Five keys to unlock CCS investment
Global investment in low-carbon energy reached USD 850 billion in 2016, with USD 297 billion of that flowing to renewable energy technologies and USD 231 billion to energy efficiency. Much of this investment has been underpinned by government policies and regulation targeted at supporting the shift to a low-carbon energy sector. Yet investment in the deployment of another critical climate technology — carbon capture and storage (CCS) — is falling well behind, with only around USD 1.2 billion invested in 2016.

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We face an unprecedented challenge in achieving climate objectives. Without CCS, this challenge becomes infinitely greater. Our scenario analysis has consistently highlighted that CCS will be critical for delivering the deep emission reductions needed across fossil fuel-based power and many industrial applications, while providing the opportunity for “negative emissions”. CCS can also help promote greater energy security, ensure continued baseload power generation capability, support diversity of power generation, and enhance economic prosperity and employment.

While some CCS facilities have been operating commercially for several decades, most CCS applications, including in power, steel and cement manufacture, are at an early stage of commercialisation and, therefore, at the top of the cost curve. While this presents an investment challenge, it also underscores the enormous potential of CCS; the first-of-a-kind CCS projects in the power sector have already identified future cost reductions on the order of 30%.

A significantly strengthened global effort is needed to accelerate the commercialisation of CCS. In this report, we offer “The Five Keys to Unlock CCS Investment”:

1. **Harvest “low-hanging fruit”** to build CCS deployment and experience from the ground up.
2. **Tailor policies** to shepherd CCS through the early deployment phase and to address the unique integration challenges for these facilities.
3. **Target multiple pathways to reduce costs** from technological innovation in carbon capture and CO₂ utilisation to progressive financing arrangements.
4. **Build CO₂ networks** and accelerate CO₂ storage assessments in key regions.
5. **Strengthen partnerships** and co-operation between industry and governments.

The International Energy Agency (IEA) will continue to play a role in helping to bring together industry, governments and our extensive technology network in support of this important global effort. We look forward to continuing our partnerships with CCS leaders and decision makers to ensure this crucial technology can play its role in a secure and cost-effective global energy transformation.

Dr. Fatih Birol  
**Executive Director**  
International Energy Agency
An unprecedented transformation of global energy systems is under way, with notable improvements in global energy intensity, three years of stable energy sector CO₂ emissions, and remarkable advances in the cost, performance and contribution of renewable energy technologies. In this context, the question is often asked: does the world really need CCS?

The answer is an unequivocal yes. Current trends are encouraging, but the gap between where global efforts are heading and agreed climate targets is immense, requiring around 760 gigatonnes of CO₂ (GtCO₂) emission reductions across the energy sector between now and 2060. This is equivalent to more than 30 years’ worth of energy emissions, and — importantly — is additional to the anticipated impact of current policy efforts and commitments. All technologies will be needed as part of the significantly strengthened and accelerated international action to bridge this gap.

CCS is particularly important because it offers a solution to some of the most challenging greenhouse gas emissions. This includes tackling emissions from industrial processes and from a large and relatively young global fleet of coal- and gas-fired power generation units. CCS in combination with bioenergy also provides the means to deliver “negative emissions” to offset emissions from sectors where direct abatement is not economically or technically feasible, such as in aviation transport or agriculture.

IEA modelling has long highlighted the role of CCS in supporting a secure, cost-effective and sustainable transformation of global energy systems. In the IEA 2°C Scenario (2DS), CCS provides 14% of the cumulative emission reductions needed in the period to 2060 to limit future temperature increases to 2°C (see Figure 1) (IEA, 2017).

**Figure 1.** CCS contributes 14% of the cumulative emission reductions needed in the 2DS

CCS is not a new or untested technology. CO₂ capture and separation has been applied in industry for many decades, and the practice of injecting CO₂ for enhanced oil recovery (CO₂-EOR) first commenced in the 1970s. Today, there are 21 large-scale, integrated projects operating or under construction throughout the world and across various applications, including coal-fired power generation, natural gas processing, steel manufacture and oil sands upgrading. These projects are in addition to around 100 pilot plants and an extensive global research and development (R&D) push. This collective experience has brought CCS to the stage where the major barrier to deployment is no longer technological, but political and commercial.
The value of **CCS** goes beyond CO$_2$ abatement

CCS is principally an emissions mitigation technology, but it is also able to contribute to broader energy security, environmental, societal and economic goals during this period of global energy system transformation. A recent study undertook a detailed evaluation of the economic and social benefits associated with CCS investment in the United Kingdom and found a 5:1 payback to the economy for every pound invested (Summit Power, 2017).

At a global level, the benefits of CCS include:

- Enabling greater energy diversity, including the continued, cleaner use of fossil fuels.
- Maintaining long-term employment and investment opportunities in emissions-intensive industrial centres, which are often geographically concentrated.
- Protecting the value of substantial capital investments in power and industrial infrastructure.
- Expanding technology choices for dispatchable power generation.
- Enabling investment in alternative energy sources, including low-emission hydrogen production from fossil fuels.
While CCS project deployment has made very encouraging progress in recent times — including 11 large-scale projects commissioned in the last seven years — this momentum is not assured as we look towards the next decade (see Figure 2). The total number of large-scale CCS projects operating, under construction, or in development has shrunk from a peak of 77 in 2010 to 37 today (GCCSI, 2017a). There are now fewer projects in development than under construction and operational, and several of these earlier-stage projects face an uncertain future without appropriate policy support. Since 2014, only one CCS project has taken a final investment decision anywhere in the world: the Yanchang Integrated CCS project in the People’s Republic of China (hereafter, “China”).

Figure 2. The shrinking project pipeline must be addressed

Source: GCCSI (2010-16), Global Status of CCS.

CCS investment will need an urgent “jump-start” if it is to contribute to future emission reductions at the scale envisaged in the 2DS. While long-term scenarios are not intended to be prescriptive, an almost ten-fold increase in CO₂ capture and storage rates would be needed by 2025 to put CCS “on track” for the 2DS. This is associated with an investment requirement of more than USD 60 billion (IEA, 2017).

CCS investment trends

To date, an estimated USD 10 billion in capital investment has been made in large-scale CCS projects that are operating or under construction globally, most of it this decade. This is in contrast to almost USD 2.3 trillion of investment in renewable technologies made between 2010 and 2016.

Three key trends emerge from the CCS investment story:

1. Predominately private capital, but with this increasingly being leveraged through government support

   More than 80% of cumulative capital investment in large-scale projects has been from the private sector; however, governments have played an increasingly important role in recent times. In the period before 2010, all of the investment in large-scale CCS projects was private capital. Since 2010, 15 projects have been commissioned or are under construction, and around half of these (8 projects) have received a capital grant, with the value of these grants totalling USD 1.6 billion (see Figure 3). Of the seven projects that have not received a direct capital subsidy, four are owned and operated by a state-owned enterprise.

2. Large-scale projects are defined according to the Global CCS Institute as “projects involving the capture, transport, and storage of CO₂ at a scale of at least 800 000 tonnes of CO₂ annually for a coal-based power plant, or at least 400 000 tonnes of CO₂ annually for other emissions-intensive industrial facilities (including natural gas-based power generation)”.

3. This figure does not include investment in large-scale projects that did not proceed to operation. It includes capital investment and excludes operational costs. The estimate is due to incomplete or unavailable data for some operating CCS projects.

4. This figure only includes capital grants and does not include grant payments that cover project operating costs over a specified project lifetime. It does not include public grants made to projects that did not proceed to operation.
2. A slow expansion in investment outside North America

More than two-thirds of CCS projects currently in operation or under construction are located in Canada and the United States. As recently as 2014, large-scale CCS experience outside North America was limited to three countries: Norway (Sleipner and Snohvit), Algeria (In Salah) and Brazil (Petrobras Santos Basin Pre-Salt Oil Field CCS). Today, projects are operating or under construction in Australia, China, Saudi Arabia and the United Arab Emirates, while South Korea and the United Kingdom have projects in earlier stages of development.

The availability of a revenue stream from CO₂-EOR has supported investment decisions in three-quarters of CCS projects to date. For example, the USD 1 billion Petra Nova CCS project received USD 190 million in grant funding from the United States Department of Energy and is now operating on commercial terms based on the additional oil revenue. The project is reportedly able to cover its costs at oil prices of USD 50-55 per barrel (Crooks, 2017).

3. Reliance on a revenue stream for the captured CO₂

The availability of a revenue stream from CO₂-EOR has supported investment decisions in three-quarters of CCS projects to date. For some early projects, the revenue from CO₂-EOR was sufficient for commercial CCS operation, while more recently EOR revenue combined with capital grants has helped to close the commercial gap and support investment in CCS applied to coal-fired power generation. For example, the USD 1 billion Petra Nova CCS project received USD 190 million in grant funding from the United States Department of Energy and is now operating on commercial terms based on the additional oil revenue. The project is reportedly able to cover its costs at oil prices of USD 50-55 per barrel (Crooks, 2017).

Commercial interest in CO₂-EOR continues to expand, including in the Middle East and China, and it is expected to remain a major factor in supporting early CCS investment notwithstanding the current low oil price environment. However, these opportunities will be limited by region and geology, and accordingly CO₂-EOR will not be an alternative to developing dedicated CO₂ storage sites.
The urgency of the investment task

A failure to boost momentum in CCS investment in the near term will have implications for future climate goals. As the Intergovernmental Panel on Climate Change (IPCC) has highlighted, the ability to achieve long-term climate targets depends “to a greater extent” on directing efforts towards “developing the technologies and institutions that will enable future deep emissions cuts rather than exclusively on meeting particular near-term goals” (IPCC, 2014). CCS holds significant potential to support these deep emission reductions — and even “negative emissions” — across the global energy sector, but this relies on building a strong foundation today.

More projects will be needed to realise the significant potential for learning-by-doing cost reductions and to accelerate the pathway to commercialisation.

The urgency of the current investment task is underscored by several factors:

- **Long lead times for projects:** Many CCS projects are relatively complex endeavours that can be as long as a decade in planning and construction, particularly if greenfield CO₂ storage assessments must be undertaken. It is illustrative that many of the projects coming online in the last two years received government funding support back in 2009 and 2010, when stimulus packages were established in response to the global financial crisis.

- **Learning-by-doing cost reductions:** More projects will be needed to realise the significant potential for learning-by-doing cost reductions and to accelerate the pathway to commercialisation. Deployment can also foster innovation in new technologies with potential for further cost reductions.

- **Confidence in CO₂ storage:** Significant further work is required to convert theoretical storage capacity into “bankable” storage, which is a prerequisite for investment in any CCS facility.

- **Avoiding stranded assets:** An understanding of the future role and availability of CCS at a local and regional level, including confidence in CO₂ storage, is important to inform today’s energy policy and investment decisions.

- **Developing institutional capacity:** Practical CCS experience is needed for policy and regulatory frameworks to evolve in key regions and to retain and expand institutional and technical capacities. This includes industry and government as well as the financial and insurance communities.

**Replicating investment success: What factors have been important to date?**

Large-scale CCS investment has occurred in circumstances where economic, policy and project-specific factors have been sufficiently aligned to establish a business case. The factors that have been critical to securing an investment decision have included:

- Strong and sustained government support for the development of CCS, including policy incentives that adequately address the additional capital and operating costs of CCS facilities.

- Well-understood geology that can support CO₂ storage (or CO₂-EOR) at the desired scale, as well as the availability of expertise to utilise it.

- A revenue stream for the captured CO₂, notably from CO₂-EOR sales.
CCS investment needs an urgent boost

- A requirement or incentive to reduce emissions through emissions performance standards, the imposition of a sector-specific carbon tax or regulatory measure — often in combination with a grant or subsidy.6

- A commercial structure, often a single enterprise or simple joint venture, that can manage cross-chain default risks for integrated projects. Alternatively, business models that enable the separation of these elements of the CCS chain have been effective in managing these integration challenges.

- A low-risk political, social and regulatory environment for CO₂ storage, including regulatory frameworks to facilitate access to pore space and to manage long-term liability for the stored CO₂ (adapted from IEA, 2015a).

Notably, for every CCS project that has successfully reached a final investment decision, at least two large-scale projects have been cancelled (IEA, 2016a). The factors that have contributed to these projects not proceeding are varied, but are often associated with the absence of those factors listed above, in combination with first-of-a-kind technology challenges. They include a lack of adequate and consistent policy support, highly prescriptive and inflexible programme requirements, a failure to resolve or balance risks that are unable to be managed or taken by commercial entities (such as long-term liability or cross-chain default), lack of commercial CO₂ storage options, higher than expected project costs, and community opposition.

6 The application of a carbon tax or regulatory requirement has been effective in supporting CCS investment in a limited set of circumstances, all involving high-margin projects producing natural gas or liquefied natural gas, with CO₂ storage in close proximity and companies with the requisite subsurface expertise.

7 It is not unusual or unexpected that some large-scale CCS projects would not proceed to a final investment decision following pre-feasibility or feasibility studies. Indeed, this is a prudent approach to projected development that is applied to all major infrastructure investment decision. The reality that not every project will proceed underscores the need to ensure more projects are entering the pipeline.

Box 1. The potential for CO₂ utilisation

The conversion of CO₂ into valuable and usable commercial products could create new revenue opportunities for CCS facilities. Global demand for CO₂ is around 200 million tonnes (Mt) per year and includes urea production, carbonated drinks, water treatment and pharmaceutical processes (IEA, 2017). New or growth markets could include use of CO₂ as a feedstock or as working fluid in some processes (including in power generation), conversion to polymers or carbonates, concrete curing and mineral carbonation. Research is also being conducted on the potential to turn CO₂ into transport fuels.

Key questions for CCU opportunities are the potential for scalability and whether the CO₂ will ultimately be re-released. While CCU will not be a substitute for the permanent storage of emissions, CCU can help to lower the commercial barrier for near-term CCS investment in niche applications. In some circumstances, CCU could also support innovation in CO₂ capture technology and the development of CO₂ transport infrastructure.

In North America, two international challenge competitions are under way to accelerate innovation in this area: the USD 20 million Carbon XPRIZE, led by the Canadian Oil Sands Innovation Alliance and NRG Energy; and the CAD 35 million Grand Challenge: Innovative Carbon Uses, led by Emissions Reduction Alberta. These innovative initiatives are likely to contribute to better understanding of the scalability and the emissions reduction potential of CCU technologies.
A renewed international commitment to CCS must revive momentum in the project pipeline, maximise the global impact of existing investments, and build a solid foundation for the rapid and immediate ramp-up of CCS deployment.

The five keys to unlock public and private investment in CCS are:
1. Harvest low-hanging fruit.
2. Tailor policies.
3. Target multiple pathways to reduce costs.
5. Strengthen partnerships.

Key 1: Harvest low-hanging fruit

The scale of the commercial barrier to CCS investment varies considerably. Identifying and pursuing opportunities where this barrier is lower provides a pragmatic basis from which to build the foundation for future deployment “from the bottom up”. These opportunities can offer a niche from which to refine CCS technologies, grow commercial experience, and reduce costs — all while delivering substantial CO₂ reductions and minimising the amount of public support required. With strategic planning, these opportunities could also form the basis of future CCS hubs and facilitate the early development of CO₂ transport and storage networks.

Where are these “low-hanging fruit” for CCS to be found?
A number of potential contexts could support a least-cost investment proposition, individually or in combination:

- Emissions-intensive industrial processes: Those that inherently produce a high-purity CO₂ stream are of interest, such as natural gas processing, hydrogen production, bioethanol production and fertiliser manufacture. For example, the additional investment required at the Sleipner CCS project to compress and inject the CO₂ separated from the reservoir gas was around USD 100 million (in 1996). This world-first investment has now supported the safe and permanent storage of 20 million tonnes of CO₂ over 20 years of operation (IEA, 2016a) (see Box 2).

- Demand for CO₂: CO₂-EOR is by far the largest source of demand for CO₂ today, with around 70 MtCO₂ used annually. EOR has the benefit of scale (with growing demand) and can also contribute to climate objectives, as the vast majority of the CO₂ can be permanently retained in the reservoir (IEA, 2015b). Other CO₂ utilisation options, including beverages, mineral carbonation, concrete curing and CO₂-based fuels, have future potential but with limitations (see Box 1).

- Proximity to CO₂ storage or transport infrastructure: Close proximity to a proven CO₂ storage site and/or access to existing transport infrastructure have played a role in reducing the investment costs of several early projects. For example, the Illinois Industrial CCS project, which applies CCS to bioethanol production in combination with a dedicated storage solution, has a transport distance of only 1.6 kilometres (GCCSI, 2017b). In some circumstances, the ability to reuse existing oil and gas infrastructure — including offshore platforms, wells and pipelines — could also reduce investment costs.

- Emerging economies: Lower construction and operational costs in emerging economies can make CCS investment more attractive relative to other regions. In China, for example, it is estimated that many coal-to-chemical plants could be equipped with CCS for less than USD 20 per tonne of CO₂ (ADB, 2015). IEA analysis suggests that even in the power sector — where the commercial gap is generally much larger — around 100 gigawatts of existing coal-fired generation capacity could be equipped with CCS for less than USD 50 per megawatt hour (IEA, 2016b).
While useful, these least-cost opportunities are limited and are not an alternative to early investment in the development of more challenging CCS applications. Industrial processes that do not produce a high-purity stream of CO$_2$ (such as cement production) and which have few alternatives to CCS for deep emission reductions are a priority if climate goals are to be met. Applying CCS to fossil fuel-based power generation facilities, especially retrofitting of existing facilities, will be important to avoid the long-term “lock-in” of emissions, support energy security objectives in some regions and to protect the value of these assets as emissions constraints are tightened.

**Box 2. Cultivating CCS opportunities in Norway and Australia**

Even with a much lower commercial barrier, early opportunities for CCS investment are unlikely to emerge organically in the absence of a sufficient market signal. Examples of how early opportunities have been cultivated by governments and industry can be found amongst the current CCS project portfolio:

- The Sleipner project in Norway, which has now been operating for more than 20 years, came about after the introduction of a CO$_2$ tax on offshore oil and gas production. The tax was complemented by a commercial need to separate the CO$_2$ from the natural gas to meet market requirements, strong subsurface expertise and knowledge, favourable geology, a culture of corporate social responsibility and relatively high product margins.

- In Australia the Gorgon CO$_2$ Injection Project was first proposed as a component of the larger Gorgon Project, by the Gorgon Joint Venture in 2003. The injection project has received an AUD 60 million capital contribution from the Australian government. The Australian and Western Australian governments have agreed to provide an indemnity against certain long-term liabilities, mirroring the provisions in the Australian offshore CCS legislation. Once operational, it is believed that the Gorgon CO$_2$ Injection Project will be the largest greenhouse gas mitigation project undertaken by industry globally, targeting the disposal of up to 4 Mt per year.

The scale and nature of the incentives needed to establish a business case for investment in early, lower-cost CCS projects will differ between projects and regions. Importantly, a “stick-only” approach (with no accompanying “carrot” or support) has proven effective in securing investment in CCS in only very limited circumstances.

**Priority actions**

1. Identify where low-cost and strategic opportunities for CCS investment may be available.
2. Identify and implement appropriate policy mechanisms to facilitate targeted investment.
3. Engage with multi-lateral development banks to identify opportunities to support lower-cost or strategic projects in key emerging regions.
Key 2: Tailor policies

Tailored, fit-for-purpose policy measures will be needed to secure commercial CCS investment. This is in much the same way that the rapid advancement of other low-emission technologies, particularly renewable energy, has been achieved with measures such as targets, mandates and feed-in-tariffs. While a carbon price or CO$_2$ tax can provide an important long-term investment signal for CCS, carbon markets are neither expanding nor maturing at a pace sufficient to support deployment of CCS at the scale required, and within the timeframe needed, to meet climate goals.

Effective policy support for CCS will need to be tailored to local conditions and recognise the unique characteristics of these investments, including the following:

- There is currently limited or no commercial driver for CO$_2$ emission reductions in the vast majority of sectors and regions where CCS is expected to play a role.
- Many of the sectors where CCS will be required, including steel and cement, operate in competitive international markets where additional costs associated with CCS cannot be passed on to consumers.
- The three elements of CCS — capture, transport and storage — are different activities with different risk and investment profiles and technical capacity requirements.
- The integration of the CCS value chain can bring complex commercial risks, including cross-chain default risks, which the private sector is unlikely to absorb in an environment that offers limited benefits for its CCS investment (adapted from IEA, 2017).

A range of tailored policies and incentives has proven effective in supporting CCS in various jurisdictions, including policies targeted at different parts of the CCS value chain and across the project life cycle (see Figure 4 for examples).

Tailored, fit-for-purpose policy measures will be needed to secure commercial CCS investment.
The five keys to unlock CCS investment

Addressing integration and CCS-specific risks

The unique technical and commercial risks associated with integrated CCS projects have proven to be a significant barrier to investment. These risks include:

- Cross-chain default (also referred to as "project-on-project" risk).
- Post-decommissioning CO₂ storage risk.
- Subsurface CO₂ storage performance risks impacting on storage rates and capacity.
- Decommissioning cost sufficiency and financial securities related to the CO₂ storage permit.
- Insurance market limitations for CO₂ transport and storage infrastructure requirements (Hackett, 2016).

A strong case exists for the transfer of some of these risks to the public sector in the early stage of CCS deployment, both to remove a significant barrier to investment and to reduce the risk premium attached to the cost of capital. For example, government underwriting of CO₂ transport and storage infrastructure, either through a regulated infrastructure approach or a publicly backed CO₂ transport and storage company, could facilitate investment in CO₂ capture across a range of industrial sectors.

Climate strategies and CCS

Policy mechanisms for CCS should ideally be implemented within the context of a clear, long-term vision for climate and energy policy that articulates a role for CCS. The Paris Agreement invites Parties to submit mid-century climate strategies before 2020, and this could provide an important opportunity to develop such a vision. Many countries will rely on CCS to meet long-term climate goals and, in almost all instances, will need to commence planning for this by the early 2020s, if not sooner. This includes undertaking CO₂ storage assessments, CO₂ network planning, and building institutional and technical capacity. Nationally determined contributions (NDCs) should be aligned and calibrated to these mid-century climate strategies, including recognition of the important role of CCS in the period to 2030.

Priority actions

1. Design and implement targeted policy mechanisms able to support early investment in CCS in power and industry.
2. Identify policy approaches to reduce integration and CCS-specific risks for early CCS projects.
3. At a national level, identify and articulate the value and role of CCS in mid-century climate strategies and in NDCs.
Key 3: Target multiple pathways to reduce costs

The potential for cost reductions in CCS is considerable, particularly as many applications are still in the early stage of commercialisation and the costs experienced by the first-of-a-kind projects will be significantly higher than subsequent projects. However, accelerating the technology learning curve for CCS will be challenging in practice, with CCS projects typically involving large capital investment with long lead times. The first projects in a region will typically also require investment in new CO$_2$ transport and storage infrastructure, with associated cost and planning requirements. Unlike solar and wind (for example), which are far more modular, involve smaller capital outlays and can benefit from production economies of scale, realising the opportunities for CCS cost reduction is likely to be a slower, “lumpier” process than that experienced by these renewable technologies.

The operators of Boundary Dam in Canada – the world’s first application of CCS to a coal-fired power unit – have assessed that they could reduce the capital costs of the next project by as much as 30%.

Multiple pathways are available to significantly reduce the cost of CCS:

- **Expand the project pipeline.** Cost reduction through learning by doing at scale is proving, in practice, to have a large impact. The operators of Boundary Dam in Canada – the world’s first application of CCS to a coal-fired power unit – have assessed that they could reduce the capital costs of the next project by as much as 30% and operating costs by 25–30% (IEAGHG, 2015). These learning-by-doing cost reductions stem from factors such as reducing the redundancies of overdesign, improved construction techniques, technology innovation and refinement, and supply chain competition.

- **Optimise CO$_2$ transport and storage infrastructure.** The UK CCS cost reduction taskforce identified optimal configuration of transport and storage networks to be a leading contributor to future cost reductions. This includes large CO$_2$ storage clusters and planning for shared, high-use pipelines that can support emission reductions across sectors (Chapman et al., 2013). The UK utility company, National Grid, also estimated that the infrastructure resulting from the now-abandoned White Rose CCS project would have reduced the transport and storage unit cost of future projects by 60–80% (CCSA, 2016).

- **Develop progressive financing.** External project financing has played a relatively minor role in CCS investments to date, but will need to expand to support future widespread deployment. Capital markets have an increasing appetite for low-carbon assets, but CCS remains a relatively unfamiliar technology for most financiers. The cost of financing can be reduced not only with increased project experience and reduced technology risk, but also through progressive financing arrangements and the involvement of international financing institutions or export credit agencies, which can offer near-zero interest rates or loan guarantees.

- **Pursue technological innovation.** The next generation of CCS technologies, most notably CO$_2$ capture technologies, could deliver step-change improvements in cost and performance. For example, in the United States, NET Power will commence a 50 megawatt thermal demonstration of its Allam Cycle process in late 2017, which has potential to make zero-emission natural gas-fired power generation cost-competitive with current technologies (NET Power, 2017). On the demand side, innovations in CO$_2$ utilisation technologies could expand the market for CO$_2$ and provide a revenue stream for CCS projects while also accelerating innovation in CO$_2$ capture technologies.

R&D support is required for both incremental improvements in current technologies and next-generation technologies, with initiatives such as Mission Innovation providing a valuable platform to increase investment and global collaboration. Continued investment in pilot and smaller demonstrations will also be necessary, with these projects making a significant contribution to CCS technology development, expanding the global knowledge base, and building public awareness and acceptance.

**Priority actions**

1. Continue sharing practical, detailed information on operating projects to deliver faster learning-by-doing cost reductions.
2. Promote opportunities to reduce financing costs for CCS projects, including through engagement with the international financial community.
3. Maintain and, where appropriate, accelerate support for R&D and pilot demonstrations for new CCS technologies, including under initiatives such as Mission Innovation.
**Key 4: Build CO₂ networks**

The widespread deployment of CCS at a scale and pace consistent with the 2DS pathway is predicated upon substantial investment in CO₂ transport and storage networks that can service multiple facilities. Planning and development of these networks needs to start now in order to promote optimal and efficient investment decisions.

**CO₂ storage assessment**

The identification and development of “bankable” CO₂ storage resources could be the single most important enabler of CCS investment across a range of industrial and power applications. A decision to proceed with an investment in CO₂ capture will only be made with a high degree of confidence in the CO₂ storage solution.

At a global level, CO₂ storage resources appear to be more than adequate to accommodate future requirements. For example, the estimated geological storage resource of the United States is between 2.376 GtCO₂ and 21,000 GtCO₂, in China it is around 1.500 GtCO₂, and in the United Kingdom 78 GtCO₂ (GCCSI, 2016). To put this in context, the cumulative global storage requirement between now and 2060 in the 2DS is around 140 GtCO₂.

However, these resource estimates should not be taken as a guarantee of future storage availability:

- Significant further work is still required to convert theoretical storage capacity into “bankable” storage that can support investment decisions at a regional and national level. In particular, to provide confidence that the desired amounts of CO₂ can be injected at desired rates, a more detailed assessment of the capacity, containment and injectivity of prospective sites will be needed, as well as the commercial, regulatory and social barriers to development.

- There is currently no globally standardised classification of potential reservoirs for CO₂ storage, and, accordingly, the estimates vary widely. However, the Oil and Gas Climate Initiative (OGCI) is working with the Society of Petroleum Engineers to “create a globally usable storage resource management system” (OGCI, 2016).

The assessment of CO₂ storage resources can take up to ten years, depending on the storage option, and is therefore becoming an urgent priority in many key regions that will rely on CCS for future emission reductions.

**Significant further work is still required to convert theoretical storage capacity into “bankable” storage.**

**Transport and storage infrastructure**

In conjunction with CO₂ storage development, early planning and co-ordination of transport networks will promote more efficient investment decisions and, as discussed above, can support significant cost reductions for future CCS facilities. This includes opportunities to re-use existing oil and gas infrastructure in some regions. An understanding of the future role of CCS at a national or regional level is required, underpinned by a long-term vision for the development of the industry that allows for strategic, incremental investment in infrastructure.

Governments will need to play a leading role in CO₂ transport and storage infrastructure planning and development, recognising that there is a strong public good element to this investment, a need for co-ordination across regions and with industry, and a current lack of incentive for the private sector to undertake this effort (see IEA, 2017 for further discussion). The approach will need to reflect national circumstances, but it could involve publicly owned or regulated infrastructure that allows for increased private investment over time.

**Priority actions**

1. **Accelerate pre-competitive CO₂ storage assessments in key regions and implement a consistent methodology for CO₂ storage resource estimates.**

2. **Undertake CO₂ transport infrastructure audits and long-term planning at a national and regional level.**

3. **Identify business models to support multi-user CO₂ transport and storage infrastructure investment.**

![Image of CO₂ storage facility](Courtesy: Petra Nova)
Key 5: Strengthen partnerships

Collaboration and shared experience will be critical to supporting rapid and widespread uptake of CCS technologies across the globe. This includes collaboration to facilitate technology transfer and to share project-based experience with a focus on reducing future costs. In some regions, including Europe, multi-user transport and storage infrastructure will be shared across countries and will require close co-operation across state actors as well as between industries.

The value of collaboration is already well recognised, with a number of global, regional and bilateral initiatives facilitating strong ties within and between government policy makers, industry, researchers and project developers. These initiatives include the Carbon Sequestration Leadership Forum, the IEA Greenhouse Gas Technologies Programme (IEAGHG), the Global CCS Institute and many regional initiatives. The IEA works closely with these initiatives and brings a unique analytical capability and global energy perspective to these important CCS discussions.

While these established initiatives are delivering significant value, opportunities should be explored to strengthen collaboration, particularly between governments and industry, with a focus on enabling investment. This could include industry and government partnerships to:

- Identify and cultivate lower-cost CCS investment opportunities.
- Map and assess CO₂ storage potential in key regions, using a consistent methodology and co-ordinating resource needs as required.
- Undertake national and regional transport infrastructure audits.
- Develop business models for CO₂ transport and storage infrastructure investment.
- Build institutional capacity, including among regulators and the financial community.

In some jurisdictions, and dependent on national circumstances, closer industry-government partnerships could be facilitated through new or improved institutional arrangements, where the implementation of CCS deployment is managed by an independent expert body. This could be through the creation of special government agencies to progress CCS deployment objectives, or the establishment of private consortiums tasked with similar objectives. Such an approach could promote greater flexibility in delivering CCS deployment objectives, including undertaking CO₂ storage assessments and development, and the implementation of infrastructure plans. This approach is proving successful in several countries.

- In Norway, Gassnova, established since 2005, is a state enterprise tasked with supporting CCS implementation, from the development of technology to full-scale deployment, while acting as a technical advisor for Norwegian authorities and climate policy makers. Gassnova has been the project co-ordinator of Norway’s programme to deliver a large-scale CCS project and is currently supporting feasibility studies for three industrial CCS projects.

- In Japan, Japan CCS Co. Ltd was established in May 2008 by a group of 24 major companies with expertise in CCS-related fields, including electric power, petroleum, oil development and plant engineering. The organisation has been commissioned by the Japanese Ministry of Economy, Trade and Industry (METI) to undertake a significant proportion of the country’s CCS programme, including investigations of potential CO₂ storage sites and the management of the Tomakomai CCS demonstration project.

- In Mexico, a working group has been established comprising representatives of government, regulators, and research and academic entities to implement Mexico’s CCS strategy, including identifying regulation, capacity building, public engagement and technology development.
The five keys to unlock CCS investment

needs. In the next four years, the first two pilot projects on CO\textsubscript{2} capture and CO\textsubscript{2}-EOR will commence and Mexico will establish a master’s degree programme on CCUS, a national

Priority actions

1. Identify opportunities to support practical collaboration between government and industry on CCS, including CO\textsubscript{2} transport and storage development at a regional and global level.

2. Support institutional capacity-building among CCS regulators and the finance and insurance communities.

3. Consider the benefits of alternative institutional arrangements, akin to a government-backed “transport and storage company” tasked with delivering clear CCS deployment objectives.


GCCSI (2010-2016), Global Status of CCS, GCCSI, Melbourne.


OGCI (Oil and Gas Climate Initiative) (2016), Taking Action: Accelerating a Low Emissions Future, OGCI.


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International Energy Agency analysis has consistently highlighted the critical role of carbon capture and storage (CCS) technologies in meeting global climate objectives. Yet investment in CCS will need an urgent boost if it is to deliver the deep emissions reductions needed in the power sector and in many industrial processes. In this report, the IEA outlines the “Five Keys to Unlock CCS Investment”:

- Harvest “low-hanging fruit” to build CCS deployment and experience from the ground up.
- Tailor policies to shepherd CCS through the early deployment phase and to address the unique integration challenges for these facilities.
- Target multiple pathways to reduce costs from technological innovation in carbon capture and CO₂ utilisation to progressive financing arrangements.
- Build CO₂ networks and accelerate CO₂ storage assessments in key regions.
- Strengthen partnerships and co-operation between industry and governments.