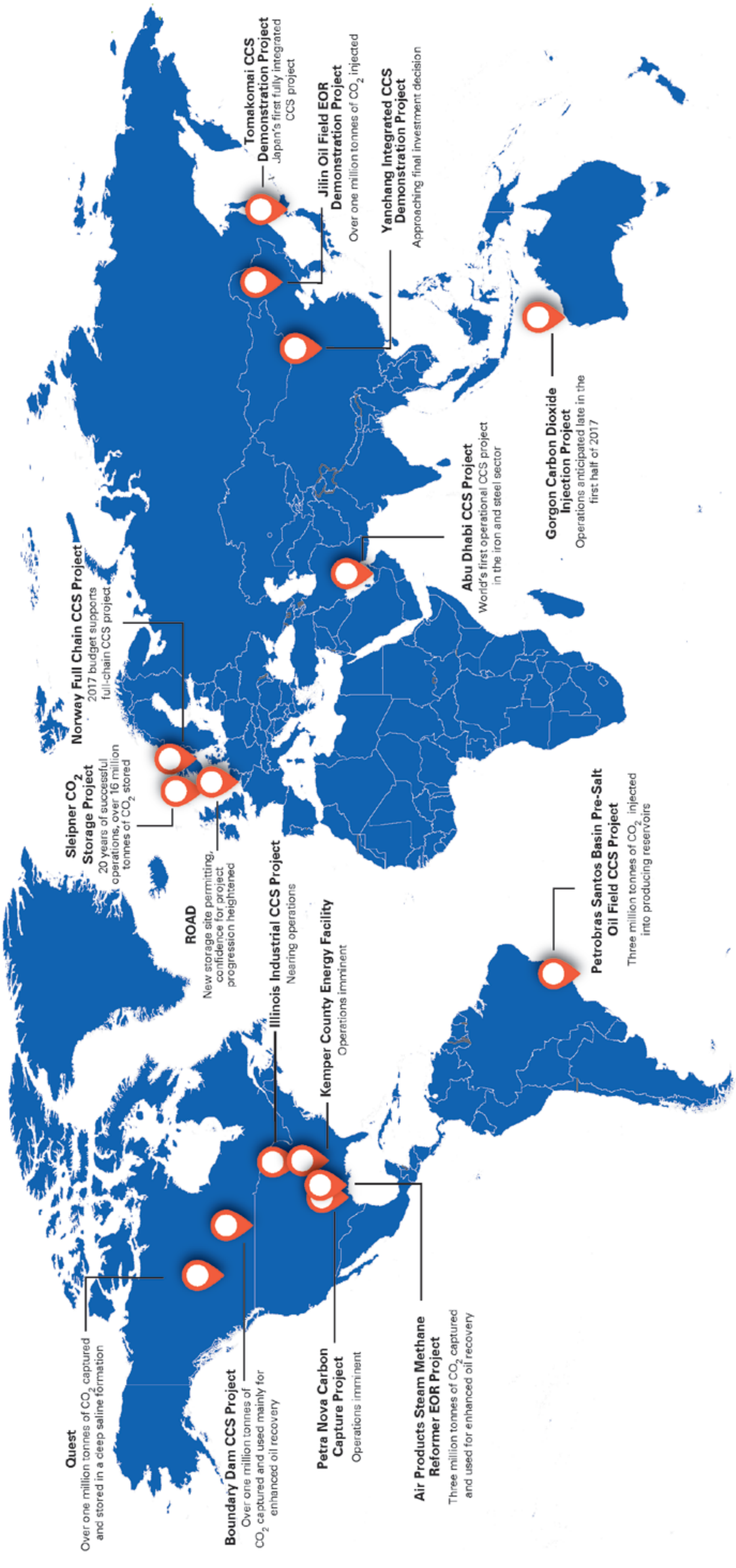


Figure 1 Key CCS project developments and milestones

Features of successful projects

Most successful projects to date (and many in development planning) have strong links to the oil and gas industry, either as a source of CO_2 or through the use of CO_2 for EOR. For widespread deployment of CCS to occur, in line with global mitigation ambitions, access to storage opportunities must ultimately move beyond EOR.

Industrial carbon capture dominates projects in operation and construction. They tend to be heavily weighted towards sectors or processes in which (a) separation of CO_2 is an inherent component of normal business operations (e.g. natural gas processing and fertiliser production) or (b) process gas streams contain CO_2 at concentrations high enough to allow for relatively inexpensive separation (e.g. hydrogen production). CCS projects are still to be progressed beyond pilot scale in major CO_2-emitting sectors such as blast furnace steel making and cement manufacture.

Projects with shorter planning time frames – such as those that have access to lower-cost CO_2 streams and/or to readily available transportation and storage infrastructure – have progressed into operations faster.

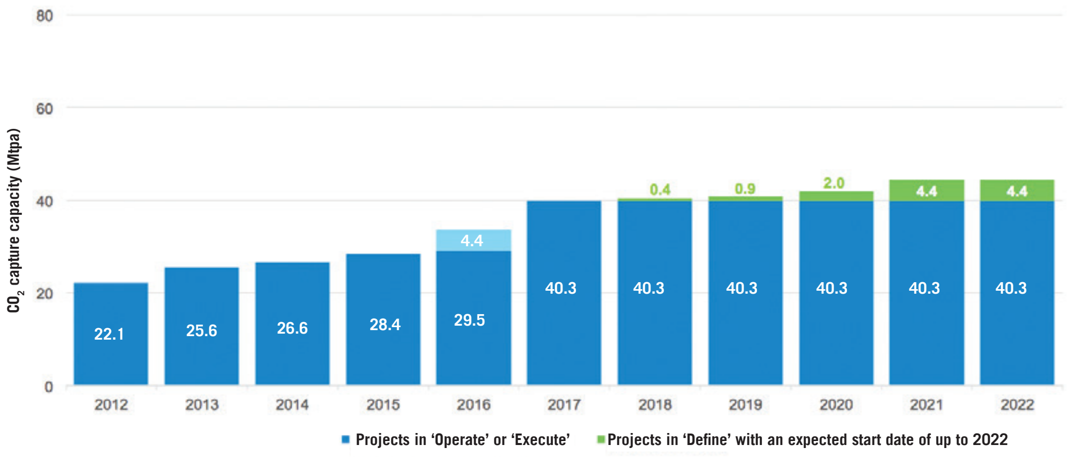
Momentum is slowing – renewed commitment and strengthened policy support is essential

The last five to seven years have heralded positive developments for many CCS projects globally. From 2010 to the end of 2017, the number of operational large-scale projects is set to rise from fewer than 10 to just over 20, with the CO_2 capture capacity of operational projects more than doubling to 40 Mtpa.

Many key projects that entered (or are soon expected to enter) operations in this period benefited from government policy initiatives developed towards the end of the last decade. However, funding for large-scale projects has tightened in a number of key jurisdictions. In Europe, the pace of CCS project development has suffered from a sharp reduction in the carbon price since the European Energy Programme for Recovery (EEPR) was established in 2009 and policy uncertainties in some countries. In China, where many CCS projects in development planning are linked to EOR, major progress in bringing these projects into construction is still awaited; the business case having been adversely influenced by the reduced oil prices of recent years.

Looking forward, in the absence of new initiatives to support large-scale project development, the pace of project progression in the next five years looks set to slow considerably (Figure 2).

Figure 2 **CO_2 capture capacity of large-scale CCS projects up to 2022 for projects in the Operate, Execute and Define stages**

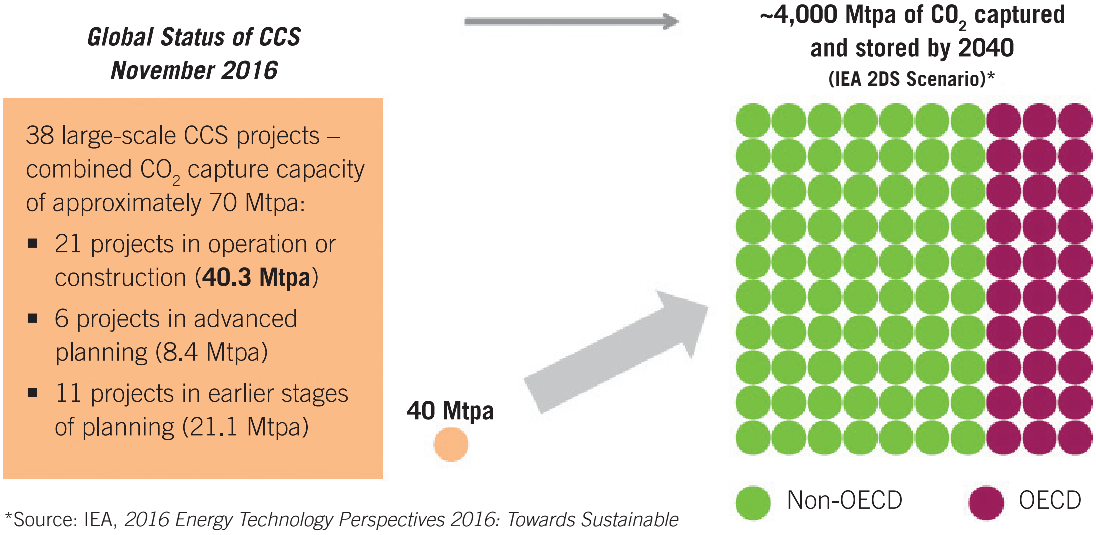


Note: At the time of writing, there were strong indications that both the Kemper County and Petra Nova projects could be operational by the end of 2016; the combined CO_2 capture capacity of these two projects (4.4 Mtpa) is included in 2016 as a distinct entry (light blue) to highlight that operations were imminent.

Acceleration of CCS development and deployment is required to meet the Paris Agreement climate goals.

The scale of the challenge must not be underestimated (Figure 3). The current level of CO_2 capture capacity is dwarfed by the amount of CCS deployment required over the next 25 years under the IEA's 2°C scenario (2DS), which is estimated at almost 4,000 million tonnes of CO_2 captured and stored per annum in 2040 (the large majority of which is expected to be in non-OECD countries).

Figure 3 A significant task for CCS deployment is required by 2040 under the IEA 2DS



*Source: IEA, *2016 Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems*. Paris. OECD/IEA.

Large-scale and pilot projects developed during the last decade contain learnings that can encourage future CCS development. Importantly, the steady progression of projects into operations in recent years, and the many milestones achieved in 2016, demonstrate that CCS technologies work. Projects that have not progressed rarely cite technical barriers to operation of the technology as a reason; more commonly, they highlight aspects of stakeholder management across a range of regulatory, commercial and risk-sharing fronts. These hurdles are often complex and inter-related and will take concerted efforts from governments and investors to rectify.

Establishing the pre-conditions for the widespread deployment of CCS post-2020 is a process that must gather momentum over the course of the next five years. In view of the urgency of the matter, much greater public support is needed.

In the near-term, important milestones in 2017 include:

- the outcome of (and reactions to) the legal action brought by 27 states against the US Environmental Protection Agency's (EPA) Clean Power Plan
- the initiation of Norwegian full-chain CCS concept definition studies
- decisions on next steps for CCS in the United Kingdom (UK)
- the decision by SaskPower whether to refurbish Boundary Dam Units 4 and 5 (with CCS) or to retire these assets.

Positive developments for CCS from these milestones can contribute to replenishing the project pipeline, though much stronger global action will be required.

Lessons from renewables development are instructive – 'policy parity' for CCS is essential

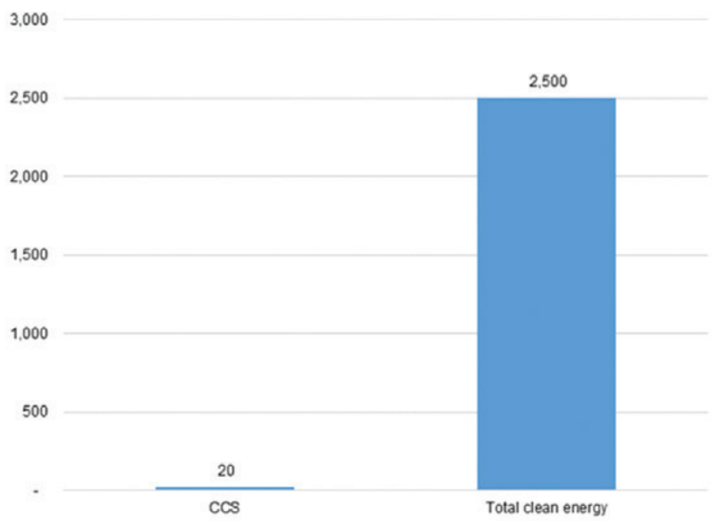
In the decade since the release of the IPCC Special Report on *Carbon Dioxide Capture and Storage* in 2005, CCS has been recognised as a major climate change mitigation option and included in all major global greenhouse gas (GHG) reduction scenarios. While there have been important CCS project advances since that time, the vital role attached to CCS in global models in the transition to a low-carbon economy has not yet translated broadly enough into policy support at national levels.

Widespread deployment of CCS must be based on 'policy parity' – namely, the provision of an equitable level of consideration, recognition and support for CCS alongside other low-carbon technologies.

For CCS, this means the design and implementation of support measures tailored specifically to the technology and its lifecycle stage. Incentive mechanisms should tackle the complexity of risks and act as economic multipliers to improve the conditions required for CCS market uptake. This must be undertaken in parallel with the development of appropriate legal and regulatory frameworks (and continued research and development efforts to further reduce CO_2 capture costs).

The growth in renewable energy is instructive (Figure 4). Worldwide, around US$2.5 trillion has been invested in clean energy technologies in the last ten years, of which US$1.8 trillion has been on wind and solar technologies. This investment activity has been driven by strong and sustained policy support. In comparison, investment in CCS during the same timeframe amounts to around US$20 billion (or, put another way, the amount invested in other clean energy technologies has been 120 times greater than that for CCS).

Figure 4 **Clean energy investment 2006-15 (US$ billion; rounded data)**



Sources:

Clean energy data sourced from Bloomberg New Energy Finance, 2016. *Clean Energy Investment By the Numbers – End of Year 2015.*

CCS data sourced from IEA, 2015. *Tracking Clean Energy Progress 2015, Energy Technology Perspectives 2015 Excerpt IEA Input to the Clean Energy Ministerial.* Paris. OECD/IEA.

In the past decade, governments have provided significant policy support to renewable generation sources through mandated energy targets and subsidies, including feed-in tariffs for households.[7] A success of these policies has been the rapid expansion of the photovoltaic (PV) industries in countries such as Germany and China, with significant reductions in the cost of PV production.

[7] The global value of subsidies provided to renewable energy technologies over the past five years has totalled around US$500 billion. In 2014 alone, the amount was US$135 billion, around seven times more than the amount invested in CCS in the past decade. Data based on various IEA sources, including annual World Energy Outlook publications.

The development of transportation and storage infrastructure is receiving greater attention

Successful projects have generally been those that utilise existing CO_2 transport and storage infrastructure, or are undertaken by large energy companies with many years of experience in sub-surface risk management practices. While developments in carbon capture have historically garnered much attention, meeting the objectives and aspirations of the Paris Agreement will require a (shared) CO_2 transportation and storage infrastructure that can service multiple sectors of the economy. Such infrastructure is essential to secure the future of those industrial regions (like Teesside in the UK) which presently are home to a considerable number of high-emitting industries.

The individual components of the CCS chain are distinct processes and each requires a different set of skills and capability, and is subject to a different value proposition. Integrating these elements into a single project structure, with agreed risk-sharing allocation, has proven difficult for many projects.

For some projects, this difficulty has been mitigated by the use of CO_2 in EOR but this opportunity is not available to all and the scale of CCS deployment in coming decades requires much greater access to non-EOR storage resources.

A growing body of research is examining various support models that could incentivise CCS. Concepts such as 'splitting the chain', or tailoring transportation and storage infrastructure development to help de-risk capture project decision-making, have emerged, along with consideration of various public/private shared investment models.[8]

Strategic CCS hubs are especially important for industrial CCS

Emissions from the industrial sector were approximately 9,000 million tonnes (or 9 gigatonnes, Gt) in 2013, accounting for approximately one quarter of global CO_2 emissions.[9] Fossil fuels are an essential input to the production process in a number of industries, including iron and steel, cement and chemical production. However, unlike power generation, it is currently not feasible to substitute renewable energy sources for fossil fuels in these production processes in order to reduce CO_2 emissions. In addition, for a number of industrial processes, CO_2 emissions are not a product of the combustion of substitutable fossil fuels, but rather an unavoidable by-product of an inherent chemical process.

As a result, aside from the application of energy-efficiency measures, CCS is the only large-scale technology available that can help achieve deep reductions in CO_2 emissions in the long term.

There are a number of industrial facilities in operation or under construction with annual CO_2 capture capacity at (or in excess of) 1 Mtpa, mainly in natural gas processing and fertiliser and hydrogen production. Across the full spectrum of industrial emission sources, there will be many individual facilities where the volume of CO_2 to be captured will be at smaller levels. As standalone developments, this can result in high costs for accessing transport and storage infrastructure. However, many emissions-intensive industries are located in tight geographical clusters. Development of strategically sized, shared transport and storage infrastructure can facilitate the efficient aggregation of smaller volumes of CO_2 from industrial sources.

Applying CCS to clusters of major industrial or other sources of CO_2 can protect regions against future forms of carbon regulation; establishment of 'low-carbon industrial zones' could also bring significant advantages in the race to attract and maintain investment.

[8] Two recent reports that examine this issue in greater detail and offer proposed implementation models include IEA, 2016. *20 Years of Carbon Capture and Storage.* Paris. OECD/IEA (to be released coincident with this *Global Status of CCS: 2016* report) and Oxburgh, R., 2016. *Lowest Cost Decarbonisation for the UK: The Critical Role of CCS. Report to the Secretary of State for Business, Energy and Industrial Strategy from the Parliamentary Advisory Group on Carbon Capture and Storage.* London. Parliamentary Advisory Group on Carbon Capture and Storage (CCS).

[9] IEA, 2016. *Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems.* Paris. OECD/IEA.

Policy, legal and regulations developments vary by region

The Americas

The key uncertainty in the United States remains the legal action brought by 27 states against the US EPA's implementation of the Clean Power Plan, which has resulted in a significant delay to the deployment of this flagship initiative. While some states have continued to develop their state-wide approach to its implementation, several have suspended all further work pending a decision from the courts.

Proposed new legislation would increase the credit value (under a provision of the US tax code known as '45Q') for all CO_2 storage, including EOR, to US$30 per tonne and eliminate the national storage cap (currently 75 million tonnes of CO_2 stored). This valuable action is co-sponsored by a regionally and politically diverse coalition of members of Congress, which bodes well for its adoption.

The US DOE continues with a robust research and development capture program and its Regional Carbon Sequestration Partnerships. Funding awards have started to advance selected capture technologies to large pilot scale.[10]

Canada has seen the realisation of its long-term policy, legal and regulatory ambitions, with the recent entry into force of the CO_2 performance standards for coal-fired power plants, which the Federal Government adopted in 2015. Prime Minister Trudeau recently announced a national 'floor price' on carbon that would require all provinces and territories to have some form of carbon pricing by 2018.

Developments at the Canadian federal level in the past year build upon the accomplishments of the country's provincial governments in supporting the deployment of CCS technology. The enabling policy frameworks developed at the beginning of this decade by the governments of Alberta and Saskatchewan contributed substantially to a number of key large-scale projects becoming operational in 2014–15 and anticipated to become operational later in 2017.

Europe, Middle East and Africa

Supranational policy development in Europe has continued to build upon initiatives launched by the European Commission in 2015. The European Union's (EU) ratification of the Paris Agreement, together with the ongoing reforms to the EU Emissions Trading System (EU-ETS) and activities under the Strategic Energy Technology (SET) Plan process, offer a platform for developing further commitments to CCS deployment and support.

The EU is looking to address the EU-ETS with various reforms, as this mechanism is a major component of EU climate policy. It is anticipated that reforms will ultimately increase the price on carbon as well as generate increased funding to support low-carbon technologies such as CCS.

The EU approach is important as carbon pricing, and its funding mechanisms, address emissions from a variety of sectors, not just emissions from power generation where many countries have historically tended to focus their deployment efforts.

In Norway, the development of Guidelines on the Financial Security and Financial Mechanism for CO_2 Storage (English translation of Norwegian text) enhances the national permitting model and complements the government's renewed commitment to the technology's deployment, including continued operations at Test Centre Mongstad and funding of activities under the CLIMIT Programme (Norway's national programme for the research, development and demonstration of CCS).

[10] On October 17, the US DOE announced the award of up to US$80 million for a six-year project to design, build, and operate a 10 megawatt electrical (MWe) supercritical carbon dioxide (sCO_2) pilot plant test facility in San Antonio, Texas. The project will be managed by a team led by the Gas Technology Institute (GTI), Southwest Research Institute® (SwRI®), and General Electric Global Research (GE-GR). http://energy.gov/under-secretary-science-and-energy/articles/doe-announces-80-million-investment-build-supercritical

In the UK, the Government continues to review and consider its policy position following the cancellation of the CCS Competition in November 2015. The UK Government has continued to affirm its interest in CCS. The findings of recent reviews into the role of CCS in the UK, including recommendations to support future deployment, may offer a timely and valuable contribution to the government's future policy decisions.

In the Middle East, large-scale projects are in operation and a significant research and development effort is in train.

Asia Pacific

Governments across the Asia Pacific region continue to adopt a host of approaches to policy, legal and regulatory development for CCS, a position that remains largely unchanged since last year's Status Report.

Australian governments (federal and state) have supported projects through funding and development of necessary legislation. In 2016, the Australian Government announced funding of around AUD$24 million for a host of organisations and projects engaged in CCS research and development.

Japan and China remain at the forefront of promoting the technology's demonstration and deployment. Japan is developing a portfolio of pilot and demonstration CCS projects. China's joint announcements with the US, pledging action on climate change, includes renewed commitments to carbon capture utilisation and storage (CCUS).

The findings of the Institute's first (Legal and Regulatory) Fellowship revealed that further legal and regulatory development will be necessary in a number of jurisdictions, if the effective enforcement of commercial deployment is to be realised across the region.[11]

Policy inertia or a period of reflection and development?

In several jurisdictions there is a perception that CCS policy deployment has undergone a slowdown in recent years; however, there are strong reasons to believe this may be more indicative of a period of reflection as governments review their national approach to the technology and commence a new phase of policy development.

A period of reflection is perhaps not surprising as the original tranche of CCS demonstration funding allocations of the last decade were made in a very different economic context than at present, and the lessons for CCS deployment that arose from these arrangements are being digested. The importance of de-risking transportation and storage infrastructure arrangements to investors and the importance of the application of CCS to industrial applications are just two areas where the conversation around CCS has deepened compared to a few years ago.

Various countries, including Japan, China and Norway, have signalled a commitment to CCS and continue to make in-roads into proving the technology at large-scale, while also promoting various developments at pilot and demonstration scale. In the UK, there is a strong constituency across a range of stakeholders that highlights the important role CCS must play in a least-cost approach to UK decarbonisation (and that calls for the reinvigoration of domestic CCS policy).

Large-scale CCS projects that are soon due to come online in the US reflect prior levels of policy support which have since been discontinued. The Clean Power Plan, designed to push decarbonisation of the electricity sector, is presently the subject of a legal challenge. A new presidency in 2017 may provide a trigger for the US to re-examine its overall energy and climate policy. In Canada, the Saskatchewan Government will decide in 2017 on whether to retrofit units 4 and 5 at the Boundary Dam power station with CCS or to retire these coal-fired units.

[11] Gibbs, M. K., 2016. *Effective enforcement of underground storage of carbon dioxide.* Melbourne. HWL Ebsworth Lawyers.

While a period of reflection is worthwhile to help guide future policy directions for CCS, it must not transform into an excuse for inaction. Most of the CCS deployment activity this decade has been in North America; not only does this need to continue but it needs to spread more widely to areas of Europe and Asia where opportunities for deployment of CCS are available.

Legal and regulatory development remains critical for deployment

Countries are continuing to reflect upon their legal and regulatory frameworks, which are critical for enabling the secure and permanent storage of CO_2.

To date however, we have seen a two-speed development of CCS-specific law and regulation globally, with only a select number of jurisdictions possessing comprehensive frameworks capable of fully regulating a CCS project throughout the project lifecycle.

Of particular concern are those jurisdictions with large-scale projects in the pipeline but which have yet to critically review and enhance their national legal and regulatory models to support deployment (e.g. China).

Timeliness of activities will be critical

National policymakers and regulators must adopt a more comprehensive and holistic approach to their development of a domestic policy, legal and regulatory environment for CCS.

A renewed focus on meeting the climate goals under the Paris Agreement, together with national emissions reduction commitments, demonstrate the scale and urgency of the mitigation effort required, and of which CCS must be a part.

CCS TECHNOLOGIES

This 2016 and prior year status reports have examined a number of areas dealing with CCS technologies and concluded that:

- Carbon capture technologies have progressed significantly in the last decade, costs have reduced and further efforts are underway on second-generation and transformational technologies to further reduce costs significantly. Capture technologies are being developed globally in several programs with support from governments, academia and industry covering both power and industrial process applications.

  Such international collaboration and knowledge sharing is key to accelerating the deployment of new technologies.
- The transportation of large volumes of CO_2 has been practised for decades with an excellent safety record, applying internationally adopted standards and codes of practice which continue to be further developed. The main issue is scale and how best to incentivise investment in CO_2 transport solutions that will accommodate widespread CCS deployment.
- The technology is already available to select, characterise, safely operate, complete and close storage sites. Secure CO_2 geological storage at various scales has already been demonstrated at a number of successful projects across the globe. Various assessments suggest that storage resources to support CCS development are vast and in excess of projected capacity requirements over the coming decades.[12]

[12] These points are echoed in an Open Letter to Christiana Figueres, Executive Secretary to the United Nations Framework Convention on Climate Change (/cop21-open-letter) of 8 October 2015, titled *The geologic storage of carbon dioxide for Carbon Capture and Storage is secure and safe.* Available at: http://www.sccs.org.uk/news/227-open-letter-to-christiana-figures-executive-secretary-of-the-united-nations-framework-convention-on-climate-change

Capture

The capture element of CCS accounts for the majority of the cost in the CCS chain. In power generation, for example, 70-90 per cent of the overall cost of a large-scale CCS project can be driven by expenses related to the capture and compression process. More cost-effective capture technologies are being developed through the following avenues:

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

Capture research and development trends, emphasising pilot-scale testing, were highlighted in the 2014 and 2015 *Global Status of CCS* reports. This 2016 report focuses on the opportunities and challenges associated with capture applications in industrial systems.

Capture research and development

Significant progress has been made in demonstrating large-scale capture operations. The lessons learned from these operating projects will provide valuable information for decreasing the cost of design, construction and operation of future carbon capture facilities. Principals from both the Boundary Dam and Quest projects have indicated that costs associated with the design and construction of subsequent (similar) CCS facilities could be reduced substantially.

Second-generation technologies under development are currently being tested at pilot-scale and are targeted to be available for demonstration testing in the 2025 timeframe with costs 20 per cent lower than currently available technologies. Transformational technologies are targeted to reduce costs by 30 per cent compared to currently available technologies and be available for demonstration testing in the 2030 timeframe (importantly, comparisons are to an 'nth-of-a-kind system').

Research underway on transformational capture approaches includes:

- development of liquid and solid materials that are optimised at the molecular level for the task of CO_2 removal
- the use of technologies not traditionally used in gas separation, such as supersonic expansion and electrochemical processes
- the development of hybrid approaches that combine the benefits of multiple technologies. These hybrid technologies may yield synergistic benefits for further cost and performance improvements than might be achievable from a single technology approach.

There are several second-generation technologies currently being tested globally at small pilot-scale (0.5-5 MWe for post-combustion systems) using actual process gases, including at dedicated technology test centres such as Technology Centre Mongstad in Norway and the National Carbon Capture Center in the US. There are also many other facilities (in, for example, Australia, Canada, China, Europe, Japan and South Korea) that can host small pilot-scale tests. Selected technologies are also being tested at large pilot-scale (10-25 MWe). These are candidates for the next significant wave of lower cost demonstrations that can eventually lead to widespread deployment.

A sample of technologies being tested at pilot-scale is presented in Table 1 on the following page.

Table 1 Pilot-scale testing of selected second-generation capture technologies

Capture Category	Focus/Approach	Benefits	Scale
Post-combustion solvent	Process integration, enhanced contacting, advanced regeneration schemes, non-aqueous solvents, catalysed absorption	Reduced capital and operating costs, enhanced energetics, process optimisation, modular approaches, scalable	0.5-25 MWe
Post-combustion sorbent	Pressure swing adsorption, thermal swing adsorption, fixed bed, moving bed, fluidised bed, supported amines, alkalised alumina, carbonates	Proof of concept, process optimisation, sorbent attrition resistance	1-10 MWe
Post-combustion membrane	Spiral wound, hollow fibre, plate-and-frame, solvent/hybrid approaches	Modular, process innovation, process intensification, reduced water use	1 MWe
Pre-combustion	Advanced solvents, carbon-based sorbents	Reduced solvent costs, process integration and intensification	0.1 MWe
Oxy-fuel combustion	Pressurised fluidised bed oxy-combustion, oxy/pressurised CO_2 power cycle, calcium- and iron-based chemical looping	Reduced cost of capture, high efficiency, reduced carrier attrition, inexpensive carrier	1-17 MWe
Cement industry	Calcium looping	Process innovation, heat integration	0.2-0.6 MWe

Industrial Capture

Fossil fuels are an essential input to the production process in a number of industries, including iron and steel, cement and chemical production. Aside from the application of energy efficiency measures, CCS is the only large-scale technology available that can help achieve deep reductions in CO_2 emissions in the longer run.

Industrial capture applications can be segregated into three basic categories:

- Sectors or processes in which production/separation of CO_2 is an inherent component of normal business operations (e.g. natural gas processing, bio-ethanol production, ammonia/fertiliser production).
- Sectors in which relevant volumes of CO_2 are present in process gas streams at concentrations high enough to allow for relatively inexpensive separation and subsequent sale or storage (e.g. hydrogen production in oil refining applications).
- Sectors that generate substantial volumes of CO_2 that will need to be mitigated in order to achieve climate goals, but that currently do not have large-scale capture projects due to either (or a combination of) lack of regulatory requirements, high capture costs, global competitive pressures and inadequate incentives (e.g. iron and steel production, cement production, petroleum refining, and pulp and paper production).

For the first two categories, CO_2 capture is relatively mature, and many commercial technologies have been proven at scale. For the third category, CO_2 capture is more challenging. Lower concentrations of CO_2 in the gas streams of these sectors necessitate the use of capture approaches that are more energy intensive and thus more expensive.

Ongoing research and development activity is targeting capture cost reductions, especially for low-concentration gas streams. Table 2 summarises the current state of CO_2 capture in several industrial sectors. Large-scale projects are clustered in sectors with high-concentration gas streams, whereas for sectors with low-concentration gas streams capture activity is focused on pilot and laboratory/bench scale development.

Table 2 Summary of the current state of CO_2 capture in various industrial sectors

Sector	Application Scale			Summary
	Large	Pilot	Lab	
Natural Gas Processing	●	●		Variable CO_2 concentrations (2-70 per cent); physical, chemical, and membrane separation processes in use at large scale; separation part of production process
Ammonia/ Fertiliser Production	●			Urea production process uses nearly pure stream of CO_2. Excess is largely vented currently, but can be compressed, transported and stored or used
Bio-ethanol Production	●	●		Fermentation process produces nearly pure CO_2 stream. Most is vented currently, but can be compressed, transported and stored or used
Hydrogen Production	●	●		CO_2 concentrations in process gas streams vary from 15 to 50 per cent. Separation from high-concentration streams captures around 60 per cent of CO_2 generated
Iron and Steel Production	●	●	●	Blast furnace production (dominant process globally) generates low CO_2 gas streams; direct reduced iron process produces high concentration stream
Cement Manufacture		●	●	CO_2 produced from fossil fuel use and from chemical reaction inherent to process; high process temperatures offer potential for unique capture approaches
Petroleum Refining		●	●	Multiple low-concentration sources not associated with hydrogen production within refinery complex complicate capture approaches
Pulp and Paper Production		●	●	Multiple low-concentration sources within production process complicate capture approaches

Transport

Transport of CO_2 by pipelines, trucks, trains, and ships is already a reality, occurring daily in many parts of the world. Pipelines are – and are likely to continue to be – the most common method of transporting the large quantities of CO_2 involved in CCS projects. In the US alone there are around 7,600 kilometres of onshore CO_2 pipelines transporting roughly 68 Mtpa of mainly naturally sourced CO_2 for EOR purposes.

Current CO_2 pipeline infrastructure has been operated with an excellent safety and performance record that results from accumulated experience, proven design methodologies and established codes and regulation.

The existing network of CO_2 pipelines has been designed and operated to meet the requirements of regulations and industry-recognised standards. As a supplement to these existing national and international pipeline standards and codes, an International Standard for CO_2 transportation systems was finalised this year (ISO Standard 27913:2016).[13] This standard covers specific issues related to transport of CO_2 in the context of large-scale CCS projects.

[13] Available at: http://www.iso.org/iso/catalogue_detail.htm?csnumber=64235

Current research programs are focused on reducing cost and further improving safety by developing and validating new predictive models for CO_2 pipeline design. Engineering efforts also target large-scale shipment of CO_2, as several recent studies show that CO_2 transportation by ship can be a flexible and cost-effective alternative to CO_2 pipelines, especially where onshore and close-to-shore storage locations are not available.

The development of large-scale 'trunk lines' for long distance CO_2 transport and distribution systems has proven to be successful in North America in terms of their ability to connect multiple industrial sources of CO_2 to a large number of mature oil fields, where CO_2 is used in EOR. The North American experience may offer valuable lessons on the importance of incentivising infrastructure development in regions with a high density (or cluster) of CO_2 emissions and economically accessible storage locations.

Storage

Geological storage of CO_2 (herein referred to as storage) has been successfully demonstrated at a number of pilot and large-scale sites over the last two decades in both onshore and offshore environments. This experience builds upon four decades of CO_2-EOR operations, principally in the US. This has resulted in well-established best practices and techniques required to select, safely operate and close (secure) CO_2 storage sites.

There are three basic technical requirements for storage sites:

1. Containment – storage sites need to be able to securely store CO_2 in a subsurface reservoir(s) with low and manageable risks, including those associated with any potential leakage;
2. Capacity – storage sites need subsurface reservoirs that can permanently store the required amounts of CO_2; and
3. Injectivity – storage sites require subsurface reservoirs that can accept CO_2 at an appropriate rate in relation to capture process at the relevant industrial source(s).

Containment

The experience gained from both CO_2-EOR and dedicated storage projects, together with industrial analogues such as natural gas storage and acid gas waste disposal, has provided the foundation for an effective risk management process that can ensure storage sites are selected, characterised, operated and closed in a secure manner.

The principles of this risk management process are described in the *Global Status of CCS: 2014* report.

The primary risk management approach for CO_2 storage is to minimise the possibility of future leakage by selecting the sites with the most suitable geological characteristics and to maintain sufficient wellbore integrity for all wellbores in contact with the storage formation. Risks associated with appropriately characterised and operated sites are considered to be very low, as demonstrated in many operating and completed projects at various scales.

Furthermore, storage-related research and development activities have led to better understanding of storage mechanisms, CO_2 plume behaviour and migration pathways. Application of CCS technology at demonstration sites has improved well design, plume/reservoir modelling capabilities, and monitoring techniques to effectively track the injected CO_2.

Operating experience plus learnings from global research and development programs have informed a range of published best practice guidance documents that are currently being integrated into an international standard for CO_2 geological storage (as part of the International Organization for Standardization (ISO) Technical Committee (TC) 265 on Carbon dioxide capture, transportation, and geological storage).

The lessons learned from pilot, demonstration and large-scale injection are well documented and publicly available for stakeholders. Collaborative programmes such as the US DOE Regional Carbon Sequestration Partnerships and the EU CCS Demonstration Projects Network foster knowledge sharing and enable projects to learn from improved CO_2 injection practices to accelerate deployment all around the globe.

Monitoring is a key component of the risk management process for storage, providing measurements of injected CO_2 and reassurance to regulators and other stakeholders that the project is developing as expected. Each storage project will require an individual approach to developing a monitoring program.

A variety of proven monitoring technologies have been deployed at pilot and commercial-scale projects, demonstrating the successful measurement, monitoring and verification of injected CO_2 in the subsurface.

Current global storage-related activities at various scales continue to improve our ability to quantify CO_2 migration in the subsurface.

Capacity

To support the acceleration of CCS deployment required by climate mitigation targets, confidence must be high that sufficient storage resources are available in key regions.

Regional storage resource assessments have been compiled by many nations. A review of these assessments is included in the *Global Status of CCS: 2015* report. The review concluded that substantial storage resources are present in most key regions of the world, sufficient to support commercial deployment of CCS in line with greenhouse gas mitigation targets.

Reliable methodologies to determine and classify regional storage resources are available, though the level of resource assessment undertaken is highly variable across regions.

Detailed regional surveys of storage resources have already been undertaken in several key nations, including the US, Canada, Australia, Japan, Norway and the UK. Multinational initiatives in Europe and South East Asia have also improved the global knowledge base of available resources. Several other nations, including China, Brazil, Mexico and South Africa, have assessed resources at a more theoretical level and are progressing towards refined estimates.

These various assessments have all shown, even using conservative assumptions, that storage resources available to support CCS deployment are vast and far in excess of projected capacity requirements over the coming decades. For example, a conservative estimate of the prospective CO_2 storage resources for regions in the US and North America assessed by the Regional Carbon Sequestration Partnerships indicates that over 2,000 billion tonnes of CO_2 could be stored in deep saline formations – subject to regulatory and economic factors.[14]

However, the precise geology of each storage project will be uniquely site-specific. Detailed site investigations are required to provide sufficient confidence in storage capacity for a final investment decision to be made by a project proponent. For this reason, regional resource assessments are not a substitute for the detailed characterisation and predictive modelling studies that need to be undertaken for site-scale storage assessment. Regional resource assessments can, however, assist project proponents with the site selection process and are important to provide context for policymakers and regulators.

The length of time required to prove site-specific storage capacity to support a final investment decision is variable. For storage in depleted oil and gas fields or associated with EOR, existing detailed knowledge of the subsurface and available infrastructure may allow rapid formulation of plans and regulatory applications to store CO_2. In contrast, proposals to store CO_2 in deep saline formations, especially where characterisation data is sparse, may require longer.

[14] US DOE, 2015. *Carbon Storage Atlas – Fifth Edition (Atlas V) 2015.*

Injectivity

Having the appropriate level of storage resources is not enough on its own to support widespread global CCS deployment; subsurface reservoirs must be able to accept CO_2 at an appropriate rate in relation to the capture process (within pressure management considerations) for storage to be economically attractive.

This *Global Status of CCS: 2016* report describes how adequate injectivity has been demonstrated in a number of dedicated storage projects around the world and across a range of geological environments.

Most of the projects reviewed have successfully targeted sandstone reservoirs in deep saline formations, including at large scale. Depleted gas fields also offer significant opportunities for dedicated storage and have been demonstrated at pilot scale.

Technical factors which control injectivity include reservoir permeability, thickness and pressure, as well as engineering factors, including well construction and CO_2 stream composition. Most of the reviewed projects conform to published site selection criteria, for example, minimum permeability of 20 millidarcy (mD) and minimum thickness of 20 metres (according to a study published by the IEAGHG).[15]
An understanding of the environment in which reservoir rocks were deposited can aid the interpretation of characterisation data for an estimation of injectivity, but reliable determination for deep saline formations requires field testing of wells to account for the heterogeneity (variability) in most reservoirs.

Technology developed by the oil and gas industry provides remedial options for potential problems with injectivity at some sites, which can include unforeseen reservoir conditions or damage to the reservoir in the vicinity of a wellbore.

A majority of the subsurface CO_2 injection undertaken to date has been in the US for CO_2-EOR, with significant quantities also injected in Canada (and growing interest in China and parts of Central and Latin America and the Middle East). CO_2-EOR operations are typified by a significant number (tens or hundreds) of injection and production wells in most fields. This very large number of wells, in comparison to the number of wells in dedicated storage sites, means that adequate injectivity can be achieved in less permeable or thinner reservoirs than is typically the case for deep saline formations.

CCS EDUCATION AND OUTREACH

While global climate and energy models continually emphasise the value and importance of CCS in meeting global emission reduction targets, the levels of public/political awareness of the technology remain persistently low. This disconnect between expert knowledge and public awareness is a challenging issue for CCS deployment.

CCS social research findings, project experience, and learnings from those working on communicating and engaging the public on broader issues around energy and climate change, all point to the value of education and informal awareness raising activities to improve understanding, set topics in a relevant context, and improve public engagement.

This *Global Status of CCS: 2016* report includes an education and outreach feature which examines some of the common challenges faced by CCS educators, and also showcases a variety of creative solutions that have been developed and adapted by educators and engagement staff around the world to engage a much wider group of stakeholders and improve understanding of CCS technologies.

Building Trust

Building trust and familiarity between project developers and stakeholders is of critical importance – trust in the messages being communicated, trust in the messengers and trust in the engagement process itself. Project experiences have shown that investment in comprehensive stakeholder and community education and outreach activities early in project development planning can create a 'virtuous circle', whereby trusted relationships form between stakeholders and developers through repeated positive interactions and a growing understanding of each other's motivations and concerns.

[15] IEAGHG, 2009. *CCS Site Characterisation Criteria.* Cheltenham. While the IEAGHG study suggested 'favourable' criteria, 'positive' criteria were suggested by Chadwick, A. et al. 2007. *Best Practice for the Storage of CO_2 in Saline Aquifers – Observations and Guidelines from the SACS and CO_2STORE Projects.* Nottingham. British Geological Survey.

A good recent example of this positive response to comprehensive, early engagement efforts is the highly successful education and outreach program conducted by the Tomakomai CCS Demonstration Project in Hokkaido, Japan.

The Tomakomai Project's interactive CCS exhibit provides an overview of the entire project but in a game format: different coloured balls are inserted into clear plastic boxes to represent different gases at the start of the process, but as you progress through the demonstration all the coloured balls are filtered out so that only the green balls (representing CO_2) are securely stored at the end.

Photo credit: Japan CCS Co., Ltd

Techniques are being developed to improve the reach of CCS education and engagement, by using less formal engagement mechanisms and aiming to set learning in a relevant context for the audience. Again, building confidence and familiarity between developers and stakeholders is key with this approach.

Institute supported research has highlighted that when stakeholders lack knowledge and confidence with a topic, they often look to close friends, family and any trusted groups (such as active, well-known environmental NGO or academic groups) in their area to help form their opinion.

Projects which manage to establish a strong, trusted presence and familiarity within communities and within the stakeholder groups of influence in these communities, are more likely to have their projects welcomed. Stakeholders are more likely to engage and feel confident enough to ask direct questions, rather than object to things simply because they are not well understood. This level of stakeholder understanding and management will usually go far beyond the standard statutory engagements and public meetings required for standard construction efforts.

In 2015, the Institute worked in partnership with Shell to create a community education event focused on geology and CO_2 storage (as part of the education and outreach approach for the Peterhead Project in north-east Scotland, see following page). The 'Geological Journey' was developed as an engaging event to improve understanding of complex geological concepts that are important for CO_2 storage: depth, scale, geological time, the movement of the Earth's plates and our planet's changing climate.

Milestone 5 – the Geo-Journey took a dramatic turn one kilometre in, when participants had to battle giant asteroids and volcanoes to learn about the iridium layer and Balmoral tuffite that might have helped to wipe out the dinosaurs!

Photo credit: Shell

Supporting educators, improving reach and tackling misconceptions

While there have been considerable advances in project communications with local communities, CCS communications more generally must tap into ‘critical stakeholders’ or influential opinion shapers such as environmental groups and educational institutions involved in informing the young people who will be our future business, government and community leaders.

While standard school science curricula are well informed about alternative energy technologies, CCS is under-represented and teachers report a lack of confidence in teaching about the technology. In response to this, there are excellent examples of high quality CCS education resources being developed around the world.

Since 2012, the Institute has been working in collaboration with education and outreach experts from around the globe to build and share a comprehensive education program that offers access to quality, up-to-date education and outreach resources on energy, CO_2, climate change and CCS. Collaborative efforts to translate and adapt the Institute’s ‘CO2degrees Education’ program to meet different language and cultural requirements have been undertaken in several locations (including Japan, China and, most recently, Mexico).

Middle school students in China take instructions to build their own CO_2-enhanced oil recovery experiment during a CO2degrees education workshop.

Photo credit: The High School Affiliated to Renmin University of China

Institute experiences and findings from the wider education literature highlight the many benefits of integrating local educators into the creation and adaptation of materials and the critical importance of supporting those in a position to teach about CCS. The variety of innovative CCS education and outreach initiatives is an encouraging indicator of the growing levels of project investment and commitment to this area.

Education and outreach should be an essential component of any good stakeholder engagement plan. Good, comprehensive programs can also serve a more fundamental purpose. Basing teaching about CCS in the wider context of tackling climate change, living more sustainably and making smart energy choices, helps education and outreach initiatives improve understanding of one of the world's most critical challenges; and helps society engage in a much more informed discussion.

GLOBAL STATUS OF CCS: 2016

This *Global Status of CCS: 2016 Summary Report* provides an overview of the key findings contained in the package of volumes that comprise the *Global Status of CCS: 2016* release, as well as from other recent releases by the Institute. Institute Members can access all materials associated with the *Global Status of CCS: 2016*.
This Summary Report is publicly available through the Institute's website.

Volume 1: International Climate Discussions and CCS considers the importance of the Paris Agreement for global efforts on climate change and the important role that CCS must play if the ambitions of the Agreement are to be realised.

Volume 2: Projects, Policy and Markets details key global CCS project and policy developments as well as regional trends in the Americas, Asia Pacific, Europe, the Middle East and Africa. A comprehensive compendium of large-scale CCS projects data is also provided in this volume.

Volume 3: CCS Technologies discusses all elements of the CCS technology chain (capture, transport and storage) and explores the current status of CO_2 capture in the industrial sector, ongoing research in transportation and how adequate injectivity has been demonstrated in a number of projects around the world and across a range of geological environments.

Volume 4: CCS Education and Outreach examines some of the common challenges faced by CCS educators and showcases a variety of tools developed by educators and engagement staff around the world to engage a much wider group of stakeholders and improve understanding of CCS technologies.

More information about the Institute can be found on its website at: www.globalccsinstitute.com

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Cover image: Aerial view of Tomakomai CCS Demonstration Project facilities, located at Tomakomai City, Hokkaido, Japan.

Image provided by JCCS.

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