

CCS 2014

What lies in store for CCS?

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Executive summary

CCS has suffered from a lack of attention by public and policy-makers over the past several years. At the same time, science increasingly points to the dangers of climate change and various mitigation plans continue to emphasise the critical role of CCS to limit temperature increase. The 2013 IEA CCS Roadmap presents a set of actions that are needed between today and 2020 to lay the foundation for scaled-up CCS deployment. It is necessary to now concentrate on concrete action by both governments and industry to drive CCS forward.

It is of particular importance to boost activity in the area of CO₂ storage, on various levels. Storage is critical to any project design and must be addressed up front. While storage is the last of the three steps of a CCS project, it must be developed simultaneously with capture and transport, from the very beginning. This is because reservoir characteristics and behaviour may determine the design and operation of the whole CCS chain. Also, available experience shows that it can take 5-10 years to qualify a new saline formation for CO₂ storage, even when theoretical estimates are already available and look promising.

To understand the emission reduction potential of carbon capture and storage (CCS), decision-makers need to understand the size and distribution of carbon dioxide (CO₂) storage resources. Therefore high-level national and regional storage data is very important and has to be developed first. This can provide information on theoretical storage capacity and reveal geographical areas with significant CO₂ storage potential. While high-level data does not replace site-specific exploration, assessment and testing, it may help individual project proponents to make informed assessments and take decisions regarding the best potential storage sites.

Assessing national storage resources is currently done through various methodologies. It would be important to achieve a clear and widely shared definition of CO₂ storage potential and an agreed method for its calculation. Moving to a uniform methodology can enable stakeholders to identify and compare different storage resources in different locations. There is also a need to enhance the co-operation between organisations that have attempted or completed CO₂ storage resource assessments and those that are looking to begin assessments.

The necessity of large up-front investment in securing storage capacity is also a critical aspect in the process of *investing* in CCS. The final investment decision for a large capture facility cannot be taken without a very high level of confidence that the resulting CO₂ can actually be stored in the envisaged site or sites. Therefore, the whole investment framework and its various stages are either strongly influenced, or actually defined, by the development of the storage site.

In order to achieve mitigation targets, CCS is also critically important for industrial applications, not only for power. Many heavy industries, such as steel and cement, produce significant GHG emissions in their manufacturing processes, and CCS may be the only option to address these emissions. Policy approaches to boost CCS in these industries need to be tailor-made, as the key sectors on question all present their specific circumstances. Many energy-intensive sectors are also exposed to global competition, which makes the policy design critically important.

Recent times have also seen a re-emergence of discussion on CO₂ utilisation. Utilisation is often seen as a means to provide revenue for CCS projects and hence to help CCS traverse the “valley of death” in the absence of sufficient climate-related policies and financial incentives. It is important to carefully categorise the various potential CO₂ utilisation options, as not all utilisation is beneficial to climate change mitigation efforts.

CCS 2014: Overview and introduction

The need to accelerate CCS development

The target date for the 2015 Paris UNFCCC Conference of Parties (COP) for a new international agreement on climate change mitigation draws nearer. Countries are looking more deeply at their potential 'contributions' in reducing their greenhouse gas (GHG) emissions, in particular with a view to achieving the 2-degree target adopted at Cancun in 2010.

As part of this process, carbon capture and storage (CCS) moves increasingly to the forefront as a critical tool, but one that has recently engendered more scepticism and doubt than comfort. CCS investment, demonstration projects and large-scale deployment are well behind the targets envisaged by analysts, governments and industry, causing some to question its viability – and by extension, the practicability of a 2-degree GHG emissions trajectory.

Despite slow progress to date, for the IEA all signs continue to point to the necessity and viability of CCS as a CO₂ abatement technology, within a portfolio of other low-carbon technologies. But important challenges remain ahead.

Last year, the IEA published an update of its CCS Roadmap, setting out some of the important policy and other actions needed to confirm the practicability of CCS as a large scale CO₂ abatement tool and to set it on the required corresponding deployment pathway. Questions exist regarding the amount of CO₂ that can ultimately be stored, in part given concerns regarding storage capacity (a point addressed further below) and correspondingly, the amount of abatement that CCS might ultimately deliver. But in the current phase of development, the challenges facing CCS seem to be less about achieving a large-scale mature business, but rather about creating a robust, credible track record of initial projects and establishing an early-mover business model. In order to help support industry in moving this important low-carbon technology forward, the IEA will continue to provide technical and economic analysis. Through a selection of topical articles, this publication represents a continuation of that effort.¹

The present is critical for the future of CCS

As the IEA Executive Director, Maria van der Hoeven, noted in her foreword to the 2013 IEA CCS Roadmap (2013), *"After many years of research, development, and valuable but rather limited practical experience, we now need to shift to a higher gear in developing CCS into a true energy option, to be deployed in large scale. It is not enough to only see CCS in long-term energy scenarios as a solution that happens some time in a distant future. Instead, we must get to its true development right here and now."*

The quote serves to highlight the need to move from scenarios to action. Given the past and current trends in fossil fuel use and the related CO₂ emissions, the urgency of CCS deployment is only increasing. This decade is critical for moving CCS through and beyond the demonstration phase. This means that urgent action is required, beginning now, from industry and governments to develop technology and the required business models, and to implement incentive frameworks that can help drive CCS deployment in the power sector and industrial applications.

¹ The IEA CCS unit also publishes another regular series, the IEA CCS Legal and Regulatory Review. The Review series is focused on legal and regulatory developments, and is based on contributions from various IEA member and partner governments and international organisations.

Apart from a few notable exceptions, CCS has suffered from a lack of attention by the public and policy-makers over the past years. Unless progress is made in these areas, CCS risks standing still while the energy system continues to evolve.

Seven key actions for next seven years

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The 2013 Roadmap presents seven key actions to be taken in the near term in order to lay the foundation for scaled-up CCS deployment between today and 2020. They require serious dedication by governments and industry, but are realistic. They address all three elements of the CCS process:

- Introduce financial support mechanisms for demonstration and early deployment of CCS to drive private financing of projects.
- Implement policies that encourage storage exploration, characterisation and development for CCS projects.
- Develop national laws and regulations as well as provisions for multilateral finance that effectively require new-build, base-load, fossil-fuel power generation capacity to be CCS-ready.
- Prove capture systems at pilot scale in industrial applications where CO₂ capture has not yet been demonstrated.
- Significantly increase efforts to improve understanding among the public and stakeholders of CCS technology and the importance of its deployment.
- Reduce the cost of electricity from power plants equipped with capture through continued technology development and use of highest possible efficiency power generation cycles.
- Encourage efficient development of CO₂ transport infrastructure by anticipating locations of future demand centres and future volumes of CO₂.

The seven key actions provide guidance to governments and policy makers – and also provide a basis for tracking progress in the development and deployment of CCS. The IEA will continue its analytic work in support of the Roadmap conclusions, and in parallel is developing a series of indicators and metrics to track progress regarding the key actions. This publication provides some additional analysis that supports these actions.

What lies in store for CCS?

One of the major challenges limiting large-scale CCS operations at a global level, both in the short-term and in the longer term is the issue of storage. This publication addresses three interrelated aspects of this puzzle.

The first chapter looks at recent experience in CO₂ storage activity in various parts of the world. Through case studies, it shows how progress has been made in achieving high-level storage area assessments, as well as at project level, where important practical experience has been gained in storing CO₂. The chapter emphasises the fact that determining the feasibility of storing CO₂ is a critical step that cannot simply be considered as the last part of a CCS project preparation process. In fact, selecting storage will actually impact the whole project design and so should be addressed right from the start. In addition to storage, the chapter also discusses transport infrastructure questions.

The second chapter proposes steps to develop a more generic and standardised storage capacity evaluation methodology that should yield more comparable assessments. Assessing storage

capacity is an important element for a government, as it enables it to ascertain the role CCS could play in its future energy mix. While country- or region-level assessments may improve understanding among industry on prospective storage areas, ultimately each and every storage site requires a very detailed site-specific assessment.

Chapter three discusses some project-level key investment steps that are strongly linked to the process of finding, characterising and developing the storage site. The capital expenditure of a CCS project tends to be weighted towards the capture plant, while project technical risk is dominated by uncertain storage availability. Storage is an important aspect in the process of reaching a final investment decision for any CCS project, an area where further analysis within the financial decision-making process is needed.

CCS is about more than power: a major role for industry

While much of the discussion on CCS to date has focussed on the power sector, and notably coal, IEA analysis shows that one of the major opportunities for CCS is to reduce emissions from a variety of industrial applications, notably in the cement and steel industries that generate GHG emissions as part of the manufacturing process. While there are alternatives, albeit costly, to CCS to reduce GHG emissions from power generation, the alternatives for industry at this point are less evident. Chapter four of this publication helps to shed additional light on industrial GHG emissions and the importance of CCS in this regard. The chapter also discusses the specific policy-related challenges facing CCS in industrial applications.

Framework for evaluating the role of CO₂ utilisation

One way to finance carbon capture and storage activities is to find ways to generate revenues that help to offset the cost of the CCS activity. This is particularly important given the reticence of governments to assume fully from its resources – or to impose fully on businesses – the “climate tax or penalty” required for CCS. As a result, there is a lot of discussion around prospects to use CO₂ to generate money, especially in North America (e.g., EOR), and increasingly elsewhere. For example, some recent analysis in China has looked into whether CO₂ can help with water extraction. Unfortunately, the discussion around ‘use’ has suffered from a lack of clarity regarding the varying impacts on climate change mitigation generated by different types of utilisation. Not all CO₂ utilisation is alike – hence the need to separate the wheat from the chaff when looking at utilisation through the climate change prism.

For the IEA, most interesting is CO₂ utilisation that results in ‘permanent’ sequestration of the CO₂. EOR is a good example of this as, under right conditions, the CO₂ can be permanently stored underground. Potentially, other forms of use could result in CO₂ being sequestered, for example in building or other materials with extremely long lives. These forms of uses can be characterised as “CCS-like” by resulting in the effective sequestration of CO₂ over time, even if it isn’t stored in the classic sense underground.

At the other end of the spectrum, many forms of commercial CO₂ utilisation result in the CO₂ being emitted into the atmosphere within months or years – and consequently fail to generate the sequestration that is at the heart of the CCS impact.

However, some cases that do not result in sequestration can generate other worthy benefits for climate change mitigation. Two are worth mentioning. First, CO₂ can be used in the production process or otherwise in a manner that reduces or substitutes for related fossil fuel emissions. Second, CO₂ utilisation can help to generate interest and funding for CCS related technological development or deployment, thereby indirectly supporting the CCS effort.

In the end, CO₂ use that directly results in permanent sequestration – namely “CCS-like utilisation” – remains the potential jackpot to catalyse CCS. Given the importance of CCS for climate change mitigation, this effort to find sequestration - like uses merits continued attention. But at the same time it is also important to understand where and when CO₂ utilisation fails this important test, and whether it still can help climate change mitigation efforts. The risk to be avoided is to allow CO₂ utilisation to become a distraction that will detract attention from effective sequestration efforts. These aspects are discussed in fuller detail in the final chapter five of this edition.

1. Lessons learned from experience in CO₂ storage

Introduction

Ultimately every CCS project depends on CO₂ storage. Timely identification, assessment, approval, and acceptance by public, of suitable CO₂ storage sites constitute a necessary prerequisite for any successful CCS project. The challenge of securing a suitable storage for each CCS project should not be underestimated. Furthermore, it needs to be recognised that this challenge is not only there for the first movers - first CCS demonstration projects. Unlike financial challenges of capture plants that may be addressed and diminished with time that allows for technology learning, cost reduction and commercialisation, the challenge with finding appropriate storage may remain and can even grow together with the scale of CCS deployment. One of the key challenges in securing a suitable storage site is time that it may take.

High-level storage assessment data show a huge global potential for geological storage of CO₂. According to the IPCC Special report on CCS published in 2009, the estimated range of economic potential for CCS over the next century is roughly 200 to 2,000 GtCO₂. However, there is a significant gap between a high-level assessment and ensuring an operational CO₂ storage site.

The available experience with storage characterisation demonstrates that firstly, it takes many steps to move from high level storage assessment to actual storage site identification. Secondly, characterisation efforts to prove the availability of an actual storage site based on initial theoretical estimates may fail. And thirdly, some feasible opportunities for storage may get discarded due to public opposition. This all points out to the need to devote substantial time, resources and attention to CO₂ storage. The IEA 2013 CCS Roadmap highlights the importance of the development of suitable storage sites simultaneously with developing capture projects.

The following storage-related actions identified by the Roadmap for a short-term implementation by 2020 may facilitate appropriate storage development:

- Implement policies that encourage storage exploration, characterisation, and development for CCS projects.
- Implement governance frameworks that ensure safe and effective storage, encourage sound management of natural resources – including pore space – and ensure that the public is appropriately consulted in the development of storage projects.
- Continue to develop and employ co-ordinated international approaches and methodologies to improve understanding of storage resources and to enhance best practices.
- Where CO₂-EOR is being undertaken as part of long-term geologic storage operations, ensure that it is conducted under appropriate, storage-specific regulatory regimes.

These recommendations are based on insights from experiences with CO₂ storage identification and selection on the ground. Some of these experiences are presented in this chapter. The chapter includes five real-life CO₂ storage case studies from different countries and circumstances. They range from high-level cross-border storage estimates, such as the North American Carbon Storage Atlas (NACSA) developed jointly by the US, Canada and Mexico, all the way to a site-specific storage development, such as the Gorgon CCS project in Western Australia.

The objective of the case studies is to extract key lessons and give a feel on what it takes to develop CO₂ storage infrastructure. The case studies give an indication of the extensive efforts and significant time it takes to demonstrate CO₂ storage and highlight the sense of urgency required from the start of any project. Selected cases do not represent an exhaustive list of

challenges and lessons on storage, nor do they provide a detailed and comprehensive description on everything that each of them has involved.

The following storage case studies² are described in this chapter:

- The North American Carbon Storage Atlas (NACSA)
- High-level government-funded efforts on storage identification in Japan
- Storage identification for the Rotterdam industrial cluster as part of Climate Change Initiative in Rotterdam area
- Specific storage site development for the CCS Gorgon project in Australia
- The Weyburn CO₂ storage project combined with EOR in Canada and USA

In addition, the chapter also includes a CO₂ transport case study, on a possible CO₂ transport infrastructure in Europe.

The case studies were selected to show different levels (a high-level cross-border storage estimate, a national level staged storage assessment, industrial cluster storage identification, a site-specific storage characterisation) and sides (technical, institutional, methodological, storage and EOR aspect, etc.) of the whole process of storage identification and selection. While they illustrate very different experiences, they all show how difficult, time-consuming and cumbersome the process of selecting a suitable storage site can be and draw important lessons.

The North American Carbon Storage Atlas case study

The North American Carbon Storage Atlas (NACSA), released in April 2012 (US DOE, 2012), provides the first coordinated overview of the carbon capture and storage potential across Canada, Mexico, and the USA. The NACSA incorporates the most current and best available estimates of potential CO₂ storage resources determined by each country using consistent peer-reviewed methodologies for a wide range of data. The Atlas is the result of extensive cooperation and coordination among carbon storage experts from local, state, provincial, and Federal Government agencies, as well as industry and academia.

Data in relation to CO₂ storage opportunities was available in each country at a variety of levels. However, the NACSA represents a more sophisticated and complex undertaking than just combining together the datasets of each of the three countries.

Project description

The NACSA was produced by the North American Carbon Atlas Partnership (NACAP), a joint CO₂ mapping initiative established to foster collaboration amongst the three countries in the area of CCS. NACAP is led by Natural Resources Canada (NRCan), the Ministry of Energy of Mexico (SENER), and the US Department of Energy (DoE). The NACAP operates under the auspices of the North American Energy Working Group (established in 2001 by the Secretary of Energy of the USA, the Secretary of Energy of Mexico, and the Canadian Minister of Natural Resources). NACAP was initiated at the North American Leaders Summit in Guadalajara, Mexico in August 2009 when it was formally announced that the three countries had agreed to produce an atlas.

The objective of the collaborative effort was to develop an atlas based on a uniform mapping methodology and data sharing regarding large CO₂ emissions sources and potential storage sites

² While all necessary efforts have been made to ensure accuracy, the main intent of this chapter is not to describe the projects in detail, but to draw out challenges, key lessons and conclusions to inform wider storage work in various parts of the world. For detailed information, the reader should contact the project proponents and authorities directly.

in North America. The overall effort was expected to result in the outcomes as set out in Box 1.1.

Box 1.1 • North American Carbon Storage Atlas initiative expected outcomes

The North American Carbon Storage Atlas Initiative was expected to:

- Facilitate the sharing of information to foster and enhance data exchange on CO₂ sources and storage formations in support of a GIS system, which is typically used to convey information in map form. The aim is to create a distributed database, rather than a central repository, where data from different states, provinces, or organizations can be accessed via a common portal and in similar format.
- Form a consensus on the methodology to be used in estimating the CO₂ storage potential of various types of CO₂ storage systems in North America. This will be particularly relevant for cross-border storage to eliminate international “fault lines” and ensure compatible estimates of storage potential in North America.
- Promote potential collaboration on research, development, and demonstration (RD&D) related to CCS. This includes sharing efforts to evaluate alternative uses of CCS technologies, such as EOR or ECBM recovery.

Source: NACSA, 2012 http://www.netl.doe.gov/technologies/carbon_seq/refshelf/NACSA2012.pdf

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The North American Carbon Storage Atlas provides the first opportunity for governments and industry to gain a high-level overview of the potential for large-scale CO₂ storage in North America, by bringing together all available data on the location of large stationary CO₂ emission sources with the potential storage resources in three storage types – saline formations, unmineable coal seams and oil and gas reservoirs. The CO₂ emissions and storage resource data were collected before April 2011.

Challenges and issues encountered

To marshal the skills and resources necessary to realise the Atlas and address challenges facing its release, two working groups (based on expertise) were formed as follows:

- Information Technology Working Group – with a remit to foster and enhance the ability to gather and share data, and support a GIS from the three countries; and
- Methodology Working Group – which was charged with the task of forming a consensus with regard to the methodology to be used in estimating the CO₂ storage resource of various types of geological formations in North America.

The Information Technology Working Group addressed challenges associated with data compilation and analysis. Given the array of data sources, input parameters, screening criteria, and analysis categories, adjustments to data had to be made to generate consistent and comparable results. In addition, to achieve the objectives of NACAP, it was essential to agree on a common methodology to ensure readily comparable storage resource estimates between the three countries.

The Methodology Working Group adopted a default calculation approach based on the resource estimation methodologies used in US DoE’s 2010 Carbon Sequestration Atlas of the United States and Canada (Atlas III). The adoption of this approach allowed for the integration of data compiled from across Canada, Mexico, and the USA in relation to the storage types under consideration. These methodologies were developed to achieve consistency across North America for the wide range of available data, with justifications added to explain the inherent differences.

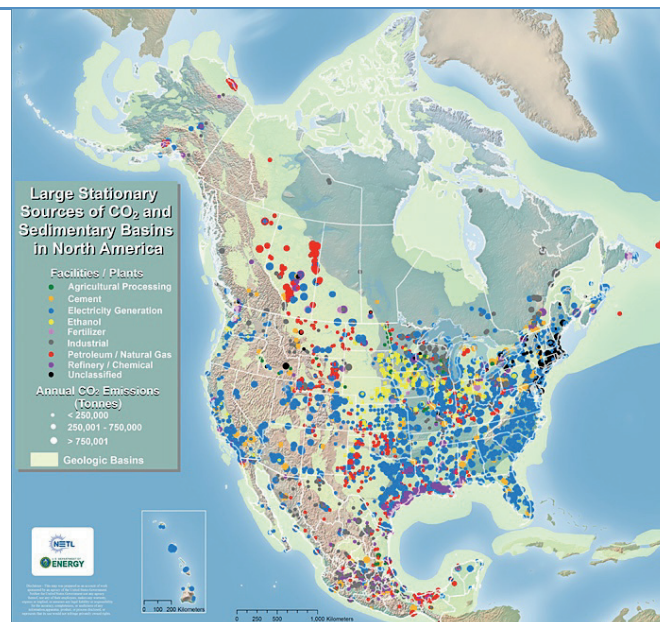
Other key parameters and country specific circumstances that had to be resolved included

terminology, data availability, funding structures and the needs of the respective countries as to what the NACSA would incorporate. There were differences in the translation of definitions which had to be resolved, particularly when agreeing on standard terminology (i.e. resource vs capacity). Also, each country had different levels of data availability and constraints on that availability. Issues were resolved through a consensus approach to ensure the needs of all three countries would be met through the development of a uniform Atlas.

Given the prior experience of the US DoE's National Energy Technology Laboratory (NETL) in compiling data from various entities to develop and produce the DoE atlases, NETL led the effort to compile all data and maps for the NACSA. Development of the Atlas took 18 months after the initial data gathering stage. All data was collected prior to August 2011, with the final Atlas, website, and viewer released in April 2012. The data gathering and acquisition aspects of the process were clearly the most expensive. Data for the Atlas was gathered by each country separately, and where possible existing sources and mechanisms were utilised. For example, the US data was gathered by the DoE's Regional Carbon Sequestration Partnerships and entered into a GIS database 'NATCARB'. In addition to the data gathering costs, development of the Atlas, website, and viewer required a wide array of expertise (geology, data analysis and display, editing, writing, graphics design, programming, and GIS). Given the distributed nature of the work it is difficult to determine an overall estimate of the total cost.

The information contained in the Atlas provides CCS project developers with a starting point for further investigations. It does not serve as a substitute for site specific assessments and testing. Furthermore, the CO₂ storage estimates are focused on physical parameters (the volume of porous and permeable rocks available and accessible), and do not include economic or regulatory constraints. The challenge for project developers is to move from the high level data at the North American regional level contained in the Atlas to finer resolution.

Figure 1.1 • Large CO₂ Stationary Sources and Sedimentary Basins in North America



Note: Magnitude and location of large CO₂ stationary sources and the areal extent of potential geologic CO₂ storage resource for various formation types.

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

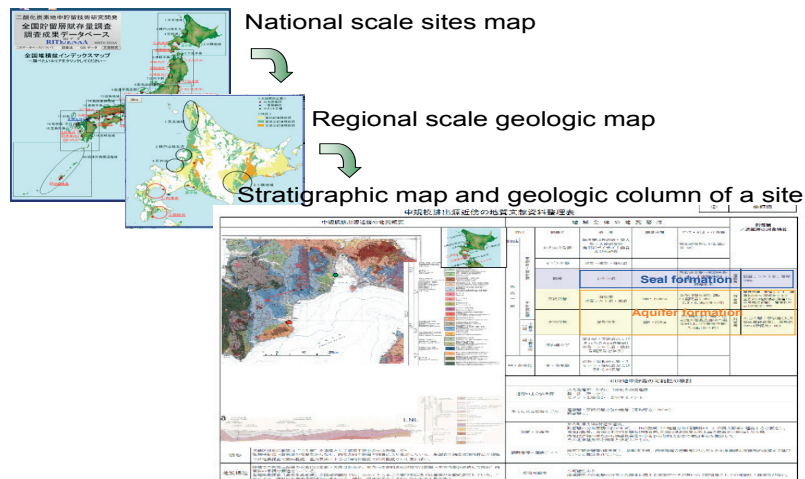
Source: NETL http://www.netl.doe.gov/technologies/carbon_seq/global/nacap.html.

Lessons learned

The Atlas clearly illustrates both the successes and challenges of working across multiple jurisdictions, whether at the international or national level. The principal lessons to be taken from the development of the NACSA relate to the underlying principles and modus operandi guiding the work.

- Through wise investment at the pre-competitive level, governments can significantly advance the availability of data to underpin CCS project deployment.
- It is essential to reach a clear understanding of, and agree on technical terminology up-front, to establish an agreed methodology and justify any differences for data collection and analysis, to decide the hierarchy for data integration, to determine funding and duration and to clearly define country and government roles, needs and expectations.
- A key issue for all data-based projects relates to the methodology to be established for ongoing maintenance and update. While a static snapshot is useful, data on CO₂ storage and emission point sources will continually evolve, especially as CCS project deployment unfolds. For NACSA, the question of whether or not there should be a follow-up Atlas (*NACAP II*) remains open. These issues need to be determined at the project design stage to ensure they can be incorporated in an optimal way.
- The NACSA clearly demonstrates the importance and value of undertaking source and storage site matching at a regional geological level, and how that can be successfully realised across multiple jurisdictions. The Atlas provides a high-level geological storage estimate, but is not intended to serve as a substitute for site specific assessment and testing.

Figure 1.2 • Representative unfolded image of the data base system for a sedimentary basin near a CO₂ emission source (Hakodate Bay area)



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

Source: Research Institute of Innovative Technology for the Earth (RITE), Japan.

National CO₂ storage identification in Japan

The Japanese Government, through its Ministry of Economy, Trade and Industry (METI), has long had an interest in establishing carbon capture and storage as a technological solution to mitigate carbon dioxide emissions from large energy and industrial point sources. In 2000 METI launched a five-year USD 32 million research programme aimed at developing a solid justification for

implementing CCS in Japanese circumstances. The program, later extended by three years with an additional USD 30 million, looked at geological storage of CO₂. Preliminary estimates showed that there was a total of 146 gigatonnes (Gt) of CO₂ storage capacity in saline aquifers in Japan (Takahashi *et al*, 2009).

Once the potential for geological storage had been clearly established, the next challenge was to focus on those sites with the most potential. Many of the sites making up the estimated 146Gt of CO₂ storage capacity were offshore and not located in close proximity to large scale CO₂ emission sources. The final phase of the project involved a more in-depth examination of 27 areas located near CO₂ sources. Based on a preliminary assessment (using national scale geological information), 14 of the most promising sedimentary regions were selected for more detailed examination with regional scale storage capacities being estimated for each (Nakanishi, 2009) as shown at Figure 1.2.

Having made significant progress in defining storage opportunities and capacity at a high level, in 2008 the Government (through METI) turned its attention towards the comprehensive investigation of a CCS demonstration scale project. In May 2008, a group of major private corporations with an interest in CCS founded Japan CCS Co Ltd (Japan CCS) to cooperate with the Government. Japan CCS was commissioned by METI in 2008 to undertake comprehensive investigations for planned large-scale demonstration projects at a cost of JY 9,5 billion (≈USD 90 million).

Challenges and issues encountered

The first challenge was to narrow the field of possible sites to be selected for a demonstration project. Initial work focused on the selection of three candidate sites from the possible 115 identified storage possibilities. These potential sites were primarily drawn from the RITE assessments described earlier. The three sites were selected based on criteria which would facilitate both project deployment and optimise demonstration lessons – i.e. storage potential, reservoir type, presence of possible seepage paths, proximity to major CO₂ sources, applicability of capture technology, and issues which could be demonstrated through each project. In effect a source/sink matching exercise was undertaken that looked to draw on existing plant. CO₂ source options included coal-fired power generation, refineries, chemical plants, natural gas processing plants, paper mills and cement kilns (Abe *et al*, 2013).

Of these criteria reservoir type was considered the most important, coupled with a strong preference to cover depleted oil and/or gas fields, saline aquifers with closure, and both Neogene and Palaeogene aquifers without closure. Gaps in knowledge were expected to be complemented through information sharing from demonstration projects in other countries. Assessment of geological faults was also critical given seismicity issues – as it was essential to avoid sites with active faults.

In late 2008, following an extensive screening process, three candidate sites were agreed upon for further investigation:

- Nakoso-Iwaki Oki with depleted gas reservoirs,
- Kitakyushu with a Palaeogene aquifer without closure and
- Tomakomai with Neogene saline aquifers with closure and without closure.

Having narrowed the field, it was essential to then test if the sites were really suitable for a large-scale demonstration project. To this end, an assessment process was undertaken based on METI's 2009 CCS guidelines "*For safe operation of a CCS demonstration project*" (METI, 2009). The guidelines, which are tailored for policy, legal and regulatory settings applicable to Japan, as well as other country-specific circumstances (e.g. seismicity), are comprehensive and require

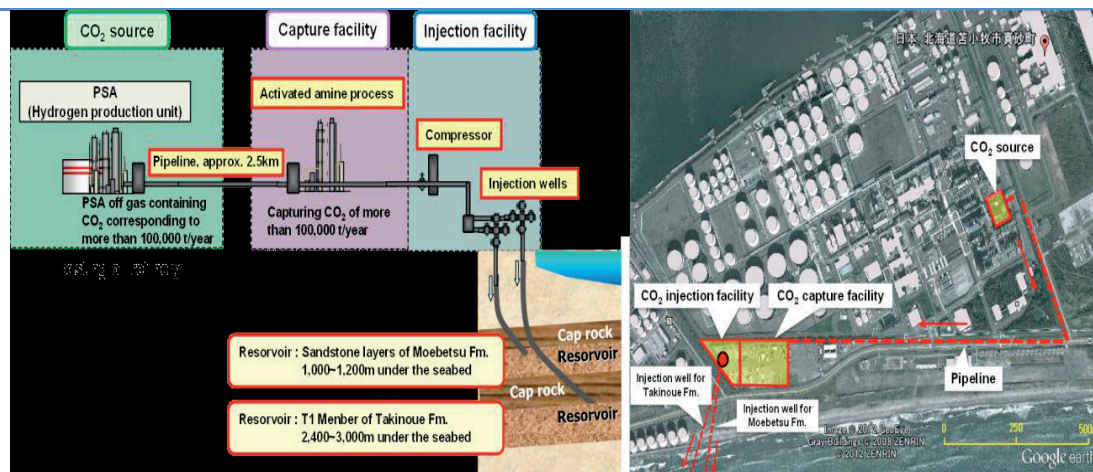
assessment of geological aspects, transportation standards, an Environmental Impact Assessment and operational standards (i.e. CO₂ purity), as well as monitoring and crisis management plans.

Final consideration of whether to proceed with a demonstration project at one of the three sites was only concluded after conceptual designs were carried out for capture, transport and injection, along with an evaluation of the feasibility of sourcing CO₂. For example at the Tomakomai site a new 3D seismic survey was acquired, and two survey wells drilled to extend pre-existing data from oil and gas exploration. The comprehensive investigation, involving further geological surveys and engineering studies carried out over three years (i) allowed METI to decide upon further action on a demonstration project in 2011. METI determined to:

- discontinue surveys at Nakoso-Iwaki Oki, given the Great East Japan earthquake on 11 March 2011,
- continue 2D seismic surveys at Kitakyushu in 2012, and
- implement a CCS demonstration project at the Tomakomai site over the period 2012-20.

Based on a public call for proposals launched on 8 February 2012, METI commissioned Japan CCS to develop the Tomakomai demonstration project over a nine-year period, at a cost of JY 47 billion (≈USD 580 million) for the first four years. The CO₂ is to be sourced from an existing refinery, with planned injection of 100,000 tonnes per annum or more. Beginning in 2016, CO₂ will be injected into two different offshore saline reservoirs, at depths of approximately 1100m and 2400m below the seabed offshore from the Tomakomai port, by two deviated injection wells (Tanase *et al*, 2013). An overview of the planned facilities is shown in Figure 1.3. Construction work is scheduled to begin in 2014, with plant commissioning at the end of 2015.

Figure 1.3 • Overview of the facilities of the Tomakomai CCS demonstration project



Source: Tanase *et al*; Tomakomai CCS Demonstration Project in Japan; GHGT 11

A comprehensive monitoring program will be deployed consisting of time-lapse 2D and time-lapse 3D seismic surveys, temperature and pressure measurements, micro-seismicity and natural earthquake observations, as well as extensive environmental marine surveys, all of which will be undertaken before, during and after the CO₂ injection until 2020. Two new observation wells will be drilled to complement an existing well, and an ocean bottom cable installed to ensure replicability of comparative data.

A further challenge has been the need to garner public support for the project. Tomakomai City (population of 174,000) is a major industrial city. The storage points are located just 2-4km offshore with the plant approximately 5km from the city centre. Initial consultations were held

with key public stakeholders prior to the initial 3D survey, during the assessment phase in 2009. Efforts have been progressively stepped up, especially prior to any field survey work, with an extensive public outreach programme during the final stages of the site evaluation in 2011. This included a CCS forum, more than 20 CCS panel exhibitions throughout the local area and presentations at various stakeholder group meetings. Detailed information on the objectives, mechanisms, safety, and environmental impact of the project has been made continuously available to the public, alongside more general information on CCS.

Lessons learned

- Storage characterisation, even for a demonstration project aiming to inject up to 200 000 tonnes per year, requires considerable time, planning and commitment well in advance of planned starting dates. The Japanese government initiated studies in 2000 which will only see injection commence in 2016. Admittedly a comprehensive approach has been adopted, and initially there was a lack of even high level data. However, even where project proponents are focused on a specific site, a three to five year work program is still likely to be required before injection can begin.
- The Japanese experience also shows the real value of having high level data sets (with appropriate interpretation) at the national level. This information would enable individual project proponents to make informed assessments and take decisions as to where the best potential storage sites would be for a demonstration project.
- METI's 2009 CCS guidelines "For safe operation of a CCS demonstration project" were instrumental in facilitating the assessment process and ultimately the decision to proceed with the demonstration project.
- Public acceptance and awareness are important issues in relation to almost all CO₂ storage proposals. Earthquakes, CO₂ leakage and other seismic activity can be issues of major public concern, and Japan, understandably given its geological setting, is at the forefront of these matters.

The Rotterdam offshore CO₂ storage identification

The port of Rotterdam is the largest port in Europe and continues to grow. It is now considered as one of the world's major industrial clusters. However, it is also becoming a significant CO₂ emitter – amongst the highest in Europe. Emissions are expected to continue to grow, and by 2025 it is anticipated that the Rotterdam area will host five refineries, four coal-fired power plants, five gas-fired power plants, an array of chemical and CHP installations, and numerous smaller CO₂ point sources (Rotterdam Climate Initiative, 2010).

The Rotterdam Climate Initiative (RCI) was launched in May 2007 (RCI, 2009), with the aim of reducing CO₂ emissions by 50% by 2025 while promoting the economy in the Rotterdam region through the active encouragement and accommodation of sustainable and low-carbon investment. It was quickly recognised that "CCS had the potential to fulfil more than half of Rotterdam's CO₂ reduction targets, with an effect of approximately 20 Mt captured and stored by 2025. Moreover, CCS is considered to be the only technology capable of directly abating CO₂ emissions from both industrial facilities and fossil fuel power plants, such as refineries or steel plants" (RCI, 2010). It is envisaged that around 20 Mt of CO₂ will be captured and stored in the area per year by 2025.

Project description

The RCI undertook a series of feasibility studies, including potential capture projects, a CO₂ shipping concept study, pipeline studies including the significant expansion of greenhouse use of CO₂, opportunities for CO₂ use for EOR, offshore storage in deep geological formations under the North Sea and a CCS hub business case. One of the key findings of this work was that planning of appropriate CO₂ storage sites was the least developed aspect of CCS in Rotterdam, and needed to be progressed urgently. With the cancellation of Shell's Barendrecht CO₂ storage project at the end of 2010 due to public acceptance issues (an independent case study detailing the lessons from Barendrecht has been developed, see Feenstra *et al*, 2010), and the 2011 decision by the Dutch government to indefinitely suspend consideration of onshore storage of CO₂, the focus moved to sites offshore from Rotterdam. The initial priority for the RCI industrial partners was to secure good information and a thorough understanding of the various offshore CO₂ storage options to inform decision making on CCS project development.

The Earth, Environmental and Life Sciences office of TNO (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek) was approached to perform an independent storage assessment of offshore CO₂ storage options for Rotterdam. The objective of the assessment was to add critical research to the CCS value chain and provide CCS project developers with detailed, credible information on the technical feasibility, potential availability, and costs of offshore storage opportunities near Rotterdam. While there had been a number of storage investigations of depleted gas fields on the Dutch continental shelf in the past, these had been high-level and hypothetical and were of limited pragmatic value to project developers. The specific objectives of the assessment (Neele *et al*, 2011a) are set out in Box 1.2 below.

Box 1.2 • Specific objectives of Rotterdam independent storage assessment

- Develop a detailed, comprehensive, independently validated and harmonized data set for CO₂ storage in the relevant portions of the Dutch North Sea, covering all potential structures, including aquifers and hydrocarbon fields, and ensuring that no good prospects were overlooked in previous reports.
- Identify the best potential CO₂ storage sites, from both technical and cost standpoints, to act as the first step in the development of a Rotterdam CCS Network targeting operation in 2015.
- Progress detailed analysis at a number of identified sites to provide sufficient alternatives should a specific site prove unavailable on desired timelines or less attractive during later stage work.
- Identify development plans for the analyzed sites, outlining actions, timelines and costs required to bring each site to operation.
- Provide greater certainty among emitters regarding the availability, viability and capacity of specific sites, enhancing their confidence to advance planning for CO₂ capture projects.

Source: Neele *et al*, 2011a

The assessment was funded by five major Rotterdam emitters, together with the Global CCS Institute. The RCI and CATO-2 (the Dutch national public-private CCS R&D cooperation) both made significant in-kind contributions. A critical issue was to ensure access to the extensive confidential operational and geological data held by petroleum companies. Following successful negotiations with the key oil and gas operators (TAQA, Wintershall, GDF SUEZ, Chevron and NAM) the data was made available under separate confidentiality agreements.

An initial survey was conducted of all potential offshore storage sites within a 160 km radius from

Rotterdam. The focus was on reservoirs which might be available before 2020 (following the cessation of natural gas production), with the five best options chosen for further in-depth study.

In Phase 1, existing data was collected and reviewed, leading to a detailed and comprehensive database. This included geology, existing wells and well-related data and hydrocarbon production history. Phase 2 then focused on the most promising fields. The assessment concluded that there were several strong offshore CO₂ storage options that could be developed before 2020, with over 200 Mt storage capacity. The assessment provided the necessary high-level assurances that there was sufficient capacity available to meet the needs of Rotterdam CCS projects for more than a decade, as well as providing valuable insights into the key technical and cost parameters for each site.

Challenges and issues encountered

In line with previous studies, a key finding of the first phases of the assessment was that while short term prospects were very positive, further information and research on storage opportunities was required to underpin the full commercialisation of CCS in the Rotterdam region. Accordingly, a third phase of the assessment was commissioned to “...provide greater certainty about the availability of high capacity offshore storage to support the large-scale deployment of CCS on a commercial basis and to provide potential CCS project developers with greater confidence in the long-term viability of any projects they might pursue” (Neele et al. (2012).

Phase 3 then examined storage options from a purely geological perspective, ignoring constraints around location, timing of availability and infrastructure issues. It concentrated on saline aquifers where less data was available, rather than just reservoirs with structural trapping mechanisms and focused on sites with high potential capacities (above 50 Mt for saline formations and 40 Mt for oil and gas reservoirs). The outcome provided project proponents with greater certainty that there were a number of attractive high capacity CO₂ storage options on the Dutch continental shelf, including several saline formations that had not previously been identified. It is important to note that the estimates for the saline formations are, in particular, uncertain due to data limitations and that further detailed site specific characterisation work will be required to underpin actual project deployment.

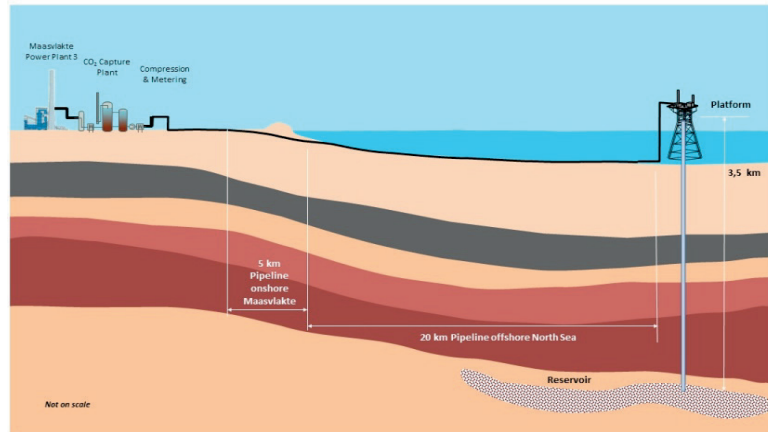
ROAD (the Rotterdam Opslag and Afvang Demonstratie project or Rotterdam Capture and Storage Demonstration Project) is one of the largest integrated CCS demonstration projects in the world, and currently one of the most advanced in the European Union. This project, jointly initiated by E.ON Benelux N.V. and Electrabel Nederland N.V. (GDF SUEZ Group), plans³ to capture CO₂ from the flue gases of a new 1100MWe coal-fired power generation unit at the Maasvlakte site in the port of Rotterdam, using post combustion technology. The aim is to capture 1,1 Mt of CO₂ per year once the plant begins operations. The captured CO₂ will be transported by pipeline (5 km over land and 20 km across the seabed) to the depleted “P18” gas reservoir. The pipeline is proposed to be oversized, to have a capacity of around 5 Mt per year. Figure 1.4 gives an overview of the ROAD project.

ROAD is effectively the first practical ‘test case’ for the new regulations and procedures for storage permits put in place by the government of the Netherlands and local authorities, implementing the EU CO₂ Storage Directive. This has been a key challenge for the project, as it was necessary to test how these regulatory requirements would work in practice (Azki et al, 2012). Delivery of the storage license requirements (i.e. building models, making plans, etc) is

³At the time of publication of this document, the final investment decision on the ROAD project is still pending.

time consuming, and hence it is essential to get early clarification of the storage facility and upfront agreement with the owner and operator. Furthermore, since reservoir behaviour is a key determinant of design and operational parameters, it is essential to have a very good early understanding of the reservoir and its characteristics (Buysse *et al*, 2012).

Figure 1.4 • ROAD Transport and Storage Project schematic



Source: ROAD project

ROAD partners with TAQA Energy B.V., the current gas field operator, for the CO₂ injection and storage. The identified gas reservoir is located at a depth of around 3,500 metres below the seabed, with an estimated storage capacity of approximately 35 Mt. The total investment costs for the P18 field are estimated to be EUR 65 million for the platform, the well work-over and also pipeline construction (cost of onshore installations excluded). Operational costs are of the order of EUR 3,2 million per year, but these do not include the costs of remotely operating the platform.

TAQA's detailed operational knowledge, coupled with the underpinning information available through the independent storage assessment, has enabled ROAD to minimise detailed site characterisation costs and the timeframes to bring the storage component into line with the overall project front-end engineering and design (FEED) study. However, even with financial and political support from the European Commission, the Netherlands government and the Rotterdam region, the project development phase has lasted longer than originally anticipated, and the final investment decision is yet to be taken.

Lessons learned

- One of the most important lessons to be taken from the Rotterdam work is that reservoir behaviour determines all design and operational conditions of the complete CCS chain, i.e. the process is ruled by the reservoir (Buysse *et al*, 2012).
- More importantly, this emphasises that storage issues are critical for project design from the very beginning. As the storage aspects of a CCS project are generally a smaller component of the overall budget (10-20% on average) they are often afforded less priority, but given their critical importance on all key project parameters, it is essential that storage is addressed up front.
- Furthermore, storage considerations may well dictate the overall project timelines, as the selection and full characterisation of a storage site requires a significant commitment in terms of both time and financial resources. As is seen with the ROAD project, which had the benefit of the completed independent storage assessment and TAQA's operational knowledge of the

potential storage site, when coupled with potential permitting delays, storage issues can easily lead to overall project delays of 18 months or more.

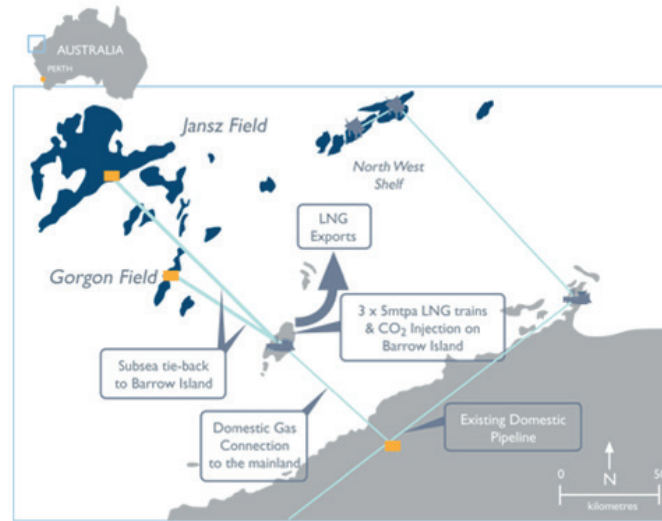
- The Rotterdam experience also points to the value of acquiring good regional level data. The independent storage assessment provided the essential information required to inform and facilitate timely decision making in relation to the ROAD project. This data also provides the confidence for other project proponents to plan for CCS investments and operations with the full knowledge that there is sufficient storage capacity in easy proximity to Rotterdam.
- Sufficient time must be factored into planning for the regulatory approval process. In particular, the Dutch experience suggests delays may be more likely to occur when projects are looking at onshore storage options and CCS projects for green field plants, mainly due to potential public objections and appeals. For future offshore CCS projects in the Netherlands, ROAD has suggested that an additional six months should be factored into planning to allow for possible permitting delays.

Gorgon CCS project: CO₂ storage case study

The Gorgon gas field was discovered in 1980, off Australia's north-west coast. Over the following three decades, a number of additional gas discoveries have been made in the Greater Gorgon Area which is now considered as a world class natural gas resource. In 2003 the Gorgon Joint Venture, which now comprises the Australian subsidiaries of Chevron, ExxonMobil, Shell, as well as Tokyo Gas, Osaka Gas, and Chubu Electric Power, started seeking approvals for the Gorgon project. This project incorporates the initial development of the Gorgon and Jansz gas fields, the two largest fields in the Greater Gorgon Area, and the development of a gas processing facility on Barrow Island, capable of exporting 15 million tonnes of LNG to international markets and supplying of up to 300 TJ per day of natural gas into the Western Australian domestic market. The Gorgon project represents the single largest resource project ever undertaken in Australia.

An integral component of the massive Gorgon project is the disposal of carbon dioxide extracted from the natural gas during the gas processing operations, by injecting it into the Dupuy Formation over 2000m below Barrow Island. When operational, the CCS part of the Gorgon project will be the world's largest CO₂ storage project and is anticipated to reduce emissions from the Gorgon project by between 3,4 – 4,0 million tonnes per year, or over 100 Mt over the lifetime of the project.

Figure 1.5 • Gorgon project



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

Source: Global CCS Institute

Project description

During the 1990's, the Gorgon Joint Venture began to consider methods to reduce the greenhouse gas emissions from any development of the Greater Gorgon Area gas fields and in 1998, amongst other measures, started investigating the potential of disposing of the carbon dioxide by injecting it into underground formations for permanent storage. A number of screening exercises were performed to identify suitable locations and eventually the most suitable site was determined to be below Barrow Island, located some 50 km off the coast of Western Australia (Figure 1.5). Prior to 2009, the site was extensively appraised so as to confirm injectivity and capacity and to develop appropriate pressure management and surveillance plans.

In 2003 a voluntary Social and Economic Review of the Gorgon Gas Development on Barrow Island was published by the Gorgon Joint Venture as part of a Western Australian government process involving extensive public consultation, to consider the proposed development. The outcome of this process was the passage into law of the *Barrow Island Act 2003 (WA)* which provided in-principal support for the consideration of the development of the Gorgon Project on Barrow Island subject to the normal environmental impact assessment and approval processes.

After obtaining all the required approvals including an authorization under the Barrow Island Act to dispose of carbon dioxide by injection into the Dupuy Formation, a final investment decision was made by the Gorgon Joint Venture to proceed with the Gorgon project in September 2009. The overall Gorgon project is now in construction and is expected to start injecting CO₂ in 2015.

Challenges and issues encountered

In 2003 there was no legislation present in Western Australia to enable the government to authorise the underground injection of carbon dioxide. In less than six months a legislative framework was developed and passed into law.

In order to make the final investment decision, environmental approvals were required to be obtained under both Federal and Western Australian law. These processes require the preparation and publication of an environmental impact assessment. As no comparable greenhouse gas storage project had previously undergone such an environmental impact

assessment, the methodology had to be developed from scratch. The Gorgon Joint Venture developed an approach based on Australian standards “AS/NZS 4360” for risk management and “AS/NZS 3931” for risk analysis of technological systems (Standards Australia 1998 and 2004).

Lessons learned

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- The investment in time and resources required to progress a large integrated greenhouse gas storage project is significant. Dedicated subsurface teams spent over 10 years assessing various storage sites and scenarios prior to final investment decision (FID).
- Availability of relevant legislation authorising underground storage and procedures assisting with its compliance are critical for making the final decision on storage.
- It is also critically important that all project teams operate under an effective interface management system and maintain alignment with respect to progress through the individual work scopes. This is particularly challenging when integrating storage site exploration and appraisal activities into overall project design.

Weyburn CCS and EOR project case study

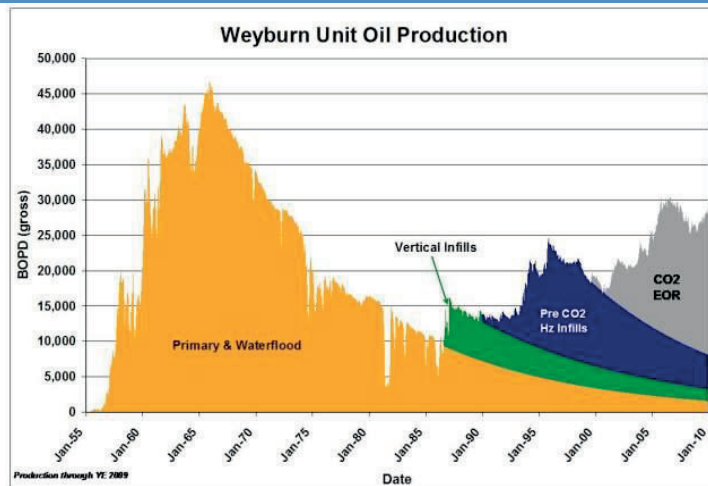
The Weyburn and Midale oil fields, located in southeast Saskatchewan, Canada, were discovered in 1954 and brought into immediate production. With original estimates of close to two billion barrels of oil-in-place, the Weyburn and Midale oil fields, currently operated by Cenovus Energy and Apache Corporation respectively, continue to be highly profitable, with combined production of approximately 35,000 gross barrels per day (Petroleum Technology Research Centre fact sheets).

Continuing oil production has been maintained in both fields through the deployment of a variety of traditional enhanced oil recovery (EOR) techniques since the 1970s. In October 2000, Cenovus (formerly PanCanadian, EnCana) began injecting significant amounts of carbon dioxide into the Weyburn field, in order to boost oil production. There are now over 100 injection wells. Apache followed suite in 2005 when it began injecting CO₂ into the Midale field. Figure 1.6 illustrates the impact of the various forms of EOR on Weyburn oil production. The two fields currently inject approximately 16,000 tonnes of CO₂ per day, approximately 50% of which is recycled CO₂. The Weyburn and Midale fields combined are expected to produce at least 220 million barrels of incremental oil through miscible or near-miscible displacement with CO₂. EOR will extend the life of the fields by approximately two to three decades.

Project description

Unlike many other EOR operations based on CO₂ injection, the Weyburn and Midale fields use CO₂ derived from an anthropogenic industrial source: the lignite-fired Great Plains Synfuels Plant in North Dakota, USA, operated by the Dakota Gasification Company. The CO₂ for the EOR operations is transported in compressed (liquid) form through a 205-mile pipeline (see Figure 1.7). The Company currently captures around 50% of the CO₂ produced at the Great Plains plant, and since October 2000 has been exporting around two-thirds of the readily available volume to the Weyburn and Midale oil fields. The pipeline was built as a commercial operation by the Dakota Gasification Company, following successful negotiations as to CO₂ off-take with Cenovus in the late 1990s. The construction costs were in the order of USD 100 million. The pipeline is operated by Souris Valley Pipeline Ltd, a subsidiary of Dakota Gasification (Dakota Gasification Website), and CO₂ is now considered a significant commercial product. The cross-border pipeline was designed and constructed with a number of “tap points” to enable the introduction of additional customers over time (as per Apache in 2005).

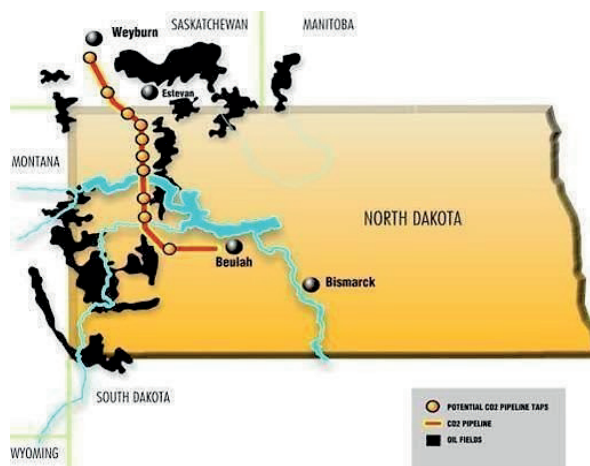
Figure 1.6 • CO₂ impact on Weyburn production



Source: Cenovus http://en.wikipedia.org/wiki/File:Cenovus_Unit_Oil_Production.jpg

The Dakota Gasification Company undertakes voluntary reporting under US legislation (EIA1605B) covering greenhouse gas emissions and sequestration of CO₂. After allowing for deductions for pipeline compression and oil field losses through flaring etc, 70% of the CO₂ sales volume is permanently sequestered – this is assured through independent verification and validation. Overall it is anticipated that around 40 million tonnes of CO₂ will be permanently sequestered over the lifespan of the project – 30 million tonnes at Weyburn and 10 million tonnes at Midale.

Figure 1.7 • CO₂ transport pipeline taking CO₂ to Weyburn oil fields



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

Source: Dakota Gasification http://www.dakotagas.com/Gas_Pipeline/CO2_Pipeline/index.html#map

A number of studies have been conducted into the underlying economics of the Weyburn/Midale operation, with perhaps the most comprehensive being presented by Torp and Brown (*Torp et al, 2005*) at GHGT-7 in 2004. The main points are summarised in Box 1.3 below.

However, what makes the Weyburn-Midale project truly unique amongst CO₂ based EOR operations is the comprehensive monitoring and verification regime introduced from day one:

The IEAGHG Weyburn-Midale CO₂ Monitoring and Storage Project. This research project was launched in July 2000 by PTRC in conjunction with the Government of Canada, the Government of Saskatchewan, and Pan Canadian. The 12-year project costing USD 85 million is part of the IEAGHG R&D Programme. In July 2010 the U.S. Department of Energy (US DoE) and Natural Resources Canada committed a further USD 5.2 million to enable the project to conclude in 2011 (US DoE providing USD 3 million and the Government of Canada, USD 2,2 million). The project has attracted 16 sponsors from government and industry including Natural Resources Canada, the US DOE, the European Commission, IEAGHG, Alberta Energy Research Institute, Saskatchewan Ministry of Energy and Resources, Japan's Research Institute of Innovative Technology for the Earth, plus ten industry sponsors from Canada, the USA, the Middle East and Europe.

Box 1.3 • Weyburn economics

Total capital cost of the entire Dakota Gasification Company project, including plant, compression, and pipeline costs – USD 100 million (plant and compression costs were 50% of the total).

- The pipeline is regulated by the US Federal Energy and Regulatory Commission to have a rate of return of 12.5% (i.e. there is a fixed yearly demand payment based on the capital cost and an allowable rate of return, plus an operational operational costs of actual deliveries plus a rate of return).
- The CO₂ injection facilities needed for EOR already existed: a field distribution system, measurement satellites, local pipelines to injection wells etc.

Initial operating costs for the system (borne by the EOR project) are estimated to be USD 270,000 per year based on normal operation and maintenance expenses.

Based on these parameters the initial annual CO₂ delivery cost for EOR is estimated to be:

- Return on Capital - 12.5% of USD 100 million USD 12,500,000
- Pipeline operating expenses (20% of plant capital + 12.5% return) USD 11,812,500
- Weyburn operating expense are USD 270,000
- First year CO₂ delivery (350 BCF averaged over 15 years) - 1,226,400 tonnes
- Weyburn CO₂ storage (initial year) thus estimated at USD 20.04/tonne.

Based on EnCana Resources data, the overall operating cost of CO₂ EOR at Weyburn is approximately USD 5 per barrel of incremental oil recovered (investment and operation cost of ≈USD 20/tCO₂).

Source: Torp and Brown <http://faculty.isd.claremont.edu/emorhardt/159/pdfs/2006/Torp.pdf>

Challenges and issues encountered

The Weyburn project is the largest full-scale CCS field study ever conducted. The programme of activity addressed a wide range of issues including trapping mechanisms and seismic activity, seal and cap-rock integrity, CO₂ plume movement and the monitoring of permanent storage. Phase I findings (2004) confirmed that the geological setting seemed highly suitable for the long term storage of CO₂, that the results established a comprehensive data set, but that additional research would be required. Phase II was completed in 2011, and based on the total work of the project PTRC has released a comprehensive *Best Practices Manual* (Hitchon, 2012). It provides essential technical guidance on key issues including site characterisation, monitoring and verification, wellbore integrity and performance assessment, as well as briefly addressing the necessity of public communication and outreach.

Lessons learned

The lessons from the Weyburn/Midale project fall within three major groupings.

- The first set relates to the successful coupling of EOR operations and CO₂ storage. The experience of the past 12 years clearly demonstrates that the two approaches can work hand in hand, that accurate CO₂ accounting is possible and that ultimate net storage of at least 70% of the CO₂ exiting the 'plant gate' can be achieved. Moreover, at a cost of USD 5 for every additional barrel of oil produced, the economics of CO₂ based EOR are compelling (this figure will of course vary depending on project-specific parameters). The project has also demonstrated that trans-border shipment of CO₂ is possible at least in the North American context. It also demonstrates that with appropriate foresight and planning it is possible to cater for future CO₂ off-take opportunities.
- Secondly, the intensive and wide ranging research and monitoring efforts by PTRC since 2000 have given rise to a wealth of best practice and technical guidance which can be drawn upon by project proponents and regulators elsewhere (through the *Best Practices Manual*). In particular, this work has been at the forefront of developing monitoring and verification techniques.
- A third set of important lessons relates to community outreach and public awareness, especially when faced with claims of CO₂ leakage and safety issues in 2011. This is a major issue confronted by each and every project globally. The Weyburn project was able to mount an effective response having prepared an emergency response plan to deal with such a crisis. Through drawing on the extensive and robust baseline data sets that could be used for comparative purposes, and through the ongoing implementation of an extensive monitoring and verification programme available for public and regulatory scrutiny, the project was able to provide clear evidence that the allegations of CO₂ leaking from the reservoir were in fact false.

CO₂ Europe pipe transport infrastructure study

In addition to the above five storage cases, below we discuss the outcomes of a recent study on CO₂ transport infrastructure in the European context. An extensive CO₂ transport infrastructure network will be required if CCS is to play a significant role in achieving the European Union's long-term CO₂ emission reduction goals. Thousands of kilometres of new high-pressure pipeline will need to be constructed, with the main effort to be expected between 2020 and 2030 since the larger part of the network needs to be in place by 2030. The rate of construction may need to be as high as 1200 – 1500 km per year in some regions. Different types of transport infrastructure could develop over Europe, depending on the location and density of capture installations and storage sites. In most areas a network connecting multiple capture locations to several storage sites is expected to emerge. Shipping will have a significant role in initial phases until volumes become large enough to justify pipeline investments.

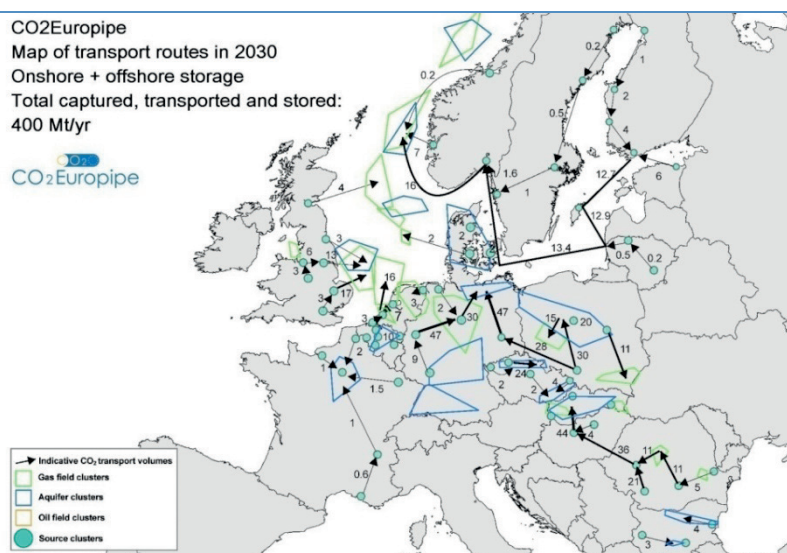
To identify needs and challenges in developing large scale CO₂ transport and storage infrastructure in Europe, the CO₂ Europe pipe project was launched, partly funded by the EU 7th R&D Framework Programme. The project was coordinated by the Dutch research institute TNO.

Project description

The CO₂ Europe pipe project explored the development of a large-scale, Europe-wide infrastructure for the transport and storage of CO₂, drawing conclusions regarding required improvements on the levels of policy, regulations, financing, organisation, risk and technology. The project followed

two distinct methodologies. First, a top-down approach resulted in Europe wide maps of the demand for transport and storage. Growth scenarios were constructed of CO₂ emission and capture requirements for most EU Member States (MS) in the period 2020 – 2050. These were combined with maps of the distribution of the size, location and availability of storage capacity. This resulted in maps of transport corridors in Europe. The map with possible routes is presented in Figure 1.8. It clearly demonstrates the need for international cooperation due to uneven distribution of emission reduction requirements and storage capacity.

Figure 1.8 • CO₂ transport corridors projected for 2030, from major industrial areas to storage locations



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

Source: CO₂ Europipe project

A second, bottom-up approach was used to identify hurdles to developing large-scale transport and storage infrastructure. It involved an analysis of several business cases, representative of early CCS developments, including the Rotterdam region, the Rhine-Ruhr region, an offshore pipeline from the Norwegian coast and the development of CCS in the Czech Republic and Poland.

The uneven distribution of capture sites, construction of transport infrastructure and injection sites across the EU Member States reveals that a relatively small number of key players may emerge. Key players in the development of CCS infrastructure are the countries bordering the North Sea where the majority of the potential storage capacity resides. Additional key players can be identified from their reliance on coal and lignite (e.g., Germany, Poland and the Czech Republic).

This project highlighted the need for early regional and Member State level cooperation in developing the proper policy and regulatory environment that supports the development of CO₂ transport and storage infrastructure. The maps generated in the project clearly show that this is an issue that EU countries cannot solve in isolation. Cooperation needs to start as early as possible, from the first demonstration projects. Outstanding issues in this respect include defining technical standards for CCS infrastructure, agreeing on cross-border transport and solving the issue of liability in the case of multi-national transport and storage projects.

Lessons learned from the study

During the project, a number of concepts and hypotheses have been tested and developed regarding the evolution of a European CO₂ infrastructure. Their outcomes have led to a series of conclusions and recommendations, outlined in Box 1.4, for the EU, for national governments, as well as for industry stakeholders (Neele et al., 2011b):

Box 1.4 • CO₂ Europe recommendations

- **Political leadership** is required both at EU and Member State (MS) level to provide clear signals to stakeholders. Key players in Europe should take the lead, especially during the early development phase.
- **Master plans** should be developed, at EU and MS level, to inform stakeholders of the expected role of CCS in emission reduction. Pre-competitive **storage capacity qualification** is required to remove storage uncertainty and to enable future-proofing of transport infrastructure.
- **Business models for CCS industry** should be developed, anticipating the transition from single-user CCS systems to complex, multi-user and multi-operator networks, which are expected to develop after the demonstration phase.
- **Regulatory certainty and stability** is required for the development of long-term CCS infrastructure. MS regulatory regimes should be harmonised and cross-border transport supported.
- A major hurdle is the price of CO₂ emission in the ETS. **Mechanism(s) to finance CCS projects and CCS infrastructure** should be put in place.
- **Commercial opportunities** to help develop CCS infrastructure should be used. CO₂-EOR offers a promising route to help finance transport infrastructure; incentives that could help exploit the mutual benefits should be investigated.
- **Safety and risk management** for CO₂ transport is not yet clarified and varies between MS. Knowledge gaps related to external safety of CO₂ pipelines should be closed. CO₂ transport by pipeline is routine business. However, there remain a number of **technical challenges** to be addressed, such as ship offloading and the effects of impurities on CCS system behaviour.

Source: Neele et al, (2011b) <http://www.co2europipe.eu/Publications/CO2Europipe – Executive Summary.pdf>

- The most important recommendation is that the international character of CCS implies that strong co-operation among relevant governments is required. In particular, the planning of CO₂ transport infrastructure and the availability of CO₂ storage sites to projects must be tackled in a manner consistent with the energy needs of a country or a region over the next few decades.
- A robust policy roadmap is fundamental for private industry and the public sector alike to efficiently manage the financial and associated risks. Government leadership in providing a guiding framework will significantly reduce the uncertainties currently facing potential CCS developments.
- Future emission sources (capture locations) can be assumed to be located at or near current emission points in many OECD countries. Suitable storage locations, however, are known with certainty only once storage capacity is proven. Therefore “future-proofing” transport infrastructure relies on early knowledge on the availability of storage capacity. As it can take 5-10 years for the full characterisation and testing of a single storage location, priority should be given to the qualification of storage locations, to reduce the uncertainty in the location of future injection points.

- Harmonisation and standardization of the method of storage qualification will help decrease the time needed for storage qualification. Particular attention should be paid to qualification of saline formations, which are expected to take 60-80% of the total amount of CO₂ to be stored, though they still lack detailed appraisal work.

Conclusions

The objective of this chapter has been to describe recent storage work and to draw out challenges and lessons. While the case studies described in this document differ in their goals, approaches, stages of development and specific features, they all point to similar conclusions regarding CO₂ storage and transport.

Firstly, storage is critical to any project design and must be addressed up front. While storage is the last of the three steps of a CCS project, it should be developed simultaneously with capture and transport from the very beginning:

- Reservoir characteristics and behaviour may determine the design and operation of the whole CCS chain. Reservoir behaviour will directly influence a range of key technical aspects of the CO₂ capture, including temperature, pressure, and purity. Physical characteristics of a storage site will also determine the optimal rate of injection, which influences the rate of capture. Location of a suitable storage site determines the need for a transportation network, including its length, trajectory, required permitting and the required stakeholder consultations processes.
- Available experience shows that it can take 5-10 years to qualify a new saline formation for CO₂ storage, even when theoretical estimates are already available and look promising. Testing of potential storage sites takes time and is necessary to prove actual availability of storage and determine its characteristics. Storage considerations may well dictate overall project timelines: while it is usually plan the time required to build a capture plant, the situation with finding a storage site is less certain.

Secondly, high level national and/or regional storage data is very important and has to be developed first. This can provide information on theoretical storage capacity and reveal geographical areas with significant CO₂ storage potential. While high-level data does not replace site-specific exploration, assessment and testing, it may help individual project proponents to make informed assessments and take decisions regarding the best potential storage sites.

Thirdly, a common methodology for storage assessment at the national and/or regional level is needed. Common methodologies would facilitate comparability of national and regional storage data and information. This would facilitate a more accurate assessment of global storage capacity. It could also assist in making strategic decisions about optimal CO₂ storage sites (including the potential benefits of trans-boundary movement of CO₂ for storage). The following chapter in this document provides a more detailed discussion on storage capacity estimation methodologies.

Fourthly, comprehensive regulations for the safe storage of CO₂ are critical and take time to develop. This aspect is often the most critical component of the whole CCS chain. It should be facilitated by laws and regulations that ensure safety of operations and provide clear permitting procedures. It takes time to develop these rules and procedures. A review of existing laws and regulations needs to be conducted to identify gaps and barriers. Various specific provisions will then need to be developed, including rules on long-term liability. All CO₂ storage must be undertaken with an appropriate safety regulation framework, and governments need to make sure that such laws and regulations are in place.

Fifthly, monitoring, reporting and verification of storage sites are very important, and need to be performed according to specific guidelines. Integrity and safety of a CO₂ storage can only be proven through appropriate monitoring. Without monitoring, an injection site cannot be considered as providing for permanent geological storage of CO₂. Monitoring data should also be reported to the relevant authorities, those responsible for safety and those responsible for national CO₂ accounting.

Sixthly, it is in the interest of project proponents to ensure adequate public outreach and stakeholder support. Gaining support from the public is an integral part of any CCS project. Lack of public support may result in project cancellation and could also create hurdles to wider CCS deployment. Project proponents need to work actively with the public to secure its support.

Finally, experience from the Weyburn project site in the past 12 years demonstrates that enhanced oil recovery and CO₂ storage can work hand in hand and that accurate CO₂ accounting is possible. CO₂-EOR is often suggested as an early business opportunity for CCS. Monitoring of this trapped CO₂ is required to provide information on how much of the injected CO₂ actually stays under the ground. More demonstration is needed to increase the data pool and enhance stakeholder confidence. The Weyburn project is so far the only CO₂-EOR project where monitoring of CO₂ underground was conducted for several years.

As regards CO₂ transport network development, an integrated approach is required, and governments have a key role to play in facilitating such planning processes, potentially involving several industrial sectors and neighbouring jurisdictions.

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2. Estimating technical CO₂ storage capacity

Introduction

To understand the emission reduction potential of carbon capture and storage (CCS), decision-makers need to understand the size and distribution of carbon dioxide (CO₂) storage resources. Prerequisites for this are a clear and widely shared definition of CO₂ storage potential and an agreed method for its calculation.

The last two decades have seen a proliferation of proposed classification schemes for CO₂ storage potential and methods to estimate CO₂ storage resources, with no one methodology being uniformly adopted around the world. These methods have been used to make estimates of storage potential that, in some cases, conflict with each other, despite being of similar vintages and covering comparable areas. For example, some estimates of potential for individual countries or regions were larger than those for the entire world (Benson and Cook, 2005; Bradshaw et al., 2007). Consequently, there remains uncertainty about what different methods to estimate potential are actually measuring, which methods are most appropriate in given settings, and whether the estimates produced by these methods provide a sound basis for policy making. Moving to a uniform methodology can enable stakeholders to identify and compare different storage resources in different locations.

This chapter reviews current work aimed at harmonizing assessment methodologies used in different countries, with a view to improving the consistency of estimates and to making them more comparable with each other. The chapter reflects a process of dialogue amongst a number of national geological survey organisations, facilitated by IEA. After a brief description of key issues and concepts, a review of different assessment frameworks that have been employed in various countries is presented. The chapter then suggests generic guidelines for the technical assessment process that would facilitate the comparison of storage assessment results between countries and ensure that these could be aggregated to yield a robust worldwide storage estimate.

The discussion in this chapter is limited to the technically available storage capacity. This only represents part of the story, as what is technically available and accessible may not be economically feasible. In addition to economics, regulatory constraints may impose yet another layer of complexity and constraint. Hence the practical real available storage capacity is a further subset of what might be technically available.

Some key elements of storing CO₂ and estimating capacity

A geologic CO₂ storage resource comprises pore space that can safely and permanently hold CO₂. Therefore a geologic formation suitable for storage must have properties that allow CO₂ to be injected and, once injected, retained through one or more trapping mechanisms. Four trapping mechanisms are generally recognised (Benson and Cook, 2005; Bradshaw et al., 2007): (i) buoyant (also referred to as structural and stratigraphic), (ii) residual, (iii) solubility, and (iv) mineral.

While all four mechanisms play an important role in ensuring that CO₂ is retained over long time scales, given anticipated injection rates and current technology, the most relevant trapping mechanisms for resource assessments are buoyant and residual trapping. In buoyant trapping CO₂ is held in place by a top and lateral seal, either a seal formation or a sealing fault (Brennan et al., 2010). Buoyant trapping relies on the geometric arrangement of the reservoir and the seal

unit. Residual CO₂ trapping occurs when CO₂ is trapped in the pore space by capillary forces. More precisely, residual trapping involves “discrete droplets, blobs, or ganglia of CO₂ as a non-wetting phase, essentially immiscible with the wetting fluid, trapped within individual pores or group of pores where the capillary forces overcome the buoyant forces” (Brennan et al., 2010). In the following we cover only assessments of buoyant and residual trapping mechanisms.

As in other industries (e.g. oil and gas), CO₂ storage classification schemes delineate between estimates of resources and reserves (or, in the case of CO₂ storage, capacity) on the basis of technology, cost and certainty. A *resource* can be described as anything that is potentially available to be exploited with available technology; however, the presence of a resource does not imply that any part of it can be exploited economically now or in the future. The portion of a geologic resource that has economic value now, and is thus a commodity, is referred to as a *reserve*. Resource estimates that take into account economic factors are typically referred to as contingent resources.

How much pore space is available – role of constraints

Any geologic CO₂ storage resource assessment process estimates the mass of CO₂ that can be stored within the pore space of subsurface rocks. The differences between various resource estimates are explained by the different constraints placed on what constitutes “available” pore space. These constraints relate to:

- geology and our understanding of the subsurface in terms of geologic data and models,
- engineering considerations that are related to technologies available to exploit the available pore space and our ability to implement them,
- economics stemming from cost to access the resource and
- regulatory limitations on the use of certain technologies, or socio-political factors including acceptance of use of the subsurface for CO₂ storage.
- Engineering, economic and regulatory/socio-political constraints can be applied at various stages of the estimation process, and may often be imposed by government policy. The minimum depth requirements in many methodologies are one such example. Therefore, before a jurisdiction or organisation attempts to estimate the geologic CO₂ storage resource of any particular area, they need to determine the exact goals of the assessment, as well as the constraints that will be involved in their estimates and how they will be applied.

Constraints can be applied to the **input** used for the estimate. These constraints limit the amount of pore space available for storage. Depending on the jurisdiction, these constraints could limit pore space to:

- storage formations overlain by a sealing formation,
- off-shore storage,
- petroleum-bearing strata,
- a certain distance from point sources of CO₂ emissions,
- stratigraphic or structural closures where CO₂ will be trapped as an immobile column,
- reservoirs associated with enhanced oil recovery or
- depth at which CO₂ exists as a dense liquid or supercritical fluid.

Constraints can also be applied to the **output** values of the estimate. Examples of such constraints are:

- assumptions about whether reservoir pressure control is practical (in essence this is an economic constraint) and

- requirements to protect underground drinking water resources.

Because of lack of data and uncertainties inherent in subsurface evaluation, our understanding of the subsurface is always limited – an issue that also faces the oil and gas businesses. The situation can be addressed by gathering more geologic data and the use of probabilistic methods that respects uncertainty in the input data used for the resource assessment and reflects this uncertainty in the assessment results, drawing on the established practices in the oil and gas subsurface analysis. In general, geological uncertainty increases with decreasing amount of input data, and that will widen the range of possible storage assessment resource values. The ranges of resource estimates still hold significant value as a prospective tool and for adding to the understanding of the global CO₂ storage endowment.

Storage efficiency

A key component of any storage assessment is the concept of storage efficiency. The storage efficiency represents the fraction of accessible pore volume that will be occupied by free-phase CO₂. It is dependent of a variety of factors including:

- the volume of rock contacted by the CO₂ plume, also known as the sweep efficiency,
- how easily CO₂ will move relative to the water present within the pore space, also known as relative permeability,
- the amount of water that will be displaced by the CO₂ plume, also known as drainage,
- how much water re-enters the pore space at the trailing edge of the CO₂ plume, also known as imbibitions,
- the ratio of the viscosity of the CO₂ to the viscosity of the water,
- the ratio of the density of the CO₂ to the density of the water and
- whether any pressure management methods will be allowed during CO₂ injection – the lack of pressure management might significantly reduce the storage efficiency values (Zhou et al., 2008).

Furthermore, CO₂ storage efficiencies are dependent on the type of CO₂ trapping. Buoyant trapping will have much higher storage efficiency values relative to residual trapping.

Current CO₂ resource assessment methodologies

The list of major storage potential assessments that have been published in the last few years include:

- United Kingdom CO₂ Storage Appraisal Project (Gammer et al., 2011),
- United States Geological Survey (USGS) (Brennan et al., 2010, Blondes et al., 2013),
- US DOE – The United States 2012 Carbon Utilization and Storage Atlas IV (US DOE NETL, 2012),
- North American Carbon Atlas Partnership (NACAP, 2012),
- Australian Carbon Storage Taskforce (Carbon Storage Taskforce, 2009),
- Queensland CO₂ Geological Storage Atlas (Bradshaw et al., 2009),
- Saline-aquifer CO₂ Sequestration in Japan (Ogawa et al., 2011),
- Geological Survey of the Netherlands (TNO) – Independent Storage Assessment of Offshore CO₂ Storage Options for Rotterdam (Neele et al., 2011a, b; 2012),
- Federal Institute for Geosciences and Natural Resources (BGR), Germany – Recalculation of Potential Capacities for CO₂ Storage in Deep Aquifers (Knopf et al., 2010) and

- CO₂ Storage Atlas: Norwegian Sea (Norwegian Petroleum Directorate, 2011).

All of these assessments employ their own specific methodologies. The next section discusses their key characteristics.

Characteristics and comparison of assessment methodologies

Although the equations used in the various assessments differ in minor respects (Prelicz, Mackie and Otto, 2012; Goodman et al., 2013), the main differences between the assessments relate to whether or not pressure build-up during storage is assumed to be managed, the storage efficiency factors that are applied and the policy constraints that have been incorporated. While there are many differences, there are equally common elements between different assessments. We discuss these issues in succession.

Pressure management

The assumption that reservoir pressure can be managed is made in all of the assessments with the exception of those for the Netherlands and the UK. In a purely technical sense, it is possible to control reservoir pressure through the production of reservoir fluids from the storage reservoir, though this may occur at significant cost. Therefore methodologies which assume that pressure can be managed are closer to a technical resource assessment than those which do not make this assumption. The former are constrained by what is technically possible regardless of cost, whereas the latter are contingent upon the (potentially prohibitive) cost of pressure management.

Assessments which assume pressure management result in larger storage potentials than those that do make this assumption because they employ storage efficiency factors that are typically larger than pressure-limited storage efficiencies.

Storage efficiency factors

The various assessments by and large attach different meaning to the concept of storage efficiency and, in cases where a similar meaning is assumed, use different methods to estimate storage efficiency. This makes the comparison the storage resource estimates from various assessments difficult, and this is one of the causes of the wide range of assessment values mentioned earlier in this document. Therefore, a consistent definition and method for estimating storage efficiency is needed.

Policy constraints

Policy constraints, applied in all the methodologies, can significantly reduce the pore volume considered in the assessment compared to the total pore volume available in the jurisdiction. This is not necessarily a disadvantage for policy makers, because it results in a realistic assessment of the available resource in each jurisdiction studied. Thus, of the eight studies that include onshore areas, the two US studies (USGS and US DoE) explicitly exclude pore space because of policy requirements to protect underground sources of drinking water. One study (Germany) excludes pore space outside known traps for buoyant fluids (i.e. structural and stratigraphic traps). Two studies (United Kingdom and Germany) exclude a fraction of the available pore space by applying minimum storage unit capacity cut-offs. Three studies (United Kingdom, Queensland, and the Netherlands) exclude pore space by applying minimum permeability or injectivity cut-offs. The Norwegian study excludes pore space in the rock volume where petroleum may have migrated, because they expect that petroleum exploration and

production will continue on the Norwegian continental shelf for the foreseeable future. The UK study excludes onshore pore space and some remote areas offshore.

Some common aspects of the assessment methodologies

All of the listed assessments consider storage potential of saline water-bearing reservoirs (saline aquifers) and none of them considers the entire pore space in reservoir rocks within the area that they cover, for a variety of technical, policy-driven and economic reasons. In addition, all the studies exclude:

- Pore space at shallow depth, where stored CO₂ is not likely to be in the dense phase.
- Pore space in inadequately sealed reservoir rocks. This is justified because although such rocks could retain a residual saturation of CO₂, creating a residual saturation of significant mass would cause significant volumes of CO₂ to leak out of the reservoir.

Looking at their differences and common elements, the reviewed assessment methodologies can be grouped into four categories corresponding to the resource type that is assessed:

- technically accessible storage resources,
- the storage resource in structural or stratigraphic traps,
- the contingent storage resource assuming pressure management wells will not be used and
- the contingent storage resource in subsurface volumes where CO₂ storage will not affect hydrocarbon production or exploration.

Table 2.1 shows how the resources assessed on the basis of the reviewed methodologies fit into these categories.

Guidelines for assessing technical CO₂ storage capacity

The discussion has so far explored the differences between methodologies and shown that and how they are related to societal and policy choices related to the CO₂ storage resource a country wishes to access. On the other hand, a key goal of international collaboration on storage assessment methods should be to create a uniform and coherent process that would facilitate the comparison of storage assessment results between countries. Such a process would need to be independent of specific policy choices. The starting point for this process is to evaluate the technical storage capacity.

In the following we propose to employ the concept of technically available storage resource (TASR). The TASR answers the question: how much storage resource is there in total? The TASR comprises the pore space that can be reasonably expected to retain CO₂ over a long period of time without adverse environmental impact. In this sense it represents an “upper limit”. Since the TASR is not constrained by economic or policy considerations, it can be used to gain a better understanding of the trade-offs that are often made when developing policies to control access to resources. Because of this, the TASR allows comparison of the endowments of countries with storage space. For these reasons, the initial assessment of a country’s endowment with storage space should aim to quantify its TASR.

After an initial assessment of the TASR, a further, more focused assessment can be performed to reflect country-specific policy requirements. Examples of such focused assessments are illustrated by the German (BGR) and the Dutch (TNO) methodologies. Please note that the following discussion only covers TASR. Assessing the economic and regulatory constraints are not part of this chapter.

Table 2.1 • Categorisation of reviewed storage resource assessment methodologies

Name of assessment	Technically accessible storage resource assessment	The resource in structural or stratigraphic traps	The resource assuming pressure management wells will not be used	The resource in subsurface volumes where CO ₂ storage will not affect hydrocarbon production or exploration
UK CO ₂ Storage Appraisal Project		•	•	
USGS	•	•		
US DOE Carbon Utilization and Storage Atlas	•			
North American Carbon Atlas Partnership	•			
Australian Carbon Storage Taskforce	•			
Queensland Geological Storage Atlas	•			
Japan – Saline-Aquifer CO ₂ Sequestration	•			
TNO – Offshore CO ₂ Storage Options for Rotterdam			•	
BGR – CO ₂ Storage Potential in Deep Aquifers		•		
Norwegian CO ₂ Storage Atlas				•

Note: Unless otherwise noted, all tables and figures derive from IEA data and analysis.

Steps in conducting TASR assessments

A TASR assessment can provide an evaluation of all the technically accessible storage resource, regardless of non-technical, *e.g.* economic and political, constraints. The guidance for assessing TASR provided by the USGS (Brennan et al. 2010, Blondes et al. 2013) takes the form of four basic steps that can be applied to all assessments, followed by three additional steps that depend on whether a buoyant-limited or pressure-limited assessment is conducted. It comprises a comprehensive and versatile assessment framework that could be applied globally. Building on steps 1-4, this section then discusses three further steps, 5-7, that can be employed to estimate subsets of TASR, depending on the allowed trapping mechanisms and on the availability of reservoir pressure management.

Step 1 – Subdivision into geological units of assessment

The basis of geologic CO₂ storage resource assessments is the characterisation of the subsurface. All the methodologies considered here use reservoir and seal pairs as their units of assessment.

In general it is advantageous to break down the assessment into ‘storage assessment units’ (SAUs) each of which comprises a mappable subsurface body of rock into which CO₂ can be injected and trapped, and which is overlain by a regional sealing formation (Brennan et al., 2010). The advantages of using SAUs as part of the assessment process include:

- each SAU is spatially limited (and thus can be included in a Geographic Information System),
- detailed assessments and reports can be compiled for individual SAUs and
- SAUs can be treated individually in any potential aggregation step.

Step 2 – Estimation of the total volume of accessible pore space in each SAU using probabilistic methods

The total volume of accessible pore space in each SAU needs to be quantified. Because geologic properties are inherently heterogeneous and data are typically sparse and have associated errors, probabilistic methods are best at considering these limitations and capturing the uncertainty in the assessment results. Therefore, for all input estimates ranges should be used rather than fixed values. These ranges determine the distribution of input parameter provided some assumptions related to the shape of the data distribution are made.

Step 3 – Use consistent storage efficiency ranges

To generate repeatable CO₂ storage assessment results, a consistent method to estimate storage efficiency ranges is recommended. For example, the USGS methodology splits storage estimates into buoyant and residual trapping and documents unique storage efficiencies for both types of storage using a calculation method suggested by MacMinn, Szulczewski and Juanes (2010). This approach could serve as a starting point for a more uniform storage efficiency estimation method.

Step 4 – Convert the volume of CO₂ to a mass of CO₂

The TASR involves specification of the mass of CO₂ that can be stored in the pore volume of the SAU, while taking into account present-day geologic knowledge and engineering practice and experience. To achieve this, for each SAU the unit volume of CO₂ stored must be converted to a unit mass by estimating the density of CO₂ within the SAU. The CO₂ density can be determined for the thermal and pressure ranges present across the SAU using a suitable thermodynamic equation (e.g. Blondes et al., 2013).

Methods to estimate subsets of the TASR

Depending on the jurisdiction in question, it may be necessary to apply certain conditions and constraints to the TASR methodology. The application of constraints would provide policy makers with storage resource assessment values that assess the contingent fraction of the TASR available for storage.

One such constraint might be related to the type of trapping allowed. If only buoyant trapping is acceptable, then a methodology that focuses only on buoyant trapping would be expedient. An example for this approach is the methodology developed by BGR to assess the storage potential in Germany (Knopf et al., 2010). Another common constraint relates to the requirement that the pressure in the storage reservoir remains below the fracture strength of the seal when it is not controlled by active pressure management. One such method for pressure-limited storage assessment is the methodology used by TNO for assessing the storage potential in the

Netherlands (Neele et al., 2011a).

The final steps in a storage assessment depend on which types of constraints the methodology wishes to adopt.

Recommended steps for buoyant-limited storage assessment

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Step 5 – Identify closure type

The closures need to be defined as stratigraphic, structural, or a combination of both.

Step 6 – Identify geologic models for existing traps

Using the information on closures, geological models can be constructed which then provide ranges for estimating distributions of area, thickness, porosity and permeability for a specific closure type. These distributions provide inputs into probabilistic assessment methodologies.

Step 7 – Use geologic models as analogues

Storage potential in formations or basins for which little or no data are available should be estimated using the geological models developed in step 6 as analogues.

Recommended steps for pressure-limited CO₂ storage assessments

In this case the assessment is completed by the following steps.

Step 5– Determine present pressure of the injection site or formation

The pressure of the injection site or formation is determined from well measurements or pore prediction modelling.

Step 6 – Identify injection rate to stay below maximum allowable pressure increase

If regulations impose a limit on the increase in pressure within the formation then the CO₂ injection rate needs to be adjusted. This rate controls how the CO₂ plume will migrate in the formation and how the pressure front will propagate.

Step 7 – Identify extent and depth of the pressure front

The extent and depth of the pressure front corresponding to an injection rate should be verified to keep within jurisdictional limits. Both injection rate and the geological model are key factors that determine the location of the pressure front in relation to the CO₂ plume. Whichever assessment methodology is chosen, it is important that all constraints are explicitly stated in order to facilitate comparisons of assessment between jurisdictions that are subject to contrasting restrictions.

Conclusions

There is a need for a common, internationally sanctioned assessment procedure to achieve a transparent and robust assessment of geologic CO₂ storage resource, throughout the world and across different geologic settings.

The TASR approach presented above summarises the consensus reached in workshops between representatives of the geological surveys of Australia, Canada, Germany, the Netherlands, the United Kingdom, and the United States, facilitated by the IEA. Given that estimates of TASR are essentially determined by geological considerations, and are not constrained by country-specific policies regarding the use of the subsurface, TASR estimates for different countries or jurisdictions can be easily compared and aggregated. Therefore, a TASR assessment should form a fundamental part of any assessment methodology. On a technical level, there is a need to identify a uniform method for calculating storage efficiency ranges and how that method might be used for future assessments.

There is also a need to enhance the co-operation between organisations that have attempted or completed CO₂ storage resource assessments and those that are looking to begin assessments. This co-operation could be fostered via agreements between national organisations or through workshops or training by those with experience in assessing CO₂ storage resource. To have the best, up-to-date estimate of global CO₂ storage resources, and the geographical distribution of those resources, some sort of formalised international co-operation would be desirable.

Finally it should be reminded that the discussion in this chapter is limited to the technically available storage capacity. This only represents part of the story, as what is technically available and accessible, may not be economically feasible. In addition to economics, regulatory constraints may impose yet another layer of complexity and constraint. Hence the real available storage capacity is another subset of TASR. Further work to define the economic and regulatory layers is thus necessary in the future.

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3. Investing in CCS: Key project gateways

Introduction

Carbon Capture and Storage (CCS) is projected to play a crucial role in a carbon-constrained world, as it is currently the only technology able to significantly reduce emissions from the use of fossil fuels (IEA, 2012). Addressing climate change risks without CCS in the portfolio is estimated to significantly increase the cost of action (IEA 2012). CCS is, at the same time, a capital intensive activity requiring large funding. The process of mobilising public and private sector finance, i.e. bringing project sponsors or lenders to a positive final investment decision, faces many challenges, but is critical to the long-term success of CCS deployment. This chapter outlines some key aspects of an investment decision for a CCS project, with particular attention paid on storage. The chapter also highlights the role that independent, outside reviews can play during the due diligence process.

CCS has potential application as a carbon abatement technology across several sectors, including fossil-fuel power generation and heavy industry sectors such as steel, cement and refining. While it is sometimes asserted that CCS is an ‘unproven’ technology, CO₂ capture technologies are commercially available today and the storage of CO₂ in geological formations is well-established. Indeed, there are currently several large-scale CO₂ storage projects in operation around the world (Global CCS Institute 2012). Nonetheless, the deployment of large scale integrated CCS projects for the sole purpose of emission reduction has, to date, fallen short of the ambitions held for the technology by policy makers and industry.

Complexity for a CCS project financing decision arises on several fronts:

- A combination of public and private funding, involving parties with varying technical capability and tolerances to financial and reputational risk means that it may be difficult to align goals around the achievement of a commercial return versus minimising risk exposure.
- Achieving a final investment decision (FID) on an integrated project is likely to have required significant at-risk investment in CO₂ storage exploration and appraisal, selecting a concept, as well as a detailed design of process and capture facilities and then making an even larger (sometimes multi-billion dollar) investment in constructing the plant.
- In traditional resource industries, this exploration and appraisal investment has been funded with private-sector equity however there is no commercial model which supports such equity investment for CO₂ storage.
- Investors in CO₂ storage resources may, in many cases, be dependent on one or more investors in capture technology associated with the power or industrial processing sectors for the CO₂ source and revenue. In such instances, in order to assure a return on their investment in exploration, appraisal and development, it is likely that the CO₂ source investor will be required to enter “send-or-pay” contracts with the CO₂ storage operator. Such agreements will be time consuming to negotiate and draft and complex to review.
- Deployment of the key capture technology is relatively new and commercial lenders will need to seek lay-off the technical risk, especially for integration (including counter-party) risk.
- Process plants (industrial or power) with CCS will be more expensive to run and may have lower availability (at least while ramping up). In the case of power plants, operating in highly competitive electricity markets, special power-purchase agreements including electricity price guarantees are likely to be needed. Such agreements will be time consuming to negotiate and draft and complex to review.

- The result of this complexity is business case complexity, which will manifest as additional project cost and schedule slippage.

The scale and complexity of projects together with the lengthy, at-risk, front-end development investment required to achieve an investment decision has typically put large scale CCS projects beyond the political commitment of governments. For the private sector, whilst there are various technical, commercial and regulatory risks to projects, it is typically a lack of commercial rationale which precludes it from investing alone. Therefore, while current projects may be led by private sector proponents, they will require significant support from governments in order to proceed. This is true for all CCS investment today, and especially in markets where the internalisation of CCS costs creates a significant competitive disadvantage.

Another specific characteristic of CCS is the necessity of large up-front investment in securing storage capacity. This is a critical aspect in the process of investing in CCS. The final investment decision for a large capture facility cannot be taken without a high level of confidence that the resulting CO₂ can actually be stored in the envisaged site or sites. Therefore, the whole investment framework and its various stages are either strongly influenced, or actually defined, by the development of the storage site.

Capital investment gateways for CCS projects

Capital investment frameworks generally mandate that significant projects be developed in stages, for the purpose of managing exposure and pacing financial commitment to the level of development and understanding of the project. Between these stages are investment decisions which govern the continuation (or otherwise) of expenditure on the project. What is more, several such stages need to be cleared *before* the final investment decision is actually taken.

Therefore, for the purposes of this chapter, the nature of project investment decision making is assumed to be stage or decision-gated. Each stage-gate represents an investment decision of the kind “stop, go or recycle”. It is important to note that the end of any stage may result in the cancellation of the project and writing off of previous investment.

Therefore a degree of investment ‘due diligence’ is required at each decision gate, commensurate with the funds to be put at risk and the risk tolerance of the investor.

Investors variously describe the project development stages and stage gates differently but each involves a phasing of investment in studies so as to increase the level of project definition, reduce risk and uncertainty and increase confidence in financial metrics. Examples of project phasing terminology are provided in Box 3.1. Figure 3.1 below lays out the generic steps in a graph.

The level of due diligence and the confidence required by investors in order to invest in the next phase will increase through the early stage gates of scoping, pre-feasibility, feasibility and so on until a final investment decision which marks the decision to invest into project completion. Different investors (especially public versus private) are likely to have different risk tolerances related to their ability to afford and accept financial loss and may have different due diligence requirements. Thus there is unlikely to be a universal standard or check-list at the end of each stage-gate decision by which to judge the prudence of the next investment phase. However, there is likely to be a common core of due diligence requirements.

Box 3.1 • Generic steps in a CCS investment process

A framework and terminology that has achieved some popularity in managing exploration and production projects in the oil industry, and is readily applicable to CCS projects, is built upon a set of activities that can be grouped into consecutive phases reflecting the maturation of a CCS project (Global CCS Institute, *The Global Status of CCS: 2013*).

Activities in the initial **Identify** phase are geared to provide an answer to the question ‘what could the project be’ by developing high-level project options and determining their business viability.

Once a range of feasible projects options and concepts has been identified, they are then further examined in the **Evaluate** phase. This phase is meant to provide answers to ‘what should the project be?’ and, crucially, involves selection of the preferred option.

In the following **Define** phase the selected option is examined in more detail. The question defining this phase is ‘what will the project be?’ The final investment decision is typically taken at the end of this phase.

The following **Execute** phase comprises activities that are undertaken to physically build the CCS facility and to put in place the organisational structure underpinning its operation.

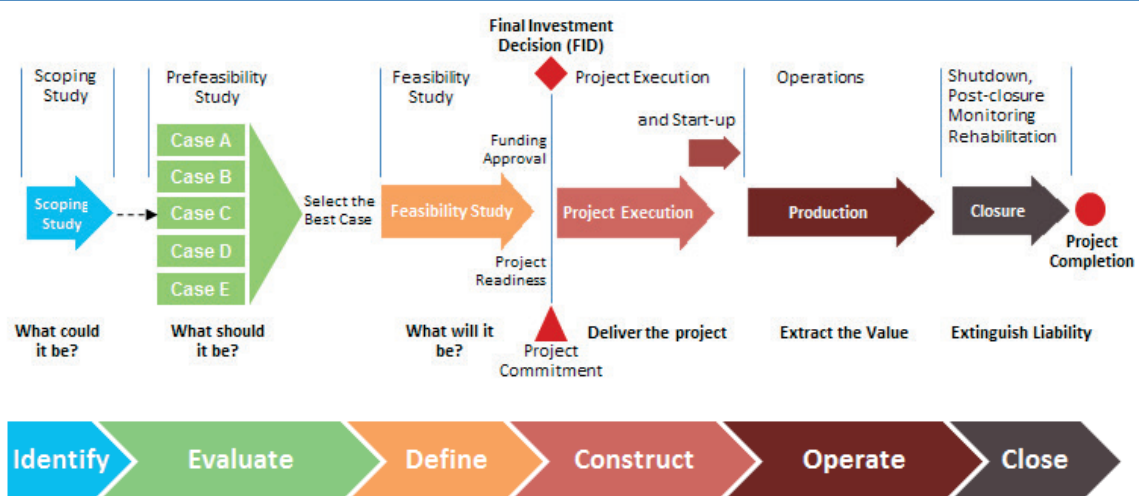
In the **Operate** phase the project is operated to achieve its performance in conformity with regulatory requirements.

Finally, in the **Closure** stage the CCS project is decommissioned in compliance with regulatory requirements and resources for post-closure activities are allocated.

It starts where it ends: importance of confidence in CO₂ storage resource

The nature of investment in integrated CCS projects is such that while capital expenditure tends to be weighted heavily towards the power and CO₂ capture plant side (whether in power or in other industries), most technical, and arguably non-technical, risk of the project is dominated by storage availability and performance. This is coupled with public acceptance and its political implications. While reduced over the course of the project, such risks remain until significant funds have been spent on “proving” storage to an acceptable level of performance and understanding and mitigating the residual risk. For example, a decision- or stage-gated storage

Figure 3.1 • Project development frameworks illustrating phasing of studies from concept to operations

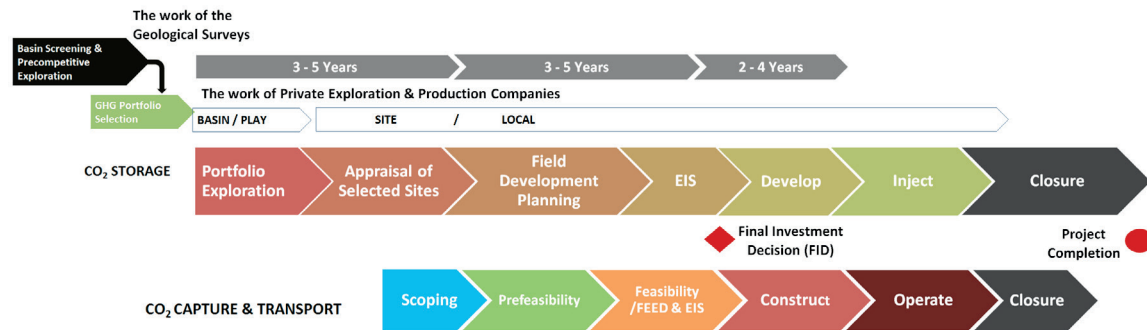


Source: Garnett, A. & Greig, C., The University of Queensland.

project roadmap has previously been developed by DNV and industrial collaborators (DNV GL 2010). Some lessons from the ZeroGen project in Queensland, Australia about risk-based phasing of investments are discussed. (Kvein et al, 2010) (Garnett, Greig & Oettinger 2012).

A critical factor for any CCS project is that it is unlikely that a final investment decision can be taken until storage is proven to a high level of confidence, pre-agreed with investors. Consequently, considerable early stage-gate due diligence efforts are required to look at the nature and maturity of the proposed storage solution within the project. The critical early investment question is how much confidence in storage presence and performance is required in order to invest much larger amounts in plant and capture? This question applies as much to investment in pre-FID studies associated with plant and capture, as it does to the decision to invest in actual physical plant because the potential scale and technical details of plant options may well be constrained or otherwise influenced by the scale and nature of the storage resource.

Figure 3.2 • Indicative timeline for development of a CCS project illustrating the relative timing for characterising CO₂ storage resources, pipeline transport and plant feasibility.



Source: Garnett, A. & Greig, C., The University of Queensland.

In any case, a high level of confidence in the presence and performance of the storage solution will only be a *necessary* but not *sufficient* requirement for FID. Hence for CCS projects, like many projects which rely on a natural resource, the characterization of that natural resource, in this case the CO₂ storage resource, ought to precede significant investment in engineering and locking-in of CO₂ source and capture plant details. In addition to financial issues, project permitting is another key process for any CCS project with Box 3.2 providing further details.

Due diligence via independent reviews

In line with a stage-gated process, there will be several levels of expert review which inform the due diligence processes, such as:

- **Technical reviews:** these may be internal to an operator e.g. in the case of a major international company, or external, independent reviews e.g. in the case of a small special purpose project company. They are expected to be at individual discipline level as well as across technical disciplines and to have taken place within a documented formal, technical review process.
- **Independent, integrated project reviews:** these will be major events and will be external or at least have a significant, expert external input, to the project proponent. They will build on the results of the technical review process and examine project risks and deliverability issues across the techno-environmental, economic, commercial, organisation and socio-political areas.

- Legal reviews: because of the nascent nature of GHG-related legislation and little or no experience with its operation, it is expected that for CCS projects, specific legal and regulatory expert reviews will also be required. These will include overlap from the independent review process.

Box 3.2 • Regulatory aspects of CCS projects

Investment confidence may also require firm indications that an Environmental Impact Statement (EIS) or assessment (EIA) has been declared acceptable by the regulator prior to FID. Depending on the jurisdiction, a detailed EIS or EIA may well require considerable storage appraisal and engineering definition.

In some jurisdictions a whole-of-project EIS will be required to cover capture, transport and storage and this may either be “case” (performance) based or more prescriptive (compliance-based). In other jurisdictions, the assessments may be considered separately for the construction and operation of the storage site, pipeline and plant. In either case, it is likely that environmental permits and storage resource licence rights are first required for the exploration and appraisal activities such as seismic tests, drilling and test injection.

Confidence in permanence of CO₂ storage (containment) is of particular interest for FID because of the implications for extinguishing or transferring the proponent’s CO₂ leakage liability upon project closure after the cessation of injection operations.

In addition to impact assessments, the general permitting framework for CCS projects will guide any project. Several permits will be required by any project in most jurisdictions, in order for the project to proceed from earlier stages to FID and beyond. The *IEA CCS Model Regulatory Framework* (IEA, 2010) outlines various regulatory and permitting aspects in most jurisdictions.

Notwithstanding that project investors may undertake their own due diligence, as a general proposition it may be beneficial for a project to ensure regular external opinions. This could be achieved via independent reviews to inform the project investors (which may be represented by project company board members, shareholder / joint venture partner representatives and other funding body representatives) on the appropriateness of proceeding to the next stage of development of the project.

Obtaining a recognised ‘external view’ of large complex projects (such as integrated CCS projects) helps to avoid potential problems of “honest delusion” and “deliberate deception” (Flyvbjerg et al. 2009), which may be seen amongst project proponents seeking to compete for investment dollars and government incentives or project contractors and consultants seeking to establish or maintain a preferred position in new projects. This can be especially the case in frontier projects where a desire to “be first” and access “free” government money can lead to a tendency to understate risks, uncertainty and cost.

Therefore, within a due diligence approach for CCS projects, it is wise for the investment decision framework to mandate that all significant projects be developed in stages punctuated by significant, external, independent reviews. Such independent reviews should examine all of the deliverables from a particular stage including, but not limited to, health and safety, environmental, commercial, technical, stakeholder relationships, etc., and focus on 5 or 6 main areas to justify the next, final and largest investment required. For example, the review process should seek to assure that:

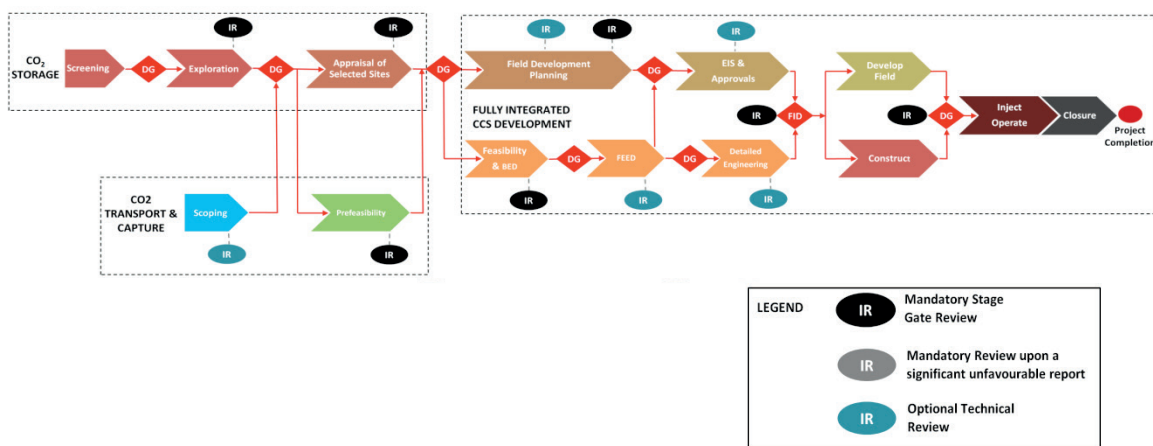
- The quality of technical work done to date is of sufficient standard and has adequately covered all risks and that predictions are robust. This is likely to require an in-depth end-of-stage technical review which pre-dates and informs a more holistic project review.

- The quality of non-technical studies done to date is of sufficient standard and has adequately covered all risks such that predictions are robust.
- The future study, capital and operating cost estimates and commercial and business models are robust against future downside scenarios for price, costs and performance.
- All necessary regulatory consents and authorities are, or will be, in place.
- The project organisation has the necessary skills and competencies to deliver the next phase of work.
- The project organisation and major contractors have the depth of resources (human and financial) to manage the project, including robustness to schedule slippage and cost over-runs.
- The project has sufficient support in the socio-political sphere.

Questions that independent reviews should aim to answer include for example:

- Do the storage screening studies support investment in exploration drilling, testing and seismic analysis?
- Do the exploration results and scoping study outcomes provide sufficient confidence to invest significant resources in storage appraisal, engineering and pre-feasibility studies and is there sufficient knowledge of a likely capture project that can be serviced by the storage resource?
- Do the appraisal results and the pre-feasibility study outcomes provide sufficient confidence to invest in further, more detailed storage appraisal and engineering feasibility studies and has the proponent demonstrated that the preferred project configuration (technology, scale, location, etc.,) delivers the maximum value?
- Do the field development planning, Environmental Impact Study and FEED study outcomes support the business case to provide significant investment (in the USD hundreds of millions and above) in the integrated CCS Project?

Figure 3.3 • Recommended timing of independent reviews



Source: Garnett, A. & Greig, C., The University of Queensland.

Based on these analyses, the independent review should make a recommendation to a decision executive or funders’ body (e.g. a board or project steering committee) as to whether they should accept to proceed to the next stage, request additional work or stop development of the project.

The role of the independent review is to review and assess industrial development decisions. It is therefore likely that the related review team is comprised of senior members with relevant development experience in major resource projects, rather than just detailed technical or scientific knowledge.

Additional interim technical reviews in specific technical sub-areas should also be convened at times other than a stage-gate boundary as part of the project proponents' quality assurance process – these may involve external specialists. This process and any applicable standards should be documented and be subject to external scrutiny. Further interim reviews may also be triggered if, in the opinion of the project leadership, shareholders or funders, an issue emerges that warrants such a review.

Figure 3.3 below shows an illustration of the decision pathway with the sequencing of the main independent and other review requirements.

Conclusions

This chapter has discussed some key aspects related to CCS project steps. CCS projects are complex, but can be better understood through generic investment gateways or steps. Capital investment frameworks generally mandate that significant projects be developed in stages, for the purpose of managing exposure and pacing financial commitment to the level of development and understanding of the project. Several such stages need to be cleared *before* the final investment decision (FID) is actually taken.

One specific characteristic of CCS is the necessity of large up-front investment in securing storage capacity. This is a critical aspect in the process of investing in CCS. The final investment decision for a large capture facility cannot be taken without a very high level of confidence that the resulting CO₂ can actually be stored in the envisaged site or sites. Therefore, the whole investment framework and its various stages are either strongly influenced, or actually defined, by the development of the storage site.

The nature of many large-scale, integrated CCS projects and their funding mix is such that investment due diligence will need to consider both pre-FID and FID decision gates. These project stages are typical for equity investment in resource projects.

Due diligence is likely to be both resource intensive and complex. It will be time-consuming and will need to consider both the content of the results of the development stages as well as the proponent's internal quality assurance processes and its overall management capabilities.

Management of risk arising from such complexity requires rigorous adherence to an investment decision roadmap, including clearly defined due diligence guidelines for investors at each stage.

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4. Policies to incentivise CCS in industrial applications

Page | 52 Introduction

In recent years, various analysts and governments have recognised that some of the world's most carbon-intensive industries may have no alternatives to CCS for deep emissions reduction. This is because much of the CO₂ is unavoidably generated by their production processes, not only from fuel use. According to a selection of these government statements, CCS in industrial applications:

- "...is critical to reducing emissions from production of industrial heat, for example from the continued use of coke-fired blast furnaces for steel production. For some industrial processes CO₂ emissions are intrinsic and can only be mitigated through abatement options such as CCS." – UK (DECC, 2012)
- "...appears to be a key solution to investigate, in order to widen and accelerate the global efforts to reduce greenhouse-gas emissions." "Various industries outside the energy sector, representing approximately 20% of global CO₂ emissions, have very few alternatives to CCS to achieve significant CO₂ emission reductions." – France (MEDDE, 2011)⁴
- "...is necessary to be able to reduce emissions in industries with process emissions that cannot be avoided." "It offers potential for a low-carbon re-industrialisation of Europe's declining industries... [and] may also help to increase public understanding and acceptance of the technology given the very visible link between jobs in local communities and continued industrial production." – European Commission (EC, 2013)

In parallel to such recognition, the Clean Energy Ministerial (CEM) Carbon Capture Use and Storage (CCUS) Action Group⁵ "called upon policymakers around the world to recognise the potential that carbon capture and storage (CCS) technologies for industrial sources of CO₂ have to help meet global greenhouse gas emissions reduction goals." (CEM, 2013)

Despite such supportive statements, there has been a notable lack of progress in both technology and policy terms for CCS in most industrial applications compared to the electricity sector. Industrial sectors are heterogeneous, with varying CO₂ sources, technology cost levels, and cost impact on final products. One important difference between industrial sectors and the power sector is that all of the industrial sectors covered in this chapter are exposed to global trade to varying degrees. The products of these sectors are generally commodities traded on international markets and their competitiveness is highly sensitive to production costs. CCS increases production costs, and these sectors have varying capabilities to pass on that cost to consumers.⁶ Enabling trade-exposed sectors to take vital climate change mitigation actions, such as CCS, while retaining a competitive position, is a key challenge for CCS policy in a world with fragmented climate policies. Due to the potential importance of CCS to industrial emissions reductions, it is

⁴ Free translation from the following original French-language text: "...apparaît comme une solution clef à explorer pour amplifier et accélérer les efforts mondiaux de réduction des émissions de gaz à effet de serre." "Pour les secteurs de la production industrielle hors énergie, qui représentent de l'ordre de 20% des émissions mondiales de CO₂, il n'existe que peu d'alternatives au CSC pour réduire de manière drastique les émissions de CO₂." – France (MEDDE, 2011)

⁵ The governments that participate in the CEM account for 80 percent of global greenhouse gas emissions and 90 percent of global clean energy investment. The 23 governments participating in CEM initiatives are Australia, Brazil, Canada, China, Denmark, the European Commission, Finland, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Norway, Russia, South Africa, Spain, Sweden, the United Arab Emirates, the United Kingdom, and the United States.

⁶ While electricity can also be traded internationally where interconnectors exist, it is more often the case that electricity is traded within national borders.

also a key challenge for achieving deep emissions reductions more broadly.

This chapter explores why CCS in industrial applications is a critical component of climate mitigation strategies and the current status of the technology. It then focuses on the policy approaches that might be appropriate to overcome the challenges to deploy CCS in industry.

Why is CCS in industrial applications of critical importance?

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At a combined emissions level of over seven gigatonnes of CO₂ (GtCO₂) in 2011, seven large industrial sectors including cement, iron and steel, chemicals and refining accounted for one-fifth of the total of 31 GtCO₂⁷ emitted globally (Figure 4.1). Emissions from each of these sectors are expected to grow by around 35% up to 2050 under current policies. This is primarily because of increasing demand for consumer products and infrastructure and the importance of commodities such as steel, cement, liquid fuels and chemicals for the growth of modern economies. Materials like steel, carbon fibres and concrete are also fundamental to the supply chains of other low-carbon technologies – *e.g.* wind and nuclear power – that seek sustainable lifecycle performance.

However, efficiency measures and non-fossil energy options only have the potential to reduce the specific emissions from the above sectors' production by around 30%.⁸ As a consequence, without CCS or an equivalent breakthrough in materials and fuels production, the total emissions from these sectors will increase if economic growth continues at expected rates rather than diminish, as required to limit global temperature increase to 2°C. In many industrial sectors there are no alternative technologies or methods on the horizon in the near- to medium-term to significantly reduce CO₂ emissions. Therefore, CCS can help break the link between economic growth and the demand for industrial output, on one hand, and increasing CO₂ emissions, on the other hand.

Industrial sectors are heterogeneous

The costs of applying CCS will vary between industrial sectors. These sectors produce different quantities and purities of CO₂, and the impact of using CCS would have different impacts on their production costs. As a result, sectors are at different stages of CCS development. Some sectors have already commercialised CO₂ capture technologies, due to the fact that there is an annual market for over 150 million tonnes of CO₂ (MtCO₂) for use in beverages, chemical manufacturing and enhanced oil recovery (EOR) (ADEME, 2010).

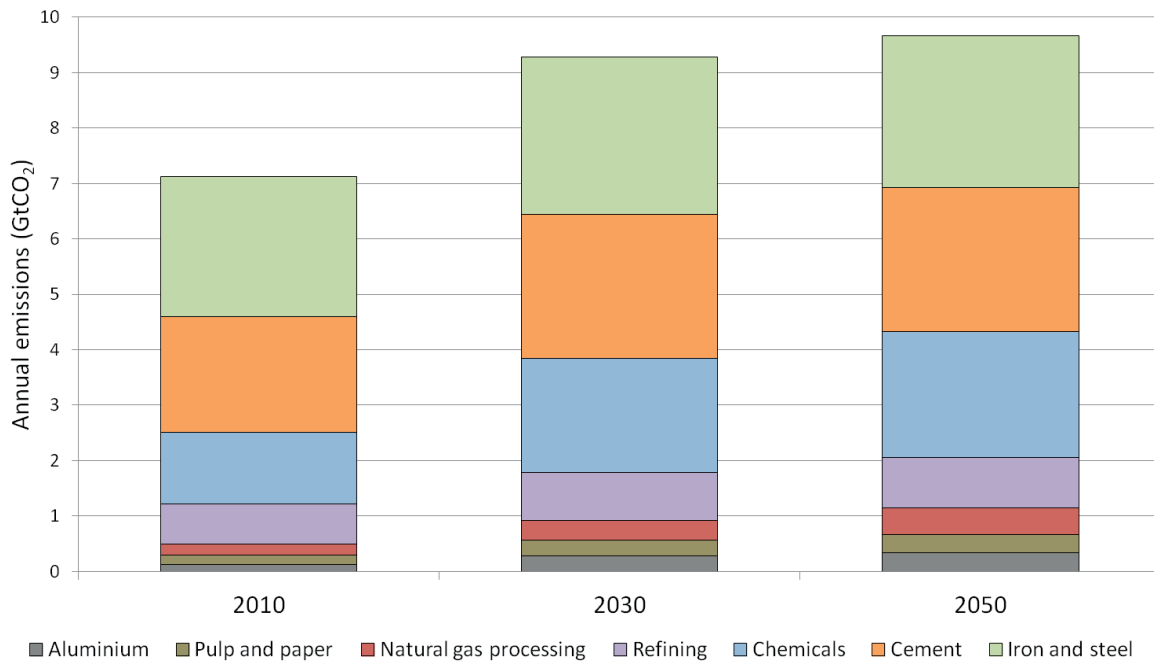
The CO₂ that is already commercially captured is, unsurprisingly, the lowest cost CO₂. For example, in gas processing, where CO₂ is an impurity in extracted natural gas, and hydrogen production (for refining and chemicals manufacture), where CO₂ is a by-product, CO₂ is inherently produced as part of normal operation and so little additional expense is required to purify and compress it for sale.⁹ It is of crucial importance to policy development that these differences in cost and technical maturity are recognised and understood.

⁷ This total does not take into account emissions from land use, land use change and forestry.

⁸ For example, around 60% of total CO₂ emissions from cement clinker production are released directly and unavoidably from the processing of limestone, not from the combustion of fossil fuels. The remaining emissions from burning fuel in the kiln arise from the need for very high temperatures. For a discussion of alternatives to CCS, see Box 4.1.

⁹ As an example, Jin et al. (2012) found that the early opportunities for low-cost CO₂ capture in China's Shaanxi province can be found only in the gas and oil industry, in ammonia industry, and in biomass conversion.

Figure 4.1 • Global emissions trends by industrial sector under current policies



Note : the IEA Energy Technology Perspectives current policies scenario, or 4DS (4°C Scenario), takes into account pledges made by countries by 2012 to limit emissions. The biofuels sector is not included here as its emissions are considered as net zero emissions in GHG accounting principles. Biofuels can in some cases provide low-cost opportunities for emissions reduction through CCS. The chemicals sector includes petrochemicals.

Source : IEA (2013b)

Costs vary between sectors and sites

One of the key determinants of using CCS is the cost of the technology. In sectors that are already undertaking large-scale CO₂ capture, costs are relatively well known. While technology improvements are foreseen, costs are expected to remain between USD 10 and USD 40 per tonne of CO₂ avoided for CO₂ capture at gas processing and hydrogen production facilities (IEA, 2013b). Costs of CO₂ capture in several sectors – such as cement and iron and steel – remain uncertain due to a lack of experience and are estimated to be higher.

A range of factors will drive costs at individual sites, including:

- **CO₂ concentration.** Whether the CO₂ is pure or mixed with impurities is an important driver of costs. Mature technologies, such as CO₂ capture from ethanol fermentation, deal with CO₂ sources that are highly pure and for which capture is relatively cheap (Ho, Bustamente and Wiley, 2013; IEA, 2013b).
- **CO₂ partial pressure.** CO₂ can be more easily and cheaply captured if it is at a higher pressure, even if the CO₂ source is less pure. Gas processing is an example of a process that has low CO₂ capture costs because the partial pressure of CO₂ is high (IPCC, 2005).
- **CO₂ volumes.** Larger CO₂ sources offer better economies of scale for CO₂ transport and storage. A modern large blast furnace site can produce in excess of 8 MtCO₂/yr, which is around 30% more than a 1 GW coal-fired power plant (IEA GHG, 2013).
- **Ease of industrial integration.** The ability to redirect excess heat from other processes to supply the heat for CO₂ capture could reduce costs significantly. However, as efficiency gains are sought by all sectors, competition exists for any such 'waste' heat at industrial sites (Johansson, 2013). In some production processes existing plants may need to be significantly

altered and prospective plants redesigned to accommodate the most effective CO₂ capture technologies (Berghout, van den Broek and Faaij, 2013). This could be the case for cement kilns and blast furnaces, which are established sectors for which major redesign is unfamiliar (IEA GHG, 2008, 2013).

- **Location.** Short distances to other CO₂ sources that can share infrastructure, heat and stimulate could stimulate the evolution of CCS clusters of CO₂ sources, sharing the provision of CO₂ transport and storage services. The country in which a project is situated will also have a bearing on cost.¹⁰

As many industrial sites comprise distributed CO₂ sources, different capture techniques would be needed to achieve high overall capture rates. Furthermore, compared with a single power plant, a 90% capture rate may not be realistic at each industrial site that applies CCS. Studies of steel production have found that a practical level of emissions avoidance via CCS for an integrated steelworks may be up to 60% for cost and energy penalty reasons (IEAGHG, 2013). Another example is a refinery site with multiple CO₂ sources, some of which have low capture costs, for example hydrogen production, but the cost of CO₂ capture from the remaining 80% of onsite emissions is likely to be much higher (van Straelen, 2010).

CCS in industrial applications: varying progress with projects

The often-stated lack of progress with CCS in industrial applications is somewhat paradoxical given that all large-scale CCS and CO₂ capture projects in operation today are in fact in industrial sectors. Altogether, 32 of the 65 large-scale integrated CO₂ capture projects that are listed by the Global CCS Institute as being either in planning or operation worldwide are on industrial processes (GCCSI, 2013).

Figure 4.2 shows the stepwise increase in the size of CO₂ capture plants for a range of sectors.¹¹ Plants that capture up to 1 MtCO₂/yr operate today in the gas processing, refining, chemicals and biofuels sectors. Sectors that have a clear head start in terms of technical maturity have developed the technologies to take advantage of commercial demand for cheap CO₂ and their relatively low specific costs of CO₂ capture. In contrast, the smaller sizes of installations in some other industrial sectors, including cement and steel in particular, shows that they are significantly lagging behind (see bottom of Figure 4.2).

¹⁰The IEA estimates that 72% of CO₂ captured from industrial facilities by 2050 could be in developing countries where costs could be lower (IEA, 2013a).

¹¹This section has focused on CO₂ capture technologies because they are specific to CCS in industrial applications, whereas CO₂ transport and storage technologies are common to all applications of CCS.

Figure 4.2 • Operational start year of the next largest CO₂ capture projects on various processes



Source : IEA analysis and GCCSI (2013)

Box 4.1 describes current vanguard projects and illustrates the differences between sectors with low CO₂ capture costs¹² and sectors with higher capture costs. Projects where capture costs are lower are larger, more integrated with storage (or sale of the CO₂) and less reliant on public funding.

¹² In terms of absolute capture costs, which are relevant if the CO₂ is being commercially sold, and relative costs as a proportion of other production costs, which are highly relevant if firms are investing in CCS to improve environmental performance.

Box 4.1 • A selection of current projects in industrial applications**1. Projects on processes with low cost CO₂ capture costs**

- **Quest** (refining, 1.08 MtCO₂/yr stored, Canada, Shell, operation 2015)

Despite being internationally traded, oil products have a diverse range of production costs. Around 75% of the CO₂ emissions from oil sands production could be captured. Canadian oil sands are economically viable at current oil prices and could be viable with CCS if competing against higher-cost unconventional fuels, if fuel standards are tightened in the United States, which buys 99% of Canada's oil exports, or if the existing Alberta penalty for not reducing emission intensity from oil production increases. The Quest project is funded by grants from the Albertan and federal Canadian governments accounting for approximately 55% and 10% of investment costs, respectively, and will receive a double-counting of its stored CO₂ under the provincial CO₂ emissions penalty scheme.

- **Gorgon** (gas processing, 3.6-4.1 MtCO₂/yr stored, Australia, Chevron, operation 2015)

40% of the CO₂ separated from the natural gas stream before production of liquefied natural gas (LNG) is to be stored in a deep saline formation. It was a condition of the permitting of the project that it would apply CCS. As a result, the project is almost entirely funded by the operator. LNG prices are high enough that the project can absorb CCS costs and profitably export LNG.

- **Illinois** (biofuels, 1 MtCO₂/yr stored, United States, Archer Daniels Midland, operation 2014)

The project has grants from the United States Department of Energy to cover two thirds of the project costs. The overall project objective is to develop and demonstrate an integrated system of CO₂ capture and geological storage from an ethanol plant. The plant's CO₂ emissions are not currently subject to regulation or carbon pricing but Illinois has a requirement for electric power utilities to source 5% of their electricity from coal plants using CCS from 2015.

- **Lula** (gas processing, 0.7 MtCO₂/yr for EOR, Brazil, Petrobras)

Gas from the deepwater Lula Oil Field contains between 8%-15% CO₂ that is separated on a floating production, storage and offloading vessel. The decision to capture the CO₂ relates to the value of re-injecting it into the oil field to enhance production. Vented emissions would not be financially penalised but additional oil sales cover the relatively low cost of CO₂ capture.

2. Projects on processes with high CO₂ capture costs

- **Brevik** (cement, 0.7 ktCO₂/yr vented, Norway, Norcem, operation 2014)

Three CO₂ capture technologies will be piloted through 2016 by different technology providers in a project that is 75% funded by the Norwegian government. Cement sector emissions are currently covered by the emissions trading system but the sector is shielded from the impact of its costs through free allocation of emissions allowances and energy price controls.

- **SkyMine** (cement, 83 ktCO₂/yr utilised, United States, Skyonic, operation in operation 2014)

Skyonic is not a cement producer but will capture CO₂ from a cement plant to provide raw material for sodium bicarbonate manufacture. To complement revenue from product sales, the project has a grant from the United States Department of Energy to cover 70% of costs.

- **Technology Centre Mongstad** (refining, 80 ktCO₂/yr vented, Norway, Gassnova, operation 2012)

The project aims to test two different CO₂ capture processes on flue gas from a refinery catalytic cracker. The primary owner is the Norwegian state though Gassnova (75.12%), while Statoil (20%), Shell (2.44%) and Sasol (2.44%) also have stakes. Unlike hydrocarbon extraction facilities, Norwegian refineries are not subject to the national CO₂ excise duty and, while they are covered by the emissions trading system, they receive free emissions allowances.

- **Florange** (iron and steel, 0.7 MtCO₂/yr stored, France, ArcelorMittal, cancelled).

The ULCOS demonstration project at Florange in France was postponed in 2012. Funding was available from the European Commission, the French government and the operator, but ultimately the steel market, costs and conditions of EU funding meant that perceived financial risks outweighed expected rewards. In April 2013 the Florange blast furnaces were mothballed.

Future availability of CCS depends on the pace of progress today

For large-scale deployment in the 2020s, it is particularly important that the different CCS technology options are tested at progressively larger scales (IEA and UNIDO, 2011). CO₂ capture technologies will move from pilot scale (less than 0.4 MtCO₂/yr) to demonstration scale (1 MtCO₂/yr and above) before deployment; each of these phases needs to operate for several years to generate the necessary knowledge and cost reductions (IEA, 2013a).

Just one or two pilot projects to date in each of the sectors with higher cost CO₂ sources is an insufficient level of experience, scale and diversity for investment in CO₂ capture at commercial scales. Sector-specific knowledge of the characteristics of the individual flue gas streams in different sectors is vital, in addition to any crossover learning between sectors. Uncertain costs are a hindrance to strategy and policy. Subsequent large-scale commercial deployment of the technology could take several decades, due to the long-lived nature of manufacturing infrastructure and slow turnover of stock. Many cement plants and integrated steelworks operating today were established many decades ago - some are 50 years old or more - and usually only undergo major refurbishments in line with the lifetimes of key pieces of equipment, often around twenty years.

Incorporating CCS into manufacturing processes faces numerous challenges to optimise heat use, oxygen provision and meet product specifications in sites and supply chains that are already highly integrated and specialised. Yet, if serious emissions cuts are to be made by the middle of this century, rapid technical progress is a pressing need. Uncertainty related to costs needs to be reduced through additional studies, pilot projects and, most importantly, demonstration projects.

Box 4.2 • Actions and milestones for CCS in industrial applications

In the IEA 2DS, industrial applications of CCS are equally important to the application of CCS in power generation at the global level (IEA, 2012a). In some regions, such as the OECD Pacific, and in some non-OECD member countries (e.g. India), industrial applications of CCS are more important than applications in power generation. The sectors in which CCS is deployed in the 2DS scenario vary between regions in accordance with anticipated industrial activity and mitigation costs (Figure 4.3).

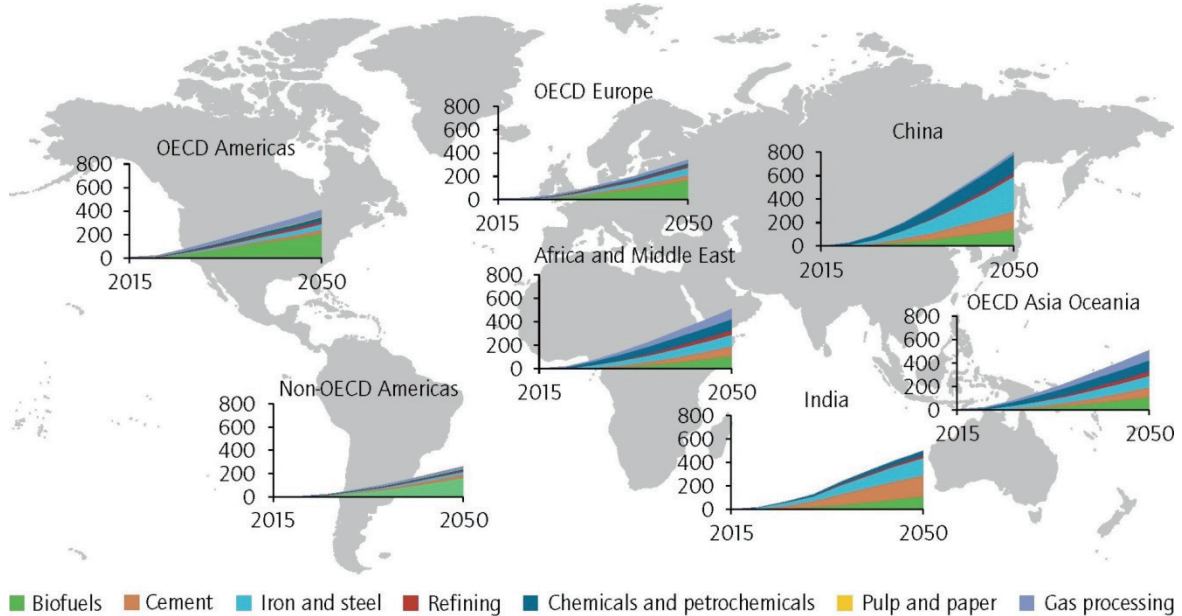
Three near-term actions relevant to delivering the 2DS are listed in the IEA CCS Roadmap (IEA, 2013):

- Demonstrate the capture and storage of CO₂ in at least 30 projects involving sectors including electricity generation; gas processing; iron and steel (DRI); refining (hydrogen production and coal-to-liquids); chemicals (ammonia, methanol and coal-to-chemicals production); biofuels (ethanol).
- Prove capture systems at pilot scale (100 ktCO₂/yr or fewer) in industrial applications where CO₂ capture has not yet been demonstrated, and link these projects to geological storage to test specific geologies and technologies where possible (cement; iron and steel (blast furnace and smelting); refining (FCC and process heater flue gases); pulp and paper; biofuels (biomass-to-liquids); chemicals (steam crackers and process heater flue gases))
- Support R&D into novel CO₂ capture technologies that will dramatically lower the cost of capture, as well as cost-effective capture techniques that can enable the aggregation of CO₂ sources at refinery and petrochemical complexes; explore operational considerations, such as whether industrial output can be varied in line with variations in other cost factors (e.g. time-of-day electricity pricing or demand fluctuations) while still providing a stream of CO₂ that is fit for the purposes of the CO₂ storage.

Meeting the technological objectives requires continued engagement and investment from public and private actors (Box 4.2). Large pilot and demonstration projects each cost upwards of

USD 100 million. It appears unlikely that, in the current policy context, firms will fully fund such projects. To be consistent with a timeframe for deployment that can have a significant impact on limiting climate change, policy will be required to establish expectations that CCS is necessary, inevitable and will lead to innovative cost-effective changes to production processes.

Figure 4.3 • CO₂ captured from industrial applications in the 2DS, by source region for seven key regions



■ Biofuels ■ Cement ■ Iron and steel ■ Refining ■ Chemicals and petrochemicals ■ Pulp and paper ■ Gas processing

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

Source: IEA (2013a)

Selected challenges for CCS in industry, including trade exposure

CCS, like other low carbon technologies that are pre-commercial, faces market failures (IEA, 2012b). Five market failures have been found to be particularly relevant for the development and deployment of CCS (Table 4.1). These can justify policy intervention. CCS in industrial applications faces additional challenges due to international competition. This section considers how trade exposure exacerbates these market failures.

Negative externality: the difficulty of internalising CO₂ costs

Adding the costs of CCS on to the production costs of traded commodities is equivalent to internalisation of the costs of CO₂. Under a carbon pricing system, firms are faced with a choice between paying to emit CO₂ and employing techniques to avoid CO₂ emissions. If the emissions constraint is sufficient – as it is expected to be in the 2020s in order to meet the goal of limiting global temperature rise to 2°C – the carbon price will be higher than the cost of operating CCS. Current carbon prices, where they exist, are well below CCS costs. The level of ambition embedded in near-term emissions constraints can be met without the use of CCS.

Climate policies today, including carbon pricing systems, are regional, yet trade is often global. If trade across borders is open, cost increases could undermine competitiveness¹³ of these sectors

¹³ Note that competitiveness is a complex notion, and depends on a firm’s product quality as well as cost of inputs and market prices (IEA, 2004). Loss of competitiveness is defined here as the loss in output – including reduction in demand and/or the potential displacement of production from one country to another.

in regions that pursue independent policies to internalise the social and environmental costs of CO₂ emissions. In comparison with the electricity sector, which is more nationally or regionally organised and where costs of more expensive technology can more easily be passed on to customers, regional climate policy in trade exposed sectors can have a more distorting effect.

Table 4.1 • Market failures leading to the undersupply of CCS technology and deployment

Market failure	Policy objective
Negative externality	Markets do not take into account the economic, social and environmental costs of CO ₂ emissions.
Public good	Knowledge about comparative efficacies and costs of different technologies can be considered to be a public good.
Capital market failures	Information asymmetry and imperfect information can result in under-provision of capital. For example, information about CO ₂ capture costs and performance for early projects may be unequally distributed between different parts of the value chain. Capital providers may be unwilling to provide finance if they are unable to assess risk dependably.
Imperfect competition	Undesirable market power leading to high prices can be exerted by firms that hold monopolistic or oligopolistic positions. This is a particular issue for technologies that rely on networks to operate most efficiently.
Complementary markets	If different parts of the vertical value chain are under different ownership, investments in CO ₂ capture, transport or storage depend upon unpredictable and sub-optimal decisions made by the other two elements.

Source: (IEA, 2012b; Krahé et al., 2013)

Facilities whose output competes for market share with production from other countries may only be able to pass on some, or even none, of the increases in production costs associated with CO₂ abatement. This can undermine the economic rationale for CCS, which can involve a significant increase in production costs.¹⁴ In globally competitive sectors, firms that compete primarily with firms that are covered by the same climate policy regime are incentivised to minimise CO₂ costs, but if their main competitors are outside the regime, then their competitors will face no equivalent increases in costs’.

Uneven regulation can therefore induce a “macro-level adjustment” between countries, in addition to, or instead of, the desired “micro-level adjustment” within industries. The consequence can initially be a reduction in capacity utilisation in regulated regions and an increase in non-regulated regions. It can also encourage location of new capital investments in non-regulated regions. The competitiveness of the sector within that country can fall and “carbon leakage”¹⁵ can result; both outcomes are generally considered to be undesirable.

Carbon leakage is only a subset of outcomes resulting from relocation of production due to diminished competitiveness. Carbon leakage refers only to the relocation of production to facilities with higher carbon intensity as a result of climate policy. It is relevant to climate policy but interacts with industrial policies. Some policymakers aim to maintain competitiveness of a national industry that faces higher labour, energy, materials and CO₂ costs, regardless of global emissions levels. Therefore, the appropriate mix of CCS incentive policies for long-term emissions

¹⁴Regional CO₂ pricing systems may only incentivise incremental efficiency improvements and not provide sufficient incentives for investment in CCS – a big impact, capital-intense, long-term technology. For example, in the EU ETS a 30% increase of production costs is considered to be the maximum that a firm could tolerate without severely threatening international competitiveness (EC, 2009a). This means that under an incrementally rising regional carbon price, firms could become uncompetitive before the carbon price reached the level at which CCS would become viable.

¹⁵Carbon leakage is said to occur if CO₂-intense production that is otherwise competitive is displaced by production in a non-regulated region that has higher specific CO₂ emissions, leading to higher global emissions for the same global output. For example if production based on coal displaces CO₂-regulated production based on natural gas solely as a consequence of CO₂ regulation, this would be considered carbon leakage. EU and Australian policy makers sought to avoid carbon leakage in emissions trading system design, for example through compensation in the form of free allocation of emissions allowances.

reduction will depend on interactions between industrial and climate policy objectives in different countries.

Looking at the impact of CCS on a sector's competitiveness, two factors are critical, and they vary between sectors:

- Exposure of a sector in a given country to international trade and
- The relative impact that CCS would have on production cost.

If a sector was an "ideal" candidate for the uptake of CCS, it would have both a low exposure to global competition and a low impact on the cost of the final product. Figure 4.4 below shows that among four sectors that will need to apply CCS, none have the ideal combination of low trade exposure and low relative cost increases. This is intuitive, because products traded over large distances are more likely to be of higher value and margin, for which the additional production costs (like the costs of shipping) represent a smaller impact.

While cement is currently a predominantly locally-traded product, a possible production cost increase of 100% in some regions is likely to make the additional transport costs for overseas firms to enter that market very attractive.

The oil and gas sector contains some partial exceptions as production costs can vary widely between firms and the costs of CCS can sometimes be absorbed within profit margin. The Australian Gorgon project, for example, is in a market in which the marginal cost of gas supply is significantly above the production cost of many fields.

In the sections that follow, the term trade exposure is used to refer to both the level of international trade for a given sector and country, and also the impact on competitiveness associated with production cost increases due to CO₂ emissions abatement.

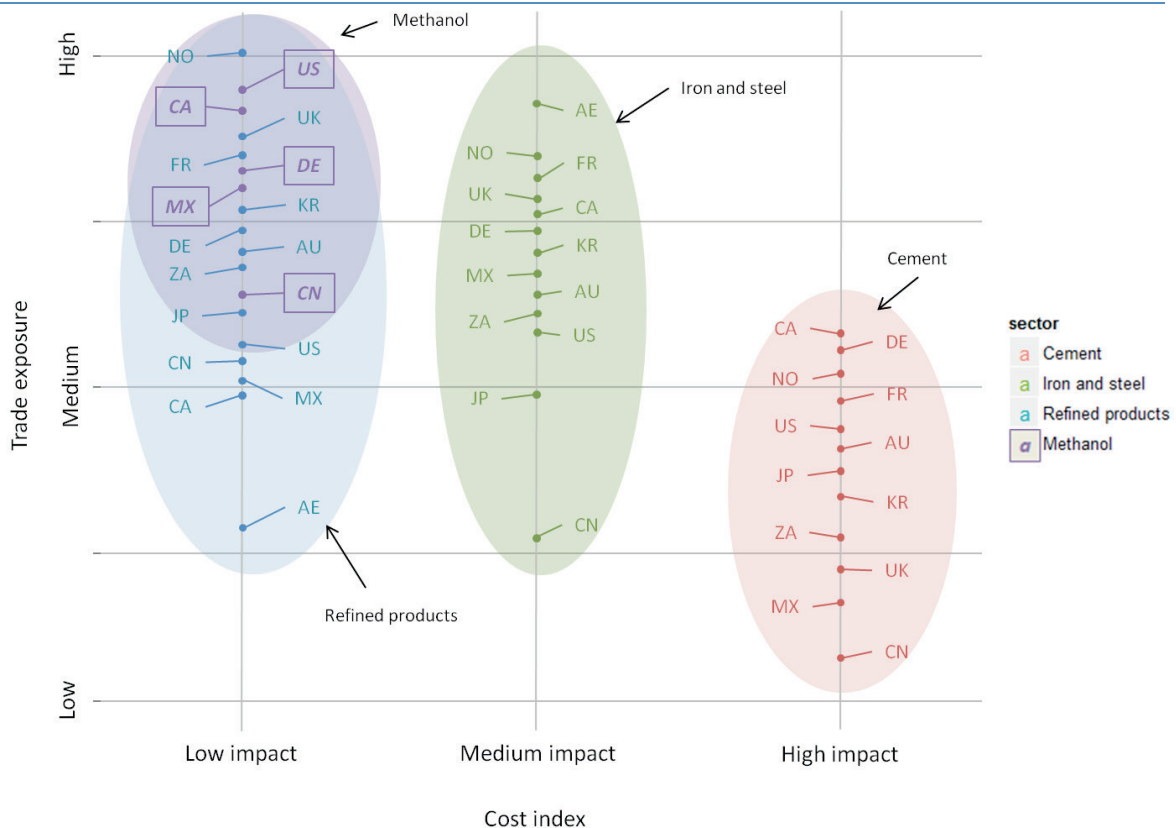
Knowledge as public good: lack of first-mover advantage

Another challenge (market failure) facing CCS is the lack of a clear first-mover advantage. This reduces the incentive to take risks in the development of a new technology. Developing CCS at pilot or demonstration scale can be a costly undertaking. If the technology is unlikely to be deployed within a timeframe in which the knowledge can be competitively appropriated, the costs are likely to outweigh the knowledge generated. The ability of a single firm to reap the rewards of technology investment are further reduced if technology projects are costly and individual firms are less able to contribute to an overall solution, increasing the risks of so-called free riders.

This problem is particularly important for CCS in industrial applications. In sectors in which the timing and costs of CCS deployment are more uncertain, the difficulties of fully privatising the resulting knowledge over a multi-year period are greater. In addition, in trade-exposed sectors the threats to competitiveness can be greater if competitor firms, which are not covered by equivalent climate policies, do not make equally large investments in technology development. The notion that regulation might stimulate innovation and thus benefit competitive firms¹⁶ is compromised by issues of regional-only regulation and uncertain timing of enforcement.

¹⁶ See Porter and van der Linde (1995) and Ambec et al. (2013).

Figure 4.4 • Sector plotted as a function of their exposure to international trade in a selection of countries and the relative impact that CCS would have on production cost



Note: Trade exposure is measured as a composite of two inputs: published analyses by competition authorities and the trade intensity metric used for the European Commission's emission trading system $[(\text{imports} + \text{exports})/(\text{imports} + \text{production})]$. Cost index represents likely relative increase in production costs. AE = UAE; AU = Australia; CA = Canada; CN = China; DE = Germany; FR = France; GB = UK; JP = Japan; KR = Republic of Korea; MX = Mexico; NO = Norway; US = United States; ZA = South Africa.

Source: (IEA, 2013b).

First movers can also face a regulatory dilemma. While the development of technological solutions can be an insurance investment against future regulation and can have reputational benefits for a firm, the commercial-scale demonstration of the technology can increase the likelihood that its use will be compelled by regulatory measures. This dilemma can constrain the extent to which firms are willing to invest in the early stages of technology demonstration.

A challenging climate for addressing market failures

In practice, the long-term challenge of internalising CO₂ costs through CCS has been compounded by economic and political realities that have hindered investment in CCS technology projects in the near-term. These compounding factors include the recent and ongoing economic and financial crisis and the changing patterns of capital stock.

The *economic and financial crisis* explains some of the lack of progress with CCS in some sectors. Investment in new technologies suffers if investment in capacity in general is stifled by falling demand. In order to develop new technology such as CCS, prospective operators need confidence that their industrial base will be maintained over the coming decades. While expansion of energy-intensive sectors continued in some regions, the regions from which leadership on low carbon technologies was expected have suffered most from the financial crisis. Another manifestation of the crisis has been the reduction of available public funds for CCS development.

Changing patterns of capital stock have resulted from demand and competitiveness factors related to the crisis but also from other factors, such as the costs of energy, land and labour and the availability of skills. Since 2008, industrial capacity additions have often been greatest where the costs of all factors of production are lower and where the rates of demand growth are higher. This includes, for example, China and South East Asia. Despite a growth in R&D activity in these regions, the geographical disconnect between regions where CCS R&D is primarily undertaken and where capital stock is added has grown.

Another result of the crisis and the changing patterns of capital stock is the current overcapacity in some sectors.¹⁷ For example, in the European steel sector, low margins mean that profits can in some cases be absorbed by maintenance of existing assets, leaving little available capital for long-term technology development, especially in a region where consolidation is more likely than capacity additions.¹⁸ Box 4.3 has more information on the European steel and cement sectors, which have asserted that internalising the full costs of CO₂ would undermine Europe's competitiveness. Both sectors have, however, put in place some coordinated actions to assess and develop CCS technology.

Stepwise policy for CCS in industrial applications

Deploying CCS for climate change mitigation purposes requires policy action. Effective support for CCS calls for a combination of policy tools within a coherent policy architecture, where each policy addresses a separate challenge or market failure. To combine flexibility and certainty, a potential solution is to set policy within a stable framework, so that the broad architecture and rules of policy evolution are certain. This can be done for example by adopting a "gateway" approach (IEA, 2012b). This approach creates a stable policy framework with clearly defined break points or gateways that denote changes in policy. Such frameworks would include a combination of policies, and would create certainty for individual CCS projects. Such policy stability is necessary for investors in long-lived assets.

A gateway approach explicitly recognises the need for different policies in different phases:

- **Phase 1.** The key aim of CCS policy is to generate and the public good of knowledge of different CCS technologies. This phase would help identify successful technologies, identify potential cost reductions and minimise information asymmetries. Early projects may not immediately be commercially useful to those undertaking the investment but would be vital to secure the option of future timely CCS deployment, which would provide returns to the public and private sectors alike.
- **Phase 2.** As learning progresses, but while sectoral CCS costs remain considerably higher than economy-wide marginal abatement costs, the key aim will be to facilitate investment in CCS projects while reducing public spending and risk exposure. In the absence of proven cross-sectoral climate policies, the key aim is to address capital market failures and unlock private investment in CCS projects for continued learning-by-doing.
- **Phase 3.** In the longer-term, the most efficient option is likely to involve addressing the market failure of externalised CO₂ costs through cross-sectoral, technology neutral penalties,

¹⁷ Between 2006 and 2012, China added 440 million tonnes of steel capacity, more than double the total European capacity (DCE, 2013). However, today it has 200 million tonnes of unused capacity and its steel mills operate today below the worldwide average capacity utilisation (EC, 2013b).

¹⁸ Although, in theory, multinational firms under carbon pricing schemes such as the EU Emissions Trading System (ETS) could receive windfall profits from the combination of free allowances and output reductions (de Bruyn et al., 2010), these revenues are as likely to be reallocated to regions where returns on investment are greater as they are to be invested in low-carbon technology.

such as carbon pricing. Public subsidies would be reduced and costs borne by the private sector.

Box 4.3 • European roadmaps for low carbon production in the steel and cement sectors

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A Steel Roadmap for a Low Carbon Europe 2050 (Eurofer, 2013). At present, 60% of EU steel production is by the blast furnace route. The electric arc furnace route is four times less CO₂ intense, but it is limited to a maximum EU market penetration of 47% by the availability of scrap steel. While the EU steel sector's emissions fell by 25%, its emissions intensity fell less than 5% between 1990 and 2010.

The roadmap concludes that no known technologies could reduce the emissions intensity of primary steel production by more than 30% without CCS. Among the technologies that can reasonably be expected to be available before 2040, the upper limit of emission intensity reduction without CCS is considered to be closer to 20%. More ambitious CO₂ cuts – of 60% or more – would require a change of technology in primary steelmaking and CCS. According to the roadmap, carbon pricing cannot bring about the emergence of these technologies and public funding will be needed.

Since 2004 the Ultra-Low CO₂ Steel (ULCOS) consortium has evaluated steelmaking technologies that could technically reduce CO₂ intensity by more than 50%. Two technologies (blast furnace with top gas recycling and CCS and bath smelting reduction with CCS) have reached pilot plant phase.

The Role of Cement in the 2050 Low Carbon Economy (Cembureau, 2013). The CO₂ intensity of EU cement production has reduced by around 8% since 1990, while aggregate emissions have reduced by 22%. According to the roadmap, there is a future for new or novel cement types, but given the early stage of their development, it will take quite some time before large-scale production becomes a reality. Clinker substitution and novel cements are calculated to have the potential to reduce emissions by only 8%.

The roadmap concludes that CO₂ capture is currently one of the most promising technology options to reduce CO₂ emissions and certainly the single solution with the biggest impact potential. To reach the 80% reduction suggested by the European Commission, 59% of cement plants would need to be equipped with, CCS. This suggests that only a 26% reduction in emissions intensity could be achieved without CCS.

The European Cement Research Academy (ECRA) is a consortium of over 40 cement producers (and three of the four main global equipment suppliers) established in 2003. CCS is one of the main research streams of ECRA, which has considered CO₂ capture designs and economics, including operation of a lab-scale test. The next phase will involve the design of a pilot project.

Phase 1: Technology demonstration to secure the option of CCS

The policy goal at this point is not to make emissions reductions *per se*, but rather to advance CCS technology, understand potential cost reductions through learning-by-doing and establish commercial arrangements between the different stages of the value chain. Success is measured in terms of knowledge and cumulative experience provided, rather than in terms of emission abatement achieved.

Projects at this stage of development are not profitable in the short term. They will generally not receive revenue as a direct consequence of using CCS (unless combined with CO₂ sales for EOR or other CO₂ utilisation) but will provide a public good. Private sources of financing are likely to be unavailable or expensive. Recalling the market failures explored in previous sections, individual firms are not likely to invest the full costs of such projects, which may need to be shared between the parties that will benefit.

Suitable public support instruments for CCS technology development include direct financing, such as grants, co-investment equity, debt, credit guarantees and insurance products. If direct

capital funding needs to be secured to mitigate the risk of insufficient investment in a public good, there are different instruments to achieve this. These instruments can share the costs and risks with the private sector in different ways (IEA, 2012b; ERM, 2009, Krahé et al., 2013).

Trade exposure and uncertainty regarding the timing of CCS deployment further reduces incentives for firms to develop CCS technologies. This means that, unless the public sector absorbs all costs, there is a need for collaboration to combine available sources of funding for CCS projects. This approach is supported by the fact that the benefits of successfully commercialising CCS will accrue to a variety of public and private bodies.

Industrial producers will directly benefit from the development of technology in the long-run if CCS enables them to meet their emissions obligations at lower cost than either paying to pollute or using alternative non-polluting technologies. They will not be the only beneficiaries, however. Other direct and indirect beneficiaries could include:

- Governments of countries with high value-added from primary/process industries and governments of countries with exportable raw materials (coal, oil, gas, iron ore etc.)
- Fossil fuel producers and users in general
- Purchasers of 'green' CO₂

Governments. Energy-intensive industries and raw material exports are potentially highly valuable to many countries future prosperity for geographical, structural and balance-of-trade reasons. Box 4.4 discusses the countries for which CCS development could be of particular importance. Governments who consider the availability of CCS, and thus the opportunity to tackle climate change at minimum cost, as a public good, can intervene to share the costs and also share the resulting knowledge. Funding need not be strictly technology neutral in this phase; governments must balance economic efficiency, the global option value of CCS for emission mitigation and the benefits of supporting sectors and technologies in which they see a potential comparative advantage.

Fossil fuel producers and in general. If the world has a limited amount of CO₂ that it can emit from fossil fuel use over the coming decades in order to stabilise the global climate¹⁹ then the only way it can use more fossil fuels than prescribed by this "carbon budget" is through the use of CCS. Ensuring that CCS becomes cost-effective may therefore be in the interest of countries and firms wishing to sell or use fossil fuels in completely unrelated sectors in future. CCS in industrial applications could create headroom for other emissions that are less attractive to avoid. The provision of liquid transport fuels to the airline or passenger vehicles sectors, where CO₂ abatement may be very expensive, is an example. The refining sector therefore indicates a potential intersection of incentives.

Purchasers of 'green' CO₂. The final category of beneficiary includes those that could make use of the captured CO₂ and may be willing to pay for it and thus help finance the technology project. Chapter 5 covers CO₂ utilisation in more detail and concludes that, for pilot and demonstration projects, valuable revenue can be raised for the purpose of knowledge generation if the price, risk and location elements can be aligned, regardless of the net CO₂ balance of the specific CO₂ use. To stimulate markets for CO₂ use, policy can create incentives for chemical or fuel producers to incorporate their CO₂ as a raw material. For example, the European Commission has proposed that renewable liquid and gaseous fuels of non-biological origin shall be considered to be four times the energy content of other biofuels (EC, 2012). Under this proposal, CO₂ considered as

¹⁹ In order to have a 50% probability of keeping global warming to no more than 2 °C, total CO₂ emissions from fossil fuels and land-use change in the first half of the century need to be kept below 1 440 Gt, which can be considered to be the planet's "carbon budget" (IEA, 2013c).

waste would be eligible for conversion to 'biofuel'.²⁰

Box 4.4 • Which countries might benefit most from CCS in industrial applications?

A Herfindahl index[‡] can be used to measure the extent to which fossil fuel and mineral reserves are concentrated or dispersed. According to this metric, coal is the most concentrated resource globally that is relevant to CCS in industrial applications, followed by iron, gas and oil.

Among countries that are categorised as Annex I under the UNFCCC process, 55% of global coal reserves are split relatively evenly between the United States, Russia and Australia. Among Annex I countries, iron ore is concentrated in Australia, which holds 20% of global reserves. Gas reserves are heavily concentrated in Russia, but the United States and Australia both have significant interests. In terms of oil reserves, Canada holds 56% of reserves among Annex I countries.

The key insight here is that knowledge is transferrable between countries. The initial technology learning associated with pilot projects might be supported by countries with a stake in the success of CCS, e.g. those for whom CCS would insure against loss of competitiveness for the use of a domestic resource in a carbon-constrained world. Demonstration plants and early deployment of CCS in these sectors would be more suited to countries for which either trade exposure or relative cost increases are lowest. Wide-scale deployment would be expected to occur consecutively in countries where the marginal costs of production would be reduced most by the use of CCS.

To illustrate the point made in the previous paragraph, Australia has significant iron ore reserves and therefore could have a strong interest in contributing financially to the development of CCS in the iron and steel sector. However, Australia exports a large amount of iron and coke to China, where new capacity investment in the steel sector is more active and where project costs tend to be lower. Thus, it does not follow that demonstration and early deployment should necessarily occur in Australia if cost-effectiveness is pursued. There are many other similar examples, which relate to both the global share of a resource represented by one country or firm, but also the share of the country's income related to the use of that resource. Proximity to easily accessible CO₂ storage sites would also play a role in determining the location of demonstration projects (Geogreen, 2011).

This rationale does not equally apply to sectors whose raw materials are evenly distributed, however. Limestone, for the cement sector, has national reserves that are adequate for all countries surveyed by the United States Geological Survey (USGS, 2013). This presents a collective action problem, since countries may wish to obtain the knowledge without providing financial support.

[‡]The Herfindahl Index is typically used as a measure of concentration of firms within a market as a proxy for the extent of competition within that market. (Rhoades, 1993) It has been modified here to consider the concentration of resources between different countries: a value of 1 implies that all of the resources are concentrated in one country, with lower values implying progressively more dispersion in resources. At a global level, the values found in this analysis are 0.16 for coal, 0.15 for iron, 0.11 for gas and 0.10 for oil. When only Annex I countries are included, natural gas is the most concentrated with a value of 0.51.

Each of these potential beneficiaries has an interest in securing the option of future timely CCS deployment in trade-exposed sectors. The challenge for policy is to capitalise on the willingness of these to provide funds in accordance with their priorities, risk and ability to commit.

If competitions for available public funds are used to support CCS projects in industrial applications, they should be designed to support technologies at their appropriate stages of development. Competitions can be effective in maximising value for money for the knowledge they will generate but need to take into account the different levels of costs in different sectors. Sectors with very different CCS costs should not compete against one another for public funds on

²⁰Under the German Energy Act, however, only fuels made from CO₂ that is mainly from renewable sources could be eligible for subsidies (EnWG, 2005). Consequently, in Germany subsidies for power-to-gas ("storage gas") manufactured from renewable electricity, water and biogenic CO₂ could play a role in developing some capacity for bioenergy with CO₂ capture.

the basis of a single uniform metric (European CCS Demonstration Project Network, 2013).

Collaboration might be encouraged through sectoral approaches to technology development. These could seek to leverage available funding in the public and private sectors for the development of joint projects that can benefit all willing actors in a given sector. Sectoral approaches have been proposed for advancing climate policy and the experiences from these efforts could inform technology-oriented initiatives (Box 4.5). Collaboration can reduce the costs to each actor of insuring against future high CO₂ prices or strict climate regulation, despite reducing the ability of each firm to gain an advantage from the resulting knowledge.

Formalised funding schemes could be considered to involve particular sectors in investments that could secure the option of CCS deployment for all firms in the sector. The Australian Coal Association voluntary contribution scheme is an example of a low level of burden spread across a large industrial output (WCA, 2011).

Maximising the benefits of this first phase involves the dissemination of information generated from projects with participants but also as a public good. This has been accounted for in many public funding agreements for CCS demonstration projects (GCCSI, 2011). For industrial applications there can be challenges relating to differences between firms that will supply technology in various parts of the value chain and firms that will need to avoid their emissions via CCS. For many industrial producers, CCS equipment and knowledge is not expected to become a core competence and will benefit from disseminated knowledge. Technology suppliers, however, could potentially raise prices in response to contractual knowledge sharing requirements that might weaken their competitive advantage. Sector specific issues will present themselves, but it will nevertheless be important to share the public good with policymakers and other stakeholders, including the finance community, as widely as is practicable.

Phase 2: Ensuring investment for early deployment

As the requisite learning from early-stage pilot and demonstration projects is achieved, a second phase is entered in which policy instruments move to those that enable a wider supported roll-out of the technology in commercial markets. The initial priority of the second phase is the lack of capital available to projects that can further move the technology along the learning curve (ERM, 2009). Cleaner production is rewarded and the competitiveness risks associated with the CO₂ cost externality are reduced.²¹ This early deployment phase is a transitional period that begins to develop the commercial structures for wide deployment with internalised CO₂ costs.

As discussed above, industrial applications of CCS are more varied than power sector applications. They also potentially face higher investment and operational risks due to their trade exposure because they often compete with firms located in regions with less strict regulation of CO₂ emissions. A desirable policy package for trade-exposed sectors will address different sectors and address the risks of reduced competitiveness, while transferring risk and responsibility to the private sector as the phase proceeds. Five principles of such a policy package would include:

- **Cross-sectoral.** These measures will incentivise the lower cost opportunities²² and reduce administrative complexity

²¹ In the electricity sector, targeted support for investments in renewable energy sources have been based on this rationale (OECD, 2013).

²² The lowest cost sources of CO₂, by capture cost, would be deployed first, followed by sectors in which CO₂ capture technologies are less mature or more expensive. For example, commercial CCS for hydrogen production for ammonia synthesis would precede CCS for steel production.

Box 4.5 • Towards sectoral approaches

Maximising the public good associated with spending on CCS will recognise that knowledge developed for one sector will have valuable consequences for others, including power generation, and more broadly, for all producers and users of fossil fuels. Firms in different sectors are typically not in competition with one another and have an incentive to identify non-competitive technology areas. Cross-sectoral collaboration to test various flue gas capture options on different flue gases could be of interest in this respect and pilot-scale CCS projects on industrial installations are most beneficial if done through open-access capture pilots (similar to the pilot facility at Mongstad in Norway). Distributed peer review, knowledge-sharing between and within sectors and process transparency should be supported as part of any publicly funded initiatives.

Sectoral collaboration could have the potential to unlock action across borders. In the absence of a global climate mitigation framework that minimises transnational competitiveness concerns, sectoral approaches have been suggested as a way to make progress in trade-exposed sectors (Baron, Barnsley and Ellis, 2008). Sectoral cooperation could also hold the potential to increase participation in international efforts to control emissions and help the international community target areas where technological breakthroughs are needed, capital investment is long-lived and where incentives to constrain emissions are inadequate (Bradley et al., 2007).

While sectoral approaches within the have not yet entered the UNFCCC policy mainstream, one of the proposed types of sectoral approach – technology-oriented approaches – appear highly relevant to CCS (Baron et al., 2007). Sectors could agree to targets and timetables for the development of CO₂ capture technologies and pool or coordinate effort to achieve them, especially in areas that are considered further from core competitive competences. In the case of CCS, much of the value chain is outside the current operational competence of the steel and cement sectors. This is of particular importance in these sectors, for which the core production equipment is supplied by a small number of engineering firms rather than being the intellectual property of the operators themselves. Consortium partners could undertake engineering and cost studies of CO₂ capture options and process integration, and jointly lead promising technologies through sequential stages from pilot to demonstration scale.

Consequently, there may be greater merit in cooperating with firms that are active in other parts of the world to ensure that CCS technology becomes available and fit-for-purpose for the sector as a whole, rather than risk that it either does not become available at all, or that free riders disproportionately obtain the benefits of R&D investments by first-movers. If established within governmental frameworks, pledges under technology oriented sectoral approaches might be credited in terms of GHG reductions or linked to global benchmarking and diffusion of best practice (Baron et al., 2007). In this case, knowledge should be published as widely as possible and IPR regimes should be structured to be favourable to cooperation. ULCOS and ECRA are just two examples of industry-led initiatives on which technology-oriented sectoral approaches could build (IEA, 2007).

- **Continuous incentive to abate.** These measures provide an incentive to abate an additional tonne of CO₂ at the margin, unlike performance standards, which can set a threshold to abatement levels
- **Shares investment risks with private sector.** These measures address capital market failures and are similar to those in the first phase, but reduce the risk burden on the public sector as development progresses
- **Reduces operational risks.** Risks of stranded CCS assets should be minimised to deliver continued learning and value-for-money. Incentives that are contingent on operating the CCS facility include those that target quantities of CO₂ captured and stored (e.g. portfolio standards) and those that are linked to prices (e.g. production subsidies and CO₂ pricing).

Compared to quantity incentives, price-based subsidies are more exposed to changes in production costs that could still lead to underutilised CCS assets, such as fuel prices.²³

- **Long-term potential for market support.** Measures that do not significantly interfere with other policy measures in ways that reduce motivation to innovate, lower economy-wide CO₂ prices or insulate sectors from competition can assist the transition to more long-term market-based support transition

The compatibility of these principles with a number of selected policy measures is presented in Table 4.2. More discussion of individual measures can be found in IEA (2012b) and Krahé et al. (2013). The message that emerges is that technology neutral CO₂ pricing systems may be most effective in the third phase, but that combinations of the other instruments will be necessary to guide trade-exposed sectors through the second phase.

Table 4.2 • Potential incentive mechanisms that could be considered for early deployment of CCS in industrial applications

Incentive mechanism	Cross-sectoral	Continuous incentive to abate	Shares investment risks with private sector	Reduces operational risks	Long-term potential for market support
Investment tax credit	Yes	Potentially	Yes	No	No
Public co-investment in projects	Yes	Potentially	Yes	No	No
Production/emissions subsidy	No	Yes	No	Potentially	No
Emissions performance standard	No	No	No	Yes	Yes
Portfolio standard	No	Up to a set limit	No	Yes	Yes
Feebate penalty and reward system	No	Yes	No	No	Yes
CO ₂ purchase commitment	Yes	Up to a set limit	No	Potentially	No
Production tax credit	Yes	Yes	No	Yes	No
CO ₂ tax/cap and trade	Yes	Yes	No	Partly	Yes
Baseline and credit reward system	No	Yes	No	Partly	Yes

Note: Long-term potential for market regulation is a judgement of whether the instrument could ultimately regulate CO₂ emissions in a technology neutral manner without imposing continuing costs or expert project assessments on government. "Potentially" is used to denote that governments have an option to adjust the measure to improve its performance with respect to a given feature. For example, CO₂ purchase commitments could be implemented via upfront bilateral contracts that guarantee revenue for operation and investment tax credits could be linked to the use of the facility.

The summary presented in Table 4.2 is not intended to be comprehensive or quantitative, but is included to guide thinking about alternative instruments for early deployment. While various instruments could have particular merits in certain regions or contexts, CO₂ purchase commitments seem particularly interesting, due to their potential to address a number of features during this phase.

²³ Price-based instruments can be contractually linked to production costs, but this adds significant regulatory complexity. Compared to the electricity sector, it is more difficult to guarantee priority sales of low-carbon products in globally competitive sectors. Exceptions could include refining, biofuels and natural gas production. Note that designing the basis for both production subsidies and portfolio standards is inherently complex in sectors that have product differentiation (e.g. different steel qualities) or multiple product streams from single plants (e.g. refining).

The concept of CO₂ purchase commitments is as follows:

- A government would announce its intention to purchase a quantity of stored CO₂ each year
- Firms whose CO₂ was stored rather than emitted would be issued with certificates verifying the amount of CO₂ stored in accordance with the regulatory regime that provides confidence that the CO₂ is geologically retained
- Firms would then compete to sell these certificates to the government agency, who would purchase at the lowest available price in a reverse auction²⁴
- A market for the certificates could be allowed to develop if parties had different expectations about certificate price evolution and wished to hedge their risks.

Box 4.6 presents further discussion on some of the advantages and disadvantages of CO₂ purchase commitments.

Desirable instruments during the early deployment phase will be those that minimise public costs while stimulating project investment. Tools such as CO₂ purchase commitments are a response to an acceptance that CO₂ costs cannot be fully internalised by the private sector, primarily due to trade exposure concerns. However, some sectors are less trade-exposed and some cost-sharing between firms and government may be preferable.

In the cement sector, for example, portfolio standards could be applied as the products are relatively homogenous. The portfolio standard could, in fact, complement a CO₂ purchase commitment by setting a proportion of production that would need to be covered by CCS use, a declining percentage of which would be purchased by the government each year through reverse auctions.²⁵

Other possible mechanisms to address less trade-exposed sectors include emissions performance standards and feebates. An approach to emissions performance standards is to apply them on a lifecycle basis, as is the case with the European Fuel Quality Directive (EC, 2009b). Emissions performance standards in the natural gas production sector could be set at a level that obliges producers of acid gas (with high CO₂ content) to store the separated CO₂ in order to be able to access the natural gas market. Experience in Norway and Australia suggests that such an approach, even at a national level, could avoid the venting of pure CO₂.

A further approach to supporting early commercial projects could be to link emissions reductions from industrial processes with other policy mechanisms in less trade-exposed sectors. This type of approach would be similar in concept to offsets in some emissions trading sectors, i.e. it would allow firms with an emissions reduction incentive and a high marginal abatement cost to benefit from cheaper mitigation options in other sectors. A conceivable situation could be one in which electricity suppliers can benefit from financial support for the application of CCS to their power plant (or face an emissions performance standard) but can equally benefit from the same level of support if they invest in a CCS project of the same magnitude in a sector with lower CCS costs. Naturally, this type of system would require appropriate allocation of liabilities and also demonstration of additionality, but in theory the transfer of costs and risks to a less trade-exposed sector could be attractive.

²⁴ It is proposed here that the government agency holds the reverse auction after the CO₂ has been captured and stored, rather than contracting for a given quantity of storage in advance. Reverse auctions held in advance can reduce the risk associated with assuming the cost of CCS but can remove the marginal incentive for continued abatement.

²⁵ An alternative approach to portfolio standards is suggested by the European Commission. A mandatory CCS certificate system could require suppliers of fossil fuels to buy CCS certificates equivalent to certain amount of their embedded emissions from regulated sectors (EC, 2013a). This would meet the cross-sectoral test and could shift some responsibility onto oil and gas firms with the necessary geological knowledge for CO₂ storage. However, administration of such a system and its interaction with other climate policies is yet to be explored.

Box 4.6 • CO₂ purchase commitments as a potential support mechanism for early deployment

The main benefits of a CO₂ purchase contract mechanism are that it has little or no impact on competitiveness for trade-exposed sectors (as public funds cover the cost of capture and storage) and is cross-sectoral. By targeting a fixed quantity of CO₂ stored, rather than subsidising output, it addresses production cost and market price uncertainty for producers. If the market for certificate sales is competitive it also encourages firms to accept higher shares of the cost and risk in order to make competitive bids.

As with any policy instrument designed to stimulate investment, careful policy design is crucial. The most efficient systems in theory would give short-term commitments to profit from future cost savings and new entrants. The shorter the commitment, however, the lower the long-term guarantee of revenue for a large capital-intensive project, and thus the higher the risk that new CCS investments will not be incentivised. Early movers face a risk that those investing later would benefit from the cost reductions generated by earlier projects, which could undercut them in future reverse auctions. In addition, while a strength of CO₂ purchase commitments is their intrinsic preference for the lowest-cost CO₂ sources, this neglects activity in sectors with more expensive CO₂ sources and may therefore lead to uneven technology learning.

The competitiveness of reverse auctions is central to the efficiency of the instrument. For example, as with other systems that compensate low-carbon production, CO₂ purchase commitments will interact with any other systems that are designed to maintain competitiveness and avoid carbon leakage, including carbon pricing. While, in theory, firms will account for any additional benefits from the avoidance of CO₂ costs or the sale of free allowances by lowering their bids, governments could pay above the socially efficient level for CO₂ abatement and carbon leakage avoidance if reverse auctions are not sufficiently competitive.

A further concern is the burden that this system could place on government if funded from general taxation. In some countries, the raising of revenue for such a system could be linked to the repeal of fossil fuel subsidies, which amounted to USD 523 billion in 2011 (IEA, 2013c).

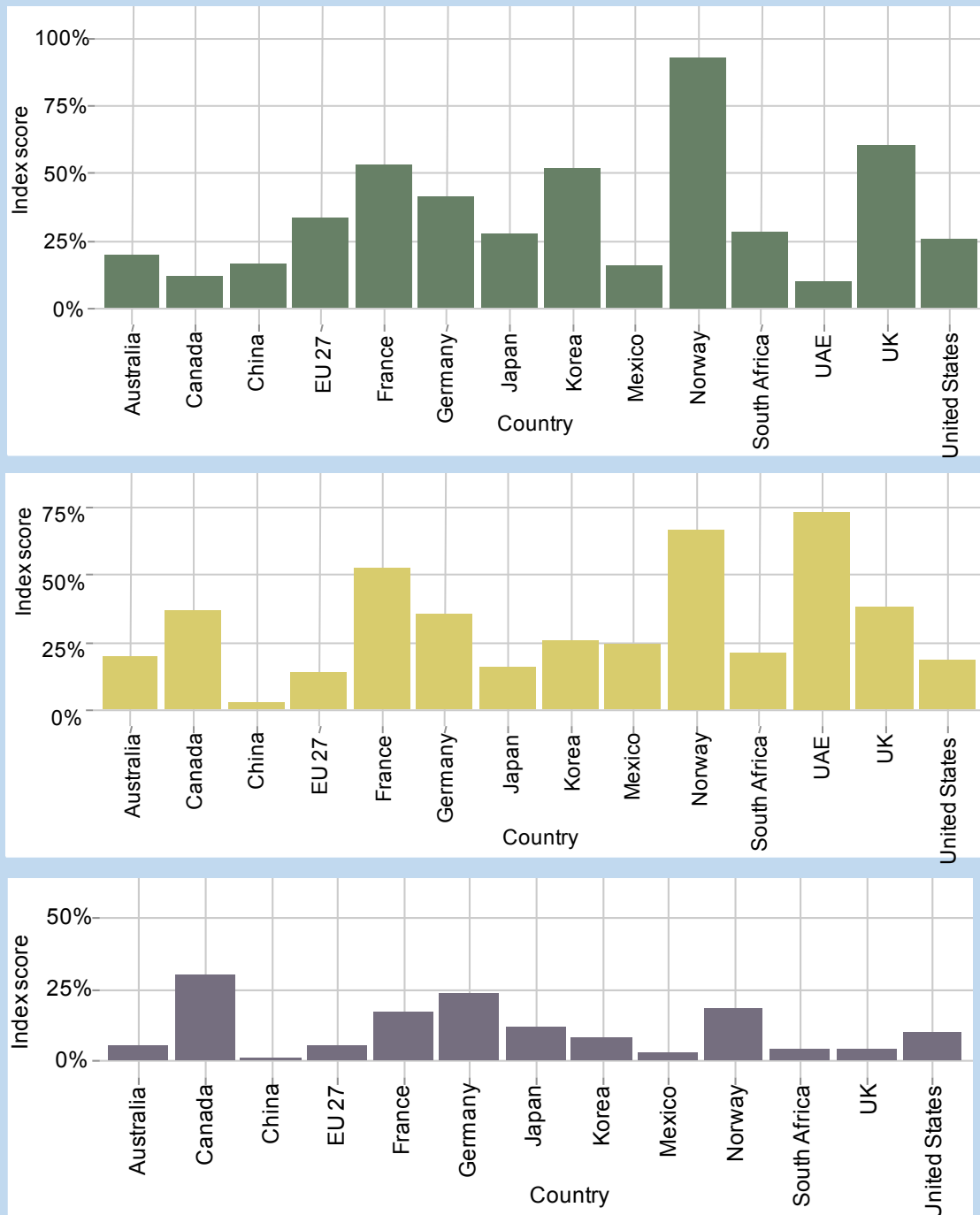
These potential drawbacks need not be show stoppers and a number of options could be available to governments to address them, including:

- Governmental commitment to purchasing an increasing minimum quantity of sequestered CO₂ annually for at least a decade to provide some certainty regarding volume and duration.
- Bilateral contracts with specific projects, made before investment in a CO₂ capture facility, could be used to guarantee purchase of a given proportion of the capacity. This proportion would reduce over the lifetime of the project and the remainder would be subject to bidding in reverse auctions. The volume and length of these contracts would need to be calibrated according to the risk that CCS capacity could become stranded if future projects benefit from cost reductions or cheaper CO₂, and the impact of this risk on the attractiveness of the investment proposition and the overall benefit of future cost reductions.
- Determination of contract prices through a tender process linked to external factors such as fuel prices and CO₂ prices to minimise any premium paid for bilateral contracts.
- Carefully structured capital or production tax credits to help facilitate access to capital or further address competitiveness concerns, depending on the impact of other policies, such as free CO₂ allowances.
- Collaboration between countries to reduce the effective level of national trade-exposure and thus increase the opportunities to share the cost burden with operators.
- Governmental commitment to purchasing a certain proportion of certificates from a specific sector, justified on the basis of increased learning for sectors that are not among the lowest-cost sources of CO₂.

Box 4.7 • Reducing trade exposure through policy cooperation

Higher levels of trade exposure potentially require governments to take on more of the costs and risks of CCS if the application of climate policy is not equal in all regions. An alternative to increasing the public burden is to take steps to reduce trade exposure. Figure 4.5 shows trade exposure levels for three sectors and selected countries that have current CCS activities. The trade exposure metric used is that which is employed for assessment of carbon leakage in the EU emission trading system.

Figure 4.5 • Selected national trade exposure indices for the refining (top) iron and steel (middle) and cement (bottom) sectors



Source: analysis for the IEA by Vivid Economics

Figure 4.6 shows the impact of recalculating the index for the hypothetical case in which trade with specific partners were not considered to be exports. The resulting percentages show by how much the index would be reduced by for each country and each partner. High percentages indicate that if

policies in the two countries were aligned, they would not need to overcome high trade-related barriers to implementation. Black cells indicate that the findings for the two countries are symmetric; for a country that would benefit most from coordination a given partner, the partner would also benefit most from coordination with that country. Canada and the US, France and Germany and Japan and Korea appear to be good candidate pairs for greater cooperation in CCS in industrial applications. To a large extent in EU countries, cooperation already exists.

Figure 4.6 • Impact of policy cooperation on trade exposure in the refining (top) iron and steel (middle) and cement (bottom) sectors



Source: analysis for the IEA by Vivid Economics

A further approach to reducing the impact of climate policy on trade could be to reduce trade exposure itself. As described in Box 4.7, in some countries a high percentage of a sector's international trade is across one border. This indicates potential benefits of coordination between these countries in terms of policy measures or project support schemes.

Phase 3: Internalising CO₂ costs for wide deployment

Wide deployment would proceed after the early deployment phase, if CCS is a cost-effective option in a given sector. This would ideally happen within a broader technology-neutral climate policy on global level. Such policy could take the form of a broad multi-sector or economy-wide carbon pricing, performance standards or a combination of the two, such as a trading system with emissions benchmarking (IEA, 2012b). The priority of this phase is to abate CO₂ emissions and fully internalise CO₂ costs within firms' decision-making, while accounting for any regional differences and carbon leakage risks.

Sectors that are trade-exposed may nevertheless justify some continued support under a functional and inclusive CO₂ emissions system. As a highly capital intensive technology, CCS investment risk varies strongly with CO₂ price volatility²⁶ and long-run societal costs might be reduced by, for example, a CO₂ price floor. For trade-exposed sectors, free allocations or tax rebates may be necessary for the duration of the period that a global CO₂ price is not in effect. However, in order to retain competitiveness and protect against carbon leakage, free allocations would need to be based on emissions intensity before the addition of CCS, and linked to output rather than installed capacity to avoid abatement through reduced capacity utilisation (Demailly and Quirion, 2006). In addition, strong political commitments or "front loading" of a firms' allocation could be necessary to encourage investments in assets with multi-decade lifetimes compared to the shorter timeframes on which free allocation or tax rebates are generally determined.

An alternative to free allocation or tax rebates for trade-exposed sectors that are sensitive to carbon prices are border carbon adjustments (BCA) (Cosbey et al., 2012). BCA regimes could prevent carbon leakage and preserve regional competitiveness by levelling the playing field. While the implementation of BCAs faces a number of political and legal challenges, it has been noted that the absence of a CO₂ price on imports could comprise an implicit subsidy to dirtier production in non-regulated markets (Helm, Hepburn and Ruta, 2012). BCAs have been discussed in much greater detail elsewhere²⁷ so consideration here is limited to CCS-specific aspects. The first point is that to incentivise CCS, the protection afforded by a BCA would need to remain after CCS were installed and long-term binding commitment to this might be required to overcome investment risks. The second is that the BCA would need to distinguish between different types of product within a sector, e.g. different types of steel, to avoid unequal impacts on more CO₂-intense production processes within a sector. Consequently, BCAs may be more easily applied in sectors such as cement (where products are more homogenous), compared to refining or steel production, all else being equal.

It could be challenging for governments to justify continued support for CCS in the third phase if it is still a relatively expensive CO₂ abatement option. This is especially true for countries with cap and trade systems whereby public support for CCS would not reduce the overall emissions under

²⁶ Abadie and Chamorro (2008) estimate that CO₂ trigger prices for CCS could rise by a factor of four for the case where CO₂ price volatility is 50% rather than 0%.

²⁷ Condon and Ignaciuk (2013), Fischer and Fox (2011), OECD (2010). One specific issue for manufacturing sectors is the possible effect of a scheme that covers only basic materials and not manufactured goods; domestic manufactured goods could be disadvantaged. Applying BCAs to all manufactured goods would be highly complex and trade flows may re-route to minimise cost impacts (Cosbey, 2008).

the CO₂ emissions cap. But, as policies move from supporting technology learning to internalising the CO₂ externality, tools such as free allocation, BCAs or equivalent may be essential to account for regional policy differences. Each tool has advantages and disadvantages and choices will be influenced by how they interact with other policy objectives, such as avoiding carbon leakage or retaining competitiveness.

Delivering success: addressing further challenges

If the undersupply of CCS knowledge, capital and the externalisation of CO₂ costs are overcome, successful deployment of CCS will still demand that a number of other challenges (market failures) are also addressed during the three phases. These include competition issues (imperfect competition) and coordination across the CCS value chain (complementary markets).

With respect to *imperfect competition*, there is some risk in the first two phases that new entrants could be disadvantaged by decisions taken when granting funding to projects. For example:

- Multi-year, bilateral CO₂ purchase contracts may exclude lower cost sources of CO₂ from the market in later years
- Incentives linked to previous production levels could provide benefits to incumbent firms only
- Public grants for projects with pipeline designs that are not optimised for future network expansion can raise the costs of future nearby projects.

These aspects can be mitigated by reducing the lengths of contracts for CO₂ or allocating to the public the risk that future local sources of CO₂ do not emerge to fill pipelines that are designed with future network expansion in mind.

Another concern is the possibility that monopoly power could be exerted by operators of CO₂ transport networks. This concern is relevant to CCS in general and has been dealt with in different ways. Two approaches to improving competition in CO₂ networks can be found in the European Commission's CCS Directive (EC, 2009c) and Alberta's Regulatory Framework Assessment (Alberta Energy, 2013).

Facilitating coordination in the CCS value chain can be an area for public intervention where sectors have limited existing contact and misaligned expectations of each other's roles in CCS. For a broader discussion, see IEA (2012b). Firms that emit CO₂ may be under pressure to develop solutions to reduce emissions in certain regions, but their equipment suppliers may be focused on regions where demand for new capacity is strongest. It has been suggested that CO₂ capture development in industrial applications need only proceed once CO₂ transport and storage have been developed and commercialised by other sectors and third parties. Yet, the developers of transport and storage solutions, who typically are not in the same sectors, may equally insist that the opposite be true. Governments can be instrumental in reducing the first-mover risks on both sides. It is unlikely that many heavy-emitting firms, with the possible exception of refiners and gas producers, will evolve to become integrated into the CO₂ storage business in the near to medium term. If CO₂ emitting firms prefer to contract with third parties for the capture, transport and storage of their CO₂, this will create complexity and potentially add costs associated with the transfer of liability. While this presents a coordination challenge for some sectors, the vertical integration of refining and gas processing into CO₂ transport and storage presents an opportunity. Vertical integration can overcome the additional costs associated with contracting in the value chain and skill shortages for early projects.

Energy-intensive industries highlight the acute need for a commercial CO₂ transport and storage business to become available for the off-take of captured CO₂. Business models for CO₂ transport

and storage must emerge to provide confidence that these services can be provided to all relevant sectors.

Ensuring that players in different sectors and different parts of the value chain are coordinated can also enable deployment at a local level. The evolution of clusters of CCS-equipped industrial facilities could be promoted by government to help sectors be “CCS ready” and plan to share a local CO₂ transport and storage infrastructure, which could be anchored by the presence of CCS on a major local emitter in the power sector. Planning for the stepwise deployment of CCS in major industrial clusters includes investigating accessible CO₂ storage sites and considering requirements that would make local sectors increasingly CCS ready, thereby potentially lowering future risks of CCS development and costs of CCS deployment.

To address the relatively lower levels of engagement of industrial sectors in shaping the wider policy context for CCS compared to the electricity sector, IEA (2013b) recommended that firms and other relevant actors from industrial sectors be involved in all broader CCS activities, graduating to equal partnership over time. These activity areas include: public engagement and awareness of the benefits of low carbon production; knowledge sharing on technical, regulatory and project development aspects of CCS; CO₂ storage capacity exploration and commercialisation; development of injection techniques and CO₂ measuring, monitoring and verification; R&D into novel techniques across the CCS value chain to exploit synergies between sectors.

Conclusions

CCS in industrial applications is essential for meeting economy-wide emission mitigation targets at least cost. Given the slow pace of progress, policy that incentivises the development and subsequent deployment of CCS technologies in industrial applications should be high on the policy agendas of countries worldwide. It is a clear area where global collaboration could help overcome barriers to progress. Analysis in this chapter suggests that CCS policy in the area of industrial applications will need to vary according to sector and country. It should be addressed to target market failures, and be flexible, long-term and sensitive to interaction with other policy instruments such as CO₂ pricing.

The key difference between developing policy for CCS in industrial applications compared to the electricity sector is that it must take greater account of both trade-exposure and the lack of alternatives for low-carbon production in some sectors. These issues can exacerbate the impacts of market failures in comparison to the electricity sector. A further crucial difference is the range of different CO₂ capture costs and scales in different industry sectors and within sectors.

In a gateway approach, technological learning is the initial primary objective. Public funds and transnational collaboration between firms is likely to be required to overcome market barriers to project financing. During this phase, the ground can be prepared simultaneously for policy measures that will act as longer-term incentives. This is the policy phase from which CO₂ capture technologies for many processes in the steel and cement sectors would benefit today.

A second, early deployment, phase also has technological and economic learning as a core objective but creates niche markets for CCS deployment to facilitate capital investment and overcome coordination and information asymmetry market failures. This is the policy phase from which CO₂ capture technologies for many processes in the refining and chemicals sectors would benefit today.

Wide deployment under an economy-wide CO₂ price is the long-term objective of the gateway approach. This phase directly targets the externality of CO₂ emissions to complete the transition

to a technology-neutral cross-sectoral regulatory framework in which risks are covered by private-sector revenues for low carbon production. Successful wide deployment means that CCS would be used to minimise costs associated with CO₂ emissions, firms using CCS will reap the benefits of reducing their marginal production costs and, in the long run, consumers will benefit from lower prices. This is the policy phase from which technologies for CO₂ capture from gas processing and hydrogen production for refining and chemicals is at today.

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The use of border carbon adjustments may continue to be necessary in some, but not all, sectors. This requirement would last as long as GHG penalties or avoidance costs substantively disadvantage industries in “more heavily regulated regions” through higher production costs.

Trade exposure of industrial sectors could mean that instruments such as tax rebates, free allocation or emissions allowances or BCAs may be valuable tools to mitigate regional competitiveness impacts and, especially, carbon leakage. However, further analysis in relation to specific priority policy objectives would be necessary and would depend on local interfaces between climate and industrial priorities. This analysis indicates that climate policy and industrial policy interact strongly in the area of CCS in industrial applications and governments will need to reconcile the two if they are to secure the necessary progress in a timely manner.

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5. Every little bit helps? Evaluating CO₂ utilisation for climate change mitigation

Page | 82 Introduction

Utilising carbon dioxide has received increasing attention in recent years, notably as a potential driver to develop carbon capture and storage (CCS). The allure of CO₂ utilisation is straightforward: instead of paying to dispose of CO₂, firms that generate large amounts of CO₂ could be paid for it, while at the same time avoiding emissions to the atmosphere and any associated penalties. If viable, CO₂ utilisation could thereby shift the focus of the CCS discourse from the disposal of an inconvenient by-product or waste towards the production and use of a commodity.

However, not all options for CO₂ would actually help tackle climate change. This chapter proposes a framework for analysing whether and under what circumstances different types of CO₂ utilisation could contribute to climate change mitigation. As Box 5.2 illustrates, there are various ways to utilise CO₂.

Millions of tonnes of CO₂ are already used industrially each year. With some 70 million tonnes of CO₂ (MtCO₂) used per annum, enhanced oil recovery (EOR) is the largest single use of CO₂ today. Around 23 MtCO₂ was supplied by industrial sources for use in North American CO₂-EOR operations in 2011. Other uses include for example carbonated drinks, dry ice and food production. Approximately 8 MtCO₂ was used in the beverage industry for carbonated drinks in 2011 (GCCSI, 2011, 2013).²⁸ Captured CO₂ is also used for urea yield boosting (up to 30 MtCO₂/yr), pharmaceutical processes (less than 1 MtCO₂/yr) and water treatment (up to 5 MtCO₂/yr) among other things (GCCSI, 2011). ADEME (2010) estimated that 113.5 MtCO₂/yr were used for non-EOR purposes in 2010.

While CO₂-EOR can result in permanent retention of CO₂ from atmosphere, many other uses of CO₂ only result in short-term storage (i.e. days to years) and the resulting emission reductions, if any, are difficult to quantify. Some uses of CO₂ may offer other non-climate benefits, such as industrial waste stabilisation or competitiveness gains. While these benefits could address other policy goals for governments, this chapter focuses on the climate benefits. A range of possible reasons for interest in CO₂ utilisation is provided below in Table 5.1.

The impact of a CO₂ utilisation option depends on three factors. The foremost of these is the achieved **emission reduction**, namely to what extent the utilisation reduces anthropogenic CO₂ emissions. To analyse this issue requires a good understanding of the fate of the CO₂ or the carbon-containing product, i.e. how much of the CO₂ is sequestered from the atmosphere and for how long. However, it is often also important to understand the CO₂ source and, whether or not the CO₂ is effectively sequestered, how the utilisation in question impacts CO₂ emissions elsewhere. Second, potential **revenue** is crucial to determining whether the use of CO₂ is commercially attractive and can help finance CO₂ capture, either in the absence of or as a complement to climate policy: does it help to reduce the reliance of CCS on long-term policy support to recoup additional costs? Third, it is important to know whether the use in question is **scalable**: is there sufficient demand for the resulting products to drive a significant demand for captured CO₂? Or, at a minimum, could it support the building of capital-intensive CO₂ capture

²⁸ Values given are for non-captive sources of CO₂, i.e. CO₂ that is captured to be introduced into another industrial process. Captive CO₂ is that which is produced by an initial step in an industrial process and then re-introduced at a later stage in the same process, e.g. urea and methanol production processes.

and transport installations? These issues, also laid out in Box 5.1, are discussed in this chapter; this chapter does not evaluate individual uses of CO₂ in detail.

Box 5.1 • Key basic criteria for assessing CO₂ utilisation options for climate change

- Have an emissions reduction benefit.
- Provide sufficient revenue, for example to help close the finances for investment in large-scale CO₂ capture equipment.
- Be scalable to a level that is meaningful in climate change mitigation terms.

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Table 5.1 • A non-exhaustive list of reasons for interest in CO₂ utilisation

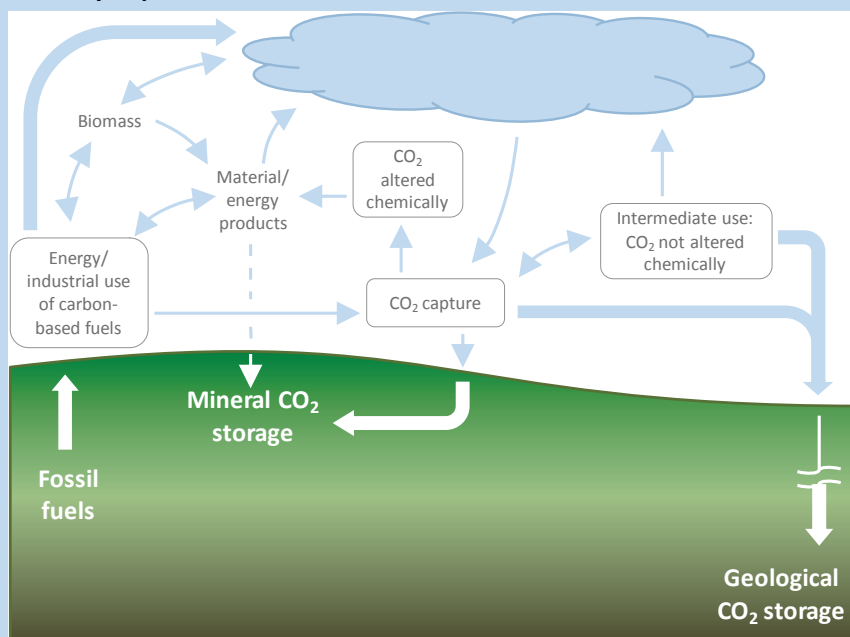
Reason	Societal or policy objective
To create a revenue stream for CO ₂ abatement from fossil fuels use based on consumer demand for CO ₂ -containing products, i.e. a revenue that is not reliant on consumers or taxpayers paying a premium related to climate change benefits	Climate
To avoid the emission of greenhouse gases (GHG), in particular CO ₂ , to the atmosphere and thus reduce negative impacts on the environment	Climate
To provide an alternative to CO ₂ geological storage on the basis that re-use of waste is preferable to disposal in accordance with the waste hierarchy, and could overcome issues of public mistrust of CO ₂ storage	Climate
To increase the supply of hydrocarbon fuels for reasons of energy security or cost control	Energy security / competitiveness
To make use of the specific attributes of CO ₂ , for instance as a solvent, in commercially competitive applications	Competitiveness / innovation
To produce valuable chemical and fuel products that are more cost-effective or less environmentally harmful to produce from the carbon in CO ₂ than the carbon in other raw materials such as petroleum or biomass	Environment / Competitiveness
To increase the supply of water in water-poor regions by exploiting saline aquifers	Competitiveness
To remediate inorganic wastes from industrial processes	Environment
To support innovation that could, in the future, facilitate the cost-effective use of CO ₂ as an abundant source of carbon for chemical or fuel production, especially as a hedge against future price or other constraints on fossil fuel or biomass supplies	Innovation / Competitiveness
To reduce the extraction and/or supply of fossil fuels for reasons of resource diversification or political preference	Energy security / Environment

Note: Unless otherwise note, all tables and figures derive from IEA data and analysis.

Box 5.2 • CO₂ utilisation forms part of a complex system

Figure 5.1 shows that many different processes can manage CO₂ in the industrial CO₂ “ecosystem”, some of which ultimately lead to the CO₂ being released to the atmosphere and some of which lead to the CO₂ being permanently retained. Geological storage is the final step in a CCS process and can be considered to set a benchmark in terms of emissions reductions as verification of the permanence of CO₂ retention in the subsurface is usually part of the regulatory framework.

Figure 5.1 • A family of processes that interact to increase or reduce total CO₂ emitted



Notes: This graph does not intend to represent the complete cycle of carbon stocks and flows. Boxed text denotes processes; unboxed text denotes stocks of carbon; the cloud denotes the atmospheric stock of carbon; arrows represent flows of CO₂.

In Figure 5.1, uses in which the CO₂ is chemically altered and “intermediate uses” in which it is not chemically altered are separated. The former type of use takes advantage of the relative abundance of CO₂ as a source of carbon, which is the basis for most of our goods and fuels. The latter in some cases enables a further decision about whether to “re-capture” the CO₂ and then store, release or further utilise it. Table 5.2 further defines the terms in Figure 5.1.

Table 5.2 • Terminology of management approaches to CO₂ within an industrial CO₂ ecosystem

Term	Definition	Example
Energy/industrial use of carbon-based fuels	Combustion of fuels for the provision of heat, light or power, plus oxidation of carbon to CO ₂ during its use as a reducing agent or industrial raw material.	Coal, biomass or gas-fired power generation; refining; vehicle propulsion; petrochemical production; steel production; cement manufacture; fuel preparation; biofuel production; other manufacturing; heat provision.
CO ₂ capture	Separation of CO ₂ from mixtures of gases (e.g. flue gases) and compression of CO ₂ .	Syngas-hydrogen capture; post-process capture; oxy-fuel combustion; inherent separation; Direct Air Capture (DAC) of CO ₂ .
Intermediate use: CO ₂ not altered chemically	The use of captured CO ₂ in commercial processes that do not chemically alter the CO ₂ .	CO ₂ -EOR; Enhanced gas recovery (EGR); Enhanced coal bed methane recovery (ECMR); coffee decaffeination; carbonated drinks; CO ₂ as a solvent.
CO ₂ altered chemically	Chemical incorporation of the carbon contained in CO ₂ into material or energy products, which would ultimately release the carbon back to the environment as a greenhouse gas during their normal use.	Manufacture of liquid and gaseous fuels via chemical or biochemical routes; chemicals manufacture; production of construction materials; use of CO ₂ as an agricultural nutrient.
Geological CO ₂ storage	Injection of the CO ₂ into a geologic formation deep underground where it is retained by a natural (or engineered) trapping mechanism and monitored as necessary.	Injection into saline aquifers, depleted hydrocarbon reservoirs, depleting hydrocarbon reservoirs or coal seams.
Mineral CO ₂ storage	Reaction of CO ₂ with minerals to form insoluble and otherwise unreactive materials that are retained out of the atmosphere on geological time scales. CO ₂ is altered chemically.	Production of inorganic carbonates, including through waste treatment.

Emission reduction benefits

From a climate perspective, it is easiest to envision the benefit of CO₂ utilisation options that would allow for permanent retention of CO₂ from the atmosphere, i.e. conceptually akin to geological CO₂ storage. Another group of potentially interesting uses include those that can achieve net CO₂ reductions through substitution effects at a system level.

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This section first considers the most straightforward question: what happens to the CO₂ during (and after) a use? It then follows with issues relating to the CO₂ source and ends with a look at what can at times be a complex challenge of establishing the potential emissions reduction for a given CO₂ utilisation option.

Evaluating what happens to the CO₂ during utilisation

Considering the fate of the CO₂ during the end-use of products from CO₂ utilisation, for the purposes of this chapter we divide uses into two types (Types A and B in Table 5.3). The main message is that all types of CO₂ utilisation are not equal from this perspective. The first type (A) includes uses that lead to permanent retention of CO₂ from the atmosphere. While few opportunities are on the immediate horizon, they could be valuable to pursue as a means to achieve long-term emission reduction goals. The second type of uses (B), are less straightforward to analyse; these could have emissions reductions potential in certain circumstances, although the opportunities are currently thought to be limited. Firms and policymakers may wish to pursue these opportunities if they also satisfy other policy objectives.

Type A. Utilisation that leads to permanent storage of the CO₂

This type includes geological uses of anthropogenic²⁹ CO₂ where the CO₂ may be verifiably and permanently retained in the subsurface. CO₂ utilisation options fit into this type if they involve concurrent geological storage of CO₂ (e.g. CO₂-EOR, see below) or incorporation of the carbon into long-lived materials that are not decomposed or combusted during their normal use and disposal.

CO₂-EOR, and other types of enhanced resource extraction, is a type of CO₂ utilisation that can lead to the concomitant permanent geological storage of the CO₂ as part of its use in oil extraction. The resulting direct CO₂ emissions from CO₂-EOR are primarily driven by the need to recycle produced CO₂ within the boundaries of the EOR project and depend strongly on the amount of CO₂ that is retained in the hydrocarbon reservoir after operations have ceased. CO₂-EOR operations could be adjusted to increase the amount of CO₂ retained per barrel of oil produced if there is an incentive to do so (ARI, 2010). With all cases of geological CO₂ storage, and CO₂-EOR is no different, monitoring of the injected CO₂ is required to provide confidence that it is retained in the subsurface (Bachu et al., 2013). Oil producers are currently reluctant to take on the additional costs of maximising and monitoring the resulting CO₂ emissions reductions. The oil produced from EOR is transported, processed and used much as any other stream of crude oil, the majority of which is ultimately burnt as a transport fuel.

Other types of enhanced resource extraction that are currently less developed than CO₂-EOR include enhanced gas recovery, enhanced water recovery, enhanced coal bed methane recovery, and use of CO₂ as a working fluid for geothermal heat recovery or as a fracturing fluid for oil and gas operations (ACCA21, 2013). Production of water from saline aquifers for industrial use and

²⁹ Anthropogenic CO₂ is CO₂ produced or emitted as a by-product of human activity. The term is used here to distinguish it from natural CO₂ produced from geological CO₂ deposits and dedicated CO₂ production from fossil fuels for the purpose of CO₂ utilisation. Natural CO₂ extraction and use for CO₂-EOR increases the total emissions of CO₂ to the atmosphere.

combined with storage of the CO₂ is of interest in water-poor regions. Water scarcity could also be a driver for the use of CO₂ as a working fluid for shale gas extraction, currently under preliminary research (Sun et al., 2013). In the case of CO₂ injection into coal seams and shale formations there is less certainty about the retention of CO₂ compared to CO₂-EOR and other more mature types of geological storage (Godec et al., 2013; Koperna et al., 2013; Liu et al., 2013). Further work on suitable site selection and the reliability of CO₂ trapping mechanisms is required to fully understand their potential. Some of these options result in a product (e.g., natural gas) that would create further emissions during its normal end-use.

Mineral carbonation of CO₂ involves reacting CO₂ with metal oxide bearing materials to create insoluble, stable carbonate materials. Mineral carbonation for long-term storage has been demonstrated at lab scale and can be achieved without large energy inputs. The resulting materials are generally considered to require little, if any, on-going monitoring to build confidence in long-term storage. The natural minerals used for the carbonation process – such as the magnesium and calcium silicates wollastonite, olivine and serpentine – are available in sufficient quantities to store billions of tonnes of CO₂ (Lackner et al., 1995). Some of the resulting carbonates are already commercial for niche markets but demand for these products, for example as aggregate fillers, is limited. Mineralisation could also be an attractive way to fix waste materials such as steel slags (Mun and Cho, 2013; Stolaroff, Lowry and Keith, 2005). It has also been proposed that waste cement could be recycled into calcium carbonate, a raw material for cement production (Iizuka, Yamasaki and Yanagisawa, 2013).

There are, however, various important challenges facing mineralisation. The availability of mine tailings and industrial wastes that could be used as mineral inputs are in limited supply. Consequently, for each tonne of CO₂ fixed, several tonnes of mineral would likely need to be mined, ground and prepared. This can have a high energy penalty and could severely reduce the CO₂ benefit (IPCC, 2005). Despite being exothermic, a feature that could potentially reduce the overall energy costs, the reaction kinetics are generally much slower than the rate at which CO₂ would be captured (Zevenhoven, Eloneva and Teir, 2006). If pure CO₂ is needed for the reaction, the energy and cost requirements of CO₂ capture and transport need to be taken into account.

Whether carbonate products in such large volumes could find viable markets in the low-cost construction materials sector is highly uncertain and may require government intervention. The potential scale of demand for affordable construction materials is nevertheless meaningful.³⁰

Type B. Utilisation that leads to subsequent emissions of CO₂ – but may result in lower overall emissions

Many recently-discussed examples of CO₂ utilisation fall into Type B, including the use of CO₂ as a feedstock for the production of carbon-containing liquid fuels and plastics.³¹ In general, this type of CO₂ utilisation does not create products with a sufficiently long lifetime to provide storage of the CO₂. Instead, the carbon is released at the end of the product's life through degradation or combustion.

Plastics, for example, have an average service life of between eight and 14 years, including recycling to new uses before disposal (Mutha, Patel and Premnath, 2006; Patel et al., 1998). This average accounts for short-lived products, such as packaging with a lifetime of one year, and

³⁰ The total projected world demand for cement in the IEA between now and 2050 is around half the mass of carbonate that could be supplied by converting all the CO₂ captured in the IEA 2DS, a cost-minimising scenario in which CCS accounts for 14% of the cumulative CO₂ emissions reductions up to 2050 (IEA, 2012a).

³¹ Practically all of the fuels and chemicals consumed in the modern economy are carbon-based and derived from fossil hydrocarbons such as oil and natural gas using energy-intensive production processes. Biomass is used in relatively small quantities for the production of fuels and chemicals today and its expansion, whilst anticipated, is likely to be limited.

long-lived products such as moulded compounds in building materials, with a lifetime of 30 years. Neither plastic packaging nor plastic building materials ensure long-term retention of the carbon from the atmosphere through normal use.³² Incineration and degradation of plastics and synthetic fibres as waste disposal options lead to the carbon returning to the atmosphere as a greenhouse gas. Products that are short-lived by design, such as fertilisers and fuels, generally remain in the economy for less than a year.

Despite not leading to effective sequestration of the CO₂, such uses may in some situations be part of systems that deliver life cycle emission reductions due to substitution effects. For instance, captured CO₂ could be utilised for the production of transport fuels, which could push some alternative fuels (e.g. gasoline) or transport modes out of the market. Substitution effects can be understood by analysing whether the emissions from the displaced system are higher or lower than in the case with CO₂ capture, fuel production and fuel combustion. To have a CO₂ emissions reduction benefit, CO₂ utilisation should lead to a carbon-containing product with higher associated life cycle CO₂ emissions no longer being required (IPCC, 2005). This concept is more fully explained in the annex of this chapter.

In the near-term, however, some CO₂ utilisation options that lead to emission of the CO₂ during end-use may still provide an indirect longer-term benefit if they can secure revenue for valuable projects that demonstrate CCS technologies at large scale (Box 5.3).

Box 5.3 • Utilisation that finances demonstration projects: a near-term opportunity

Several large-scale CO₂ capture demonstration projects have successfully been financed despite an absence of climate policy-driven incentive systems. Revenue from CO₂ sales for use in CO₂-EOR and sodium bicarbonate, urea and methanol production lowers the cost of essential early large-scale CO₂ capture projects for which financing and revenue are scarce (GCCSI, 2013). These projects do not always have beneficial impacts in terms of direct CO₂ emission reductions, but contribute societal knowledge and cost reduction for CCS and CO₂ capture and utilisation technologies that support the long-term deployment of CCS. For example, the emissions reductions associated with EOR cannot be fully understood without appropriate site characterisation and monitoring of the CO₂ in the subsurface.

This type of CO₂ utilisation can be tolerated in climate terms, regardless of any lack of direct CO₂ benefit, if essential revenue for commercial CO₂ capture and transport projects is provided. The associated technological learning could be highly valuable in the near-term if the contribution of knowledge is significant; for example if it is linked to CCS technologies that are not yet commercially available and proven.

The opportunity is likely to be limited to the coming decade as a limited number of demonstration projects may be required to advance CCS technologies in the absence of sufficient climate policy incentives. The IEA CCS roadmap envisages that about 30 CCS demonstration projects are necessary to assist CO₂ capture and transport technologies to pass to commercial viability (IEA, 2013). This is an indication of the potential scale of CO₂ utilisation options that generate revenue for technological learning. To support large-scale projects in the coming years, technologies may already need to be commercially viable at a scale of tens of thousands of tonnes of CO₂ input.

³² Von der Assen, Jung and Bardow (2014) recommend taking into account time-corrected global warming potentials to incorporate the benefits of delaying emissions through temporary binding of CO₂ carbon into products. Such an approach demands assumptions about advances in global emissions mitigation in parallel to the use phase of a chemical product.

Table 5.3 • Two types of CO₂ utilisation in terms of their end-use emissions

Type	Summary	Examples
A. Utilisation that leads to permanent storage of the CO ₂	<p>Through the production and use of commercial goods with CO₂ as an industrial input, the carbon is effectively prevented from reaching the atmosphere as a greenhouse gas.</p> <p>The expected level of CO₂ emissions reduction could be comparable to or greater than that from geological storage of CO₂ if the processes or products of CO₂ utilisation displace alternatives that have larger carbon footprints, assuming equal upstream emissions from both systems. For example, oil from CO₂-EOR being used in place of transport fuels with a lower emissions profile.</p>	<p>Enhanced extraction of geological resources, including oil, gas and potentially water, whilst ensuring the effective retention of CO₂ in the subsurface.</p> <p>Manufacture of construction materials or long-lived polymers for which normal use and the regulatory environment ensure very low risks of the CO₂ being emitted.</p>
B. Utilisation that leads to subsequent emission of CO ₂	<p>Through the production and normal use of commercial goods with CO₂ as an industrial input, the carbon is not prevented from reaching the atmosphere as a greenhouse gas.</p> <p>CO₂ reductions of varying levels could accrue depending on the fossil fuel feedstock that CO₂ use displaces and/or the fossil fuel that the use of the commercial good substitutes.</p>	<p>Manufacture of fuels, plastics, polymers, agricultural inputs, foods and fine chemicals.</p> <p>Enhanced extraction of geological resources that do not ensure the effective retention of CO₂ in the subsurface.</p>

Evaluating emission reductions— upstream emissions and the CO₂ source

Understanding the total emission reduction benefits of CO₂ utilisation, whether type A or type B, requires knowledge across the whole CO₂ chain. As with CCS projects that rely on geological storage, the upstream source of CO₂ matters (see annex of this chapter for definitions of upstream and downstream in this context), but it can be a more important factor for CO₂ utilisation if the CO₂ is not permanently stored or, for example, if the CO₂ source is not from fossil fuels.

Some approaches to CO₂ utilisation employ purposefully generated CO₂. An example is using CO₂ from fossil fuel combustion strictly for the purpose of CO₂ production, such as CO₂ from coal gasification units dedicated to CO₂ production for sodium bicarbonate (baking soda) manufacture. As another example, most CO₂ used for EOR is taken from natural deposits that would not be exploited without CO₂ demand for EOR operations. CO₂ can also be supplied from the atmosphere, either directly or indirectly through the processing of biomass.³³ In these cases, special treatment is required when assessing emissions reductions.

To illustrate how the CO₂ source is critical to evaluating the emissions reduction benefits, consider the following CO₂ sources for an EOR project. Source 1 is an underground CO₂ reservoir that would not otherwise have been produced. Source 2 is a coal combustion facility that exists only to supply CO₂ to the EOR operator. Source 3 is a coal-fired power plant that would otherwise be retired and replaced by a solar thermal power plant. Source 4 is a coal-fired power plant that would otherwise continue operation unabated. Looking only at this upstream part of the CO₂ utilisation value chain, sources 1, 2 and 3 do not appear conducive to net emission benefits from the utilisation in question. Source 4 is much more promising.

In addition, the CO₂ capture process itself produces emissions. Most proposed CO₂ utilisation options are based on pure CO₂. Geological storage of CO₂ for CCS requires nearly-pure CO₂ and is therefore preceded by a CO₂ capture step that separates the CO₂ from a mixture of other gases (if necessary) and compresses it. This capture step is not 100% efficient and generally results in some associated CO₂ emissions; it also requires additional energy inputs, usually from fossil

³³CO₂ capture directly from ambient air is possible but costs are currently high and are likely to remain substantially higher than capture of CO₂ by biomass or from flue gases; possibly much higher than other CO₂ abatement options in the economy (Royal Society, 2009; Ranjan and Herzog, 2011).

fuels.³⁴ Most proposed CO₂ utilisation options are based on pure CO₂. However, unlike CCS, utilisation can in some cases be undertaken directly from a mixture of gases, without passing through a CO₂ capture step.³⁵

Assessing net emissions reductions from CO₂ utilisation

Assessing emissions associated with CO₂ utilisation is often complex. In addition to understanding the source, the assessment requires many assumptions to be made about the nature of end-use and disposal of products in the economy that are often far removed from the original CO₂ source.

Assessment of the emissions associated with the CO₂ utilisation option needs to be complemented by a calculation of how the service provided by (the product of) CO₂ utilisation would otherwise have been supplied. A benefit will accrue if an equivalent process or a product with a worse life cycle CO₂ balance is displaced. Such a displacement effect is an important consideration for both types of utilisation options because all CO₂ utilisation produces a commodity to be sold. It can however have a greater impact for Type B options for which the emissions benefit can in some cases be more marginal. The importance of a life cycle approach to assessing emission reductions is described in the annex of this chapter.

As noted above, CO₂ utilisation options in **Type B** require consideration of life cycle emissions for other likely production routes. As an example, coal could be used to generate electricity and the resulting CO₂ could be incorporated into synthetic natural gas (by reacting it with hydrogen from nuclear-powered electrolysis); if these two products were to displace electricity and synthetic natural gas from two unconnected and unabated facilities based on coal, there would be a likely net emissions reduction.

The displacement effect is also relevant for **Type A** utilisation options. For example, durable building material products from CO₂ utilisation that could lead to the permanent retention of CO₂ may displace the production and use of wood, cement or synthetic polymer materials. In the case of cement and polymers, the displaced emissions can be considerable and may be higher than the direct emissions from producing carbonate minerals from CO₂. Crude oil produced using CO₂-EOR competes on the market with other fuel sources and, at least from a market economics standpoint, the production from CO₂-EOR would not likely displace production from other sources in the long-run (van't Veld, Mason & Leach, 2013).

From complex to more simple assessment

As illustrated by the above discussion, the analysis of emissions reductions can be complex given the need to analyse two systems that provide the same services (one involving CO₂ utilisation and one without), each of which require a life-cycle assessment. Box 5.4 outlines this approach. It also suggests that the emissions reductions from feedstock switching to CO₂ are not likely to be dramatic.³⁶ For example, they might be similar to the emissions reductions associated with feedstock or fuel switching from coal to natural gas.

³⁴ Taking into account the additional energy demand of the CCS technologies themselves, the CO₂ avoidance for power generation with CCS is generally understood to be in excess of 80% compared to a reference plant without CCS. For industrial applications it varies, but is often at least 80% of the emissions stream to which CO₂ capture is applied.

³⁵ This includes the production of organic chemicals directly from flue gas (North, Wang and Young, 2011), the promotion of algae growth using flue gas (Sun et al., 2011) and concrete curing in atmospheric or CO₂-rich conditions (Fernández Bertos, 2004).

³⁶ Theoretically, greater emission reductions could be achieved if CO₂ used as a feedstock for fuel production were then re-captured when the fuel were combusted in a large stationary application. However, as CO₂ capture is generally 90% efficient or less and because it has an associated energy penalty, this option is subject to diminishing returns. If a capture rate of 90% is assumed and an energy penalty of 25%, only half of the CO₂ would remain non-emitted after five cycles, assuming that the processing of CO₂ into fuel is 100% efficient and not powered by the CO₂-containing fuel.

Box 5.4 • Considering life cycle emissions by expanding the system boundary to include multiple products

The most useful way to think about the combination of upstream and downstream emissions is to “share” them between the primary product and the product of CO₂ utilisation. The result is a single two-product system with an overall life cycle emissions impact. This system can be compared against an alternative system that produces the same products in a different way.

For example, if 1 MtCO₂/yr is captured from coal-fired power generation and sold to a fuel producer who converts all the CO₂ to fuel, 1 MtCO₂/yr is later released when the fuel is combusted in a motor vehicle. This system has emissions of 1 MtCO₂/yr and it displaces a system that produces electricity and fuel separately with combined emissions of 2 MtCO₂/yr. The emission reduction is therefore 50%.

In this simplified case, however, we have unrealistically assumed that the capture, purification, transport and processing of the CO₂ (including supply of other raw materials such as hydrogen) as well as the processes for the production of the displaced motor fuel, have no associated emissions. Since CO₂ is thermodynamically more challenging to convert to motor fuel than crude oil reserves, and requires extra hydrogen inputs, it is likely that net lifecycle emissions reductions would be below 50%.

If, instead of displacing an identical motor fuel, it were more likely that our CO₂-containing fuel would substitute for a biofuel or electricity in an electric vehicle, the emission reduction may be lower than 50%. Likewise, if a chemical that degrades to methane (which has a higher global warming potential than CO₂) when it is discarded were produced from the CO₂ instead of a motor fuel the emission reduction would probably be lower than 50%. However, if the CO₂-containing fuel would substitute diesel produced from coal without CCS, the reduction may look more attractive.

With the exception of CO₂-EOR, only a handful of assessments of the emissions reduction potential of CO₂ utilisation have been undertaken to date (von der Assen et al., 2014). These indicate emissions reductions from 75% to less than 0% and set the system boundary in a variety of ways (Aresta and Galatola, 1999; Giannoulakis, Volkart and Bauer, 2014; Glyn Griffiths et al., 2013; von der Assen and Bardow, 2014; von der Assen, Jung and Bardow, 2014). Furthermore, existing life cycle analyses tend to compare novel, immature production processes with current fossil fuel-based routes. The correct comparison would be with a scenario representing likely conditions at the time when the technology is expected to reach market, which could be significantly less CO₂ emissions-intensive (ISO, 2006).

The lack of obvious “win-win” CO₂ utilisation options in terms of emissions reductions should not be a big surprise as it reflects the stable chemical nature of the CO₂ molecule. CO₂ requires considerable additional energy input to separate the carbon for further processing.³⁷ Its stability also makes it the final product of decomposition during end-use, usually leading to its release to the atmosphere. Equally, this incontrovertible property of CO₂ is the reason why it is a relatively safe substance to handle and store geologically.

Simplified criteria for evaluation CO₂ utilisation and storage options may need to be developed. Standardised assumptions could be beneficial to support policymakers in determining whether a proposed utilisation option is likely to result in reduced emissions. This could be helpful for identifying promising technologies or providing policy support. However, for mature technologies, economy-wide CO₂ pricing systems could eliminate the need for policymakers to assess emissions reductions.

³⁷ Research into catalysts that can reduce the energy required for CO₂ conversion is an active area (Centi, Quadrelli and Parathoner, 2013; Cole and Bocarsley, 2010; Peters et al. 2011; Wu et al., 2014).

Sufficient revenue

The second key question concerns the economics of CO₂ utilisation. Utilisation of CO₂ holds the promise of financing CO₂ abatement using commercial market dynamics and partially or totally avoiding reliance on subsidies or rewards for emission reductions. In an ideal case, the user of the CO₂ could produce a carbon-containing material or fuel that has a market price that fully covers the costs of CO₂ capture, transport and processing. Even if revenues would insufficient to fully finance CO₂ capture, transport and processing, CO₂ utilisation could make the difference between positive or negative investment decisions, in combination with climate policy incentives. This would represent a potentially crucial advantage over geological storage of CO₂ for emissions reduction.³⁸

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While economic revenue may be possible through CO₂ utilisation, in practice there are a number of issues that require further consideration and which may make investment in CO₂ utilisation more challenging than investment in CCS, despite the prospect of revenue for CO₂ sales. One such issue is the cost of capturing and providing CO₂ (Box 5.5); others include:

- **Diverging interests across the value chain.** Like CCS, CO₂ utilisation value chains can be expected to have at least three entities: the source of the CO₂, a transporter of the CO₂ and the user of the CO₂. Investment decisions can only be taken when the full value chain is aligned in terms of costs, benefits and risks.
- **Mismatch between plant sizes.** CO₂ capture plants that are operated or constructed today for CCS have capacities from several hundred thousand to over one million tonnes of CO₂ per year. Future CCS plants would be even larger and matched with geological CO₂ storage options of an equal scale. Matching this supply any smaller streams of demand for CO₂ would thus represent challenges as the user would not be able to benefit from economies of scale in CO₂ capture unless geological CO₂ storage were also available to the same facility. In this instance a user of CO₂ might have the opportunity to purchase and divert a slipstream of the CO₂. However, in such a situation the challenges of deploying CCS, including political and public acceptance, would have already been overcome and geological CO₂ storage would most likely offer the greater emissions reduction potential.
- **Inflexibility of industrial CO₂ demand.** Contracts for purchase of CO₂ for industrial use are likely to require the supply of fixed volumes of CO₂ over a given period. Such contracts would need to align with the operating schedule of the capture plant, especially if it is in the power sector where the capture plant might operate in accordance with the power market if electricity sales were more profitable or inflexible than CO₂ sales.

³⁸ CCS is struggling to attract serious levels of commitment and investment in part because the revenue streams associated with CCS are expected to be dependent on climate-related policies. In this situation, consumers of products made using CCS would be likely to be charged a CO₂ avoidance premium on top of the price of their electricity, gasoline, plastics, cement, steel etc. Price rises in existing markets and reliance on the stability of government policy, creates concerns about competitiveness and financing risk that deters investment and will remain an unavoidable hindrance to CCS deployment.

Box 5.5 • What is the value of CO₂?

As regards the economic dynamics of CO₂ utilisation, many complex issues and relationships will require solutions. CO₂ is not a free resource if it needs to be captured, purified and transported, but some producers may be interested in transferring CO₂ for 'free' to a user if it can relieve their regulatory responsibility for their CO₂ emissions.

Today's large-scale CCS projects (for which costs are dominated by the capture plant) have capital costs in the range of USD 200 million to USD 1.25 billion for 1 MtCO₂/yr scale (Giove, 2013; SaskPower, 2013). Costs for these projects range from CO₂ capture from hydrogen production at a refinery (cheapest) to coal-fired power plants (most expensive). It is not expected that CO₂ capture costs will fall far below USD 10 to 30/tCO₂ for CO₂ from natural gas processing (IEAGHG, 2008) or USD 26 to 74/tCO₂ from coal-fired power generation in the next decade (IEA, 2011). CO₂ utilisation could however have a positive economic impact on a CCS project, as it could be able to offset, totally or partly, the additional cost of CCS.

If CO₂ is not free, the costs need to be allocated between the beneficiaries of CO₂ utilisation. The source of the CO₂ (e.g. a power plant) could perceive that they were selling a commodity to a profitable industry who should cover the costs of capture plus any associated risks. But the user of the CO₂ could perceive that they were providing a CO₂ management service and should be paid for reducing the other party's responsibility or liability for its emissions. There is an obvious tension in these commercial arrangements that can be overcome through negotiation or policy.

Several simplified examples are shown in Table 5.4 for CO₂ sources and users of purified CO₂. This shows the importance of how regulation of CO₂ determines the value of the CO₂ to an emitter that has a choice between venting, selling or geologically storing the CO₂ it generates. The table highlights conceivable cases in which the regulator considers that CO₂ sold for utilisation removes the CO₂ liability (example 2), and cases in which the liability is transferred to the user of the CO₂ (example 3). It also indicates the potential benefit of avoiding a capture and purification step by using CO₂ directly from flue gases (example 6). In practice, these minimum prices may be negotiable.

Would a CO₂ producer ever give the CO₂ away for free? Consider a future situation with a strong climate policy and an 80 USD/tonne emission penalty. This penalty has to cover not only the cost of capture, but also of transport and storage. Assume also that a separate service for CO₂ transport and storage emerges as a future business model, at 10 USD/tonne. If the operator had a possibility to reduce this cost by either selling the CO₂ to a user for less than 10 USD/tonne or even giving it away, this might be economically interesting. In such a case the CO₂ user would need to assume the related liability.

A reliable commercial revenue for CO₂ emissions reduction is a potential key advantage of CO₂ utilisation. The ability to reduce the reliance on climate policy to finance projects is perhaps the key difference between geological storage and CO₂ utilisation. The considerations above are challenges to be overcome for investors in CO₂ utilisation options, but are not presented as show-stoppers. A number of situations in which these challenges would be minimised could be:

- CO₂ utilisation options that do not require pure CO₂ but can directly utilise a proportion of the CO₂ from flue gases (or ambient air), thus reducing the capital costs, investment risks and number of steps in the value chain
- Vertical integration of the emitter and user of the CO₂, reducing the number of contracting parties in the value chain
- Close matching of the size and cost of the CO₂ capture source and CO₂ utilisation route. While coal-fired power plants may have the largest potential for CO₂ supply in volume terms, some smaller sources of CO₂, such as ammonia plants, are also the less costly sources of CO₂.

- Finally, the emergence of innovative “silver bullet” CO₂ utilisation options that generate goods that are valued by the market and result in permanent retention of the CO₂ leading to clear emissions reductions.

Table 5.4 • Simplified examples of how CO₂ purchase price might vary with regulation and capture cost

	Approximate CO ₂ capture cost (USD/tCO ₂)	Emissions penalty for CO ₂	Is CO ₂ utilised considered in regulation as “not emitted”?	Is a geological CO ₂ storage option available?	Transport and Storage cost (USD/tCO ₂)	Possible minimum CO ₂ purchase price for utilisation (USD/tCO ₂)
1. Coal power plant; no CO ₂ regulation	60	0	N/A	No	N/A	60
2. Coal power plant; CCS; cap-and-trade; no liability	60	80	Yes	Yes	10	80
3. Coal power plant; CCS; cap-and-trade; liability	60	80	No	Yes	10	0 (minus USD 80/tCO ₂ liability)
4. Coal power plant; performance standard	60	0	Yes	Yes	10	0
5. Ammonia plant; cap-and-trade; liability	25	15	No	No	N/A	10
6. Coal power plant; no capture step	0	0	N/A	No	N/A	0

Note: performance standard for CO₂ emissions per unit of power generation is assumed to be below that which is achievable by a coal fired power plant without CCS

Meaningful scale

Scalability relates to the limits of demand and supply of the products of CO₂ utilisation. The ability to produce a vast amount of material (using in this case CO₂) is only of benefit if there is an equal potential to find willing buyers. Fuels are consumed by buyers and then replaced, which makes them good candidates for scalable CO₂ utilisation options. At the other extreme, long-lived products that permanently lock up the carbon will accumulate and in some sectors demand could become saturated; in the building sector this will depend on construction rates and materials recycling.

For a given CO₂ utilisation option with an attractive life cycle emissions balance, scalability will be affected by two factors: (1) the potential demand for the product made using CO₂ at a particular production cost; or (2) the potential supply of CO₂, raw materials and energy needed for the given production process.³⁹

³⁹ As an example, hydrogen is often required as an essential input to make products from CO₂. Supplies of industrial hydrogen are today based on fossil fuels but can be produced by electrolysis from renewable electricity and water in order to improve

By way of illustration, EOR projects use large volumes of CO₂ and thus provide an incentive for maximising CO₂ supply. Many chemical uses of CO₂ are smaller, however.⁴⁰ From the processing capacity of typical commercial plants we can convert the carbon content of their inputs to a rough indication of CO₂ equivalence.

- Fine and high added-value chemicals: < 0.01 MtCO₂/yr
- Bulk chemicals (e.g. methanol): 1 to 2.5 MtCO₂/yr
- Basic petrochemicals (e.g. ethylene or polypropylene): 1.5 to 4.5 MtCO₂/yr
- Refineries: 15 to 45 MtCO₂/yr

Meaningful scale is not easy to assess. It will change as the family of CO₂ capture, utilisation and storage technologies matures. For example, at a stage of technology development where these technologies only avoid a combined total of a few million tonnes of CO₂ per year, an additional ten thousand tonnes of CO₂ could be meaningful. In the longer term, the IEA lowest-cost climate change mitigation scenario estimates that at projected CCS costs, CCS could capture and store over 7 GtCO₂/yr by 2050 (IEA, 2013).⁴¹

Conclusion

This discussion has focused on the issues that are relevant for considering what role CO₂ utilisation could play in climate change mitigation. Three criteria have been identified as being of particular relevance.

First, it is imperative to assess the emission reduction benefit. Second, it is important to analyse whether the use in question can generate sufficient revenue to help finance the necessary elements of the value chain and reduce the reliance of investors on the evolution of climate policy instruments (which stymies investment in CCS with geological CO₂ storage). Third, it is important to know whether the use in question is scalable.

Understanding the emissions reductions that arise from different CO₂ utilisation options can often be complex, and not all CO₂ utilisation is equally beneficial from a climate perspective. Approaches to CO₂ utilisation have been considered in a number of publications, for example by the Intergovernmental Panel on Climate Change (IPCC, 2005), the Global CCS Institute (GCCSI, 2011) and most recently the Administrative Centre for China's Agenda 21 (ACCA21, 2013). Current and potential uses of CO₂ in these analyses have yet to satisfy the three main criteria, with the notable exception of certain approaches to CO₂ enhanced oil recovery (CO₂-EOR). This paper intends to provide a consistent framework for the next step for policymakers and others: assessing the potential benefits of utilisation options, as new ideas and proposals arise.

life cycle emissions. However, not only is this method relatively costly at large scales, its availability depends on how much renewably-generated electricity could be directed to hydrogen production under probable electricity market conditions. It has been suggested that hydrogen could be generated at times when renewable electricity generation exceeds demand or time when thermal generation is underutilised. Such a model requires further consideration of issues, including: the economics of operating large capital-intensive electrolyzers on an occasional and variable basis; the synchronisation between hydrogen production at times of high renewable electricity output and CO₂ capture operation at times of high fossil-based electricity output; or the attractiveness of purchasing electricity for hydrogen production from power plants at times when they are uncompetitive on the grid and thus potentially above market prices.

⁴⁰ Non-biomass CO₂ utilised in all polymers and plastics today is in the order of 100 ktCO₂/yr but this could grow (Quadrelli et al., 2011). In total, the global plastics industry today produces products containing an amount of carbon that would equate to 220 MtCO₂/yr (roughly 80% of 280 Mt of plastic) (Rochman et al, 2013). This is equivalent to just 3% of the CO₂ captured in 2050 in the IEA 2DS. Most plastics and polymers produced today are not readily amenable to replacement by CO₂-based polymers due to the oxygen content and absence of hydrogen in CO₂.

⁴¹ The IEA 2DS scenario for meeting an emissions constraint consistent with limiting global average temperature change to +2°C involves the capture and storage of 120 GtCO₂ between 2015 and 2050. This captured CO₂ could be stored non-geologically through utilisation if permanence and cost-effectiveness criteria were satisfied.

Furthermore, most of the utilisation technologies proposed are at a relatively immature stage of development (GCCSI, 2011). Intermediate uses of CO₂ to recover geological resources – such as oil – before storing the CO₂ safely underground are a notable exception. CO₂-EOR, however, may be a limited opportunity regionally and its impacts are dependent on how it is implemented and the fuel it displaces.

The role that CO₂ utilisation could play in the economy will depend on technological developments and incentives in other policy areas, such as competitiveness, innovation and energy (or feedstock) security. These areas may create additional local value for the products of CO₂ utilisation beyond climate benefits (Styring et al., 2011). For its potential contribution to be more than a very small fraction of the potential of CCS, major advances in innovation (“technology push”) and policy support (“market pull”) appear to be necessary. In order to harness potential emissions reductions, this policy support will need to be sensitive to upstream and downstream impacts of CO₂ utilisation in the economy.

If successfully deployed, CO₂ utilisation could lower the costs of climate mitigation and shift some of the costs onto willing consumers who would readily pay for the resulting goods and services. Despite this, the risk remains that pursuit of ideal but immature CO₂ utilisation options could become a distraction from tackling the various critical challenges that face deployment of CCS with geological CO₂ storage, including the need for significant reduction of CO₂ capture and other costs via further R&D and economies of scale.

Annex A: Life-cycle analysis approach

As this chapter illustrates, assessing emissions associated with CO₂ utilisation is more complex than for most CCS value chains that involve geological CO₂ storage without utilisation. This is predominantly for two reasons:

- the products from CO₂ utilisation often do not lock up the CO₂ (for instance a fuel made from CO₂ releases its carbon as CO₂ during end-use); and
- CO₂ utilisation generates products that displace other goods in the economy, sometimes in sectors that are completely unrelated to the CO₂ source.

A life cycle approach is needed to evaluate the impacts of CO₂ utilisation options on emissions. Such an approach accounts for all emissions within the defined boundaries of the assessment; typically both upstream and downstream from the utilisation process, including any emissions associated with end-use.

A simplified illustration is provided below in Figure 5.2. Within this simplified system boundary, two final products are being produced and brought to the market, a primary product and a product from CO₂ utilisation.

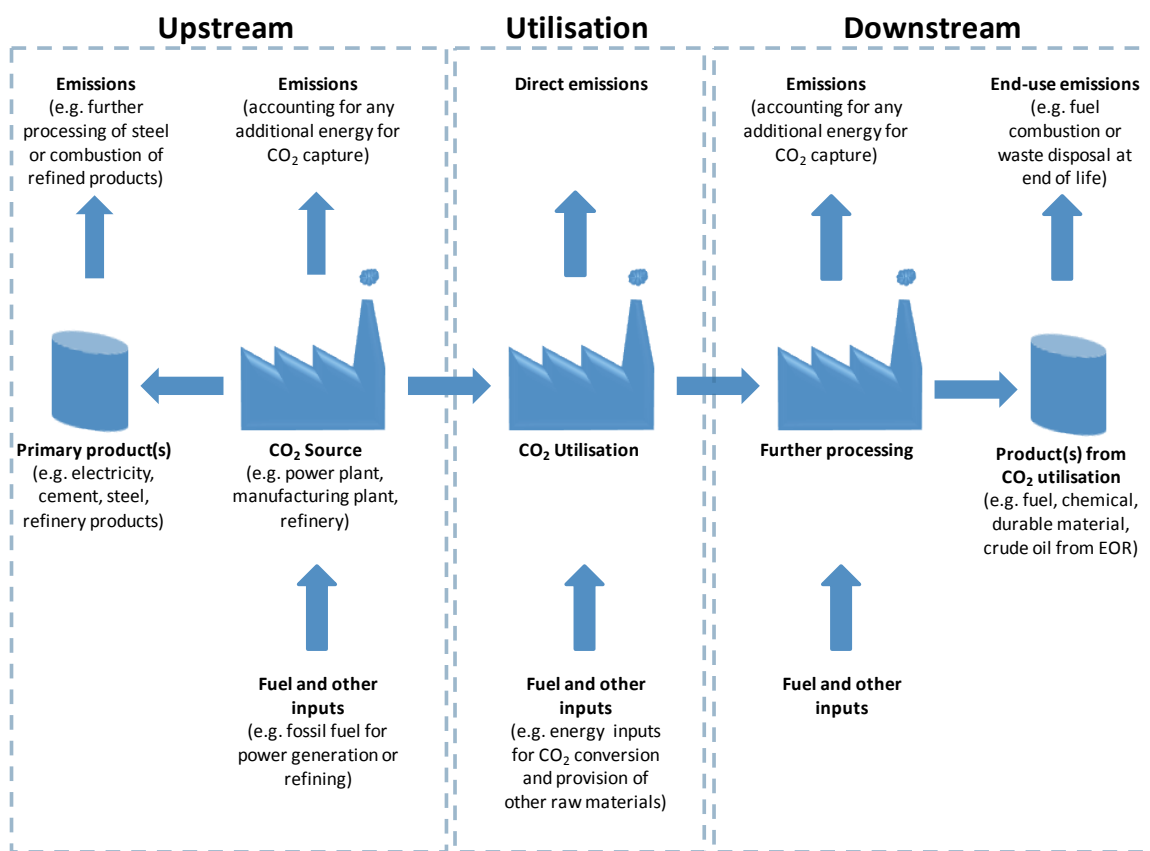
Considering the three elements within the system boundary in turn:

- **Utilisation.** Direct sources of emissions arise from the process of utilising CO₂, including emissions associated with provision of other raw materials such as hydrogen.
- **Upstream.** This includes the source of the CO₂, extending back to the extraction of the fossil carbon (e.g. coal, oil, or natural gas) or even relatively pure CO₂ when extracted from geologic accumulations. The production of the primary product in most relevant cases unavoidably involves the oxidation of carbon to CO₂. Whether the CO₂ is looked at as a waste product or secondary product informs how upstream emissions can be allocated between the primary product and the product from CO₂ utilisation. In the case that the CO₂ is considered to be a waste (as with CCS involving direct geological CO₂ storage) all the upstream emissions might

be allocated to the primary product. If the CO₂ is a valuable by-product to be sold to users, a proportion of the upstream emissions should be allocated to the CO₂ diverted for utilisation. To properly perform such an allocation would require considerable knowledge about the additional energy consumption of any CO₂ capture processes. These allocation issues can be overcome by expanding the system boundary to encompass the entire system. In Figure 5.2, the wider system (including upstream, utilisation and downstream) is one that produces and uses two products, the primary product and the product of CO₂ utilisation. This approach is at the heart of life cycle assessment and is discussed in the next section.

- **Downstream.** These emissions are those associated with transportation and use of the resulting products, which could include: manufacture of consumer goods from CO₂-based plastics; blending and distribution of CO₂-based fuels; or refining of crude oil produced using CO₂-EOR.

Figure 5.2 • Three groups of emissions accounted for in a life cycle approach to CO₂ utilisation



In any example for which the initial source of carbon is fossil-based, the emissions over the life cycle will always be positive, but they may be lower than those associated with provision of equivalent products in the absence of CO₂ utilisation. Comparison with a second “system” is therefore needed if emissions reductions are to be assessed.

Once an assessment of the emissions associated with a CO₂ utilisation option has been undertaken, the emissions reduction can then be calculated as a function of how the service provided by the product of CO₂ utilisation would have been supplied otherwise. A benefit will accrue if an equivalent process or a product with a worse life cycle CO₂ balance is displaced. Emissions reductions can only be estimated in the context of the impacts of CO₂ utilisation in the economy and this involves comparison of two systems.

In the simplified case in Figure 5.2, the life cycle emissions associated with the system that produces and uses the primary product and the product from CO₂ utilisation needs to be compared with an alternative likely system that produces the same two products (or services) without involving CO₂ utilisation.

It is worth noting that these difficult considerations could in theory be overcome by policies, such as economy-wide cap-and-trade systems, that let the market determine which products and services to provide within an acceptable total carbon footprint. In the absence of such a system, which would need to encompass all end-uses, such as vehicle transport, the considerations in this section provide a framework for understanding emissions reductions.

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CCS challenge: Looking ahead

As we state in the introduction to this document, the present is critical for the future of CCS. This publication has highlighted a number of recent and relevant topics that require further attention.

While there remains a need to continue to test, improve and deploy CCS technologies in capture, transport and storage, there is arguably also a need to take a fresh new look at some of the challenges facing CCS. This allows to explore how to potentially reposition and reorient the “product”, to be able to deliver better on its potential. To this end, the IEA is conducting and exploring a variety of other related efforts. To conclude this document, we highlight in the following a number of potential points of interest.

Allocating the costs of CCS

A first issue is who should pay for CCS. Currently, the cost of CCS has been largely targeted at users of fossil fuels, namely the transformation industries in the value chain, such as power companies that use coal or gas to create electricity, or industries that use other fossil fuels to make their products. But, at the same time, their contribution to climate change is similar to that of other users of fossil fuel, including those that use fuels for transport, for residential heating, and elsewhere in the economy. Accordingly, initial exploration should be being given to whether the cost of CCS might be better borne by the fossil fuel producers that extract and sell all the fossil fuels that generate the emissions, as opposed to being limited to a targeted set of transforming industries.

Drilling down on the interplay between fuel and CCS costs

A second issue is better understanding the costs of CCS. Currently, when added to cheap coal, or to gas, CCS represents a costly alternative source of power generation. But what if we could bring down the cost of CCS? A better understanding of the cost of CCS under different fuel and CO₂ price scenarios can help us better understand what the cost challenges facing this technology (ultimately, the climate premium or penalty that is required) are, as well as the circumstances under which CCS can provide a competitive alternative. A better understanding of these relative prices can also shed light on the required cost reductions in CCS (either capital or operating) that could shift the economics in favour of CCS compared to fuel switching.

Generating a ‘CCS supply curve’: hundreds, not millions, of point sources

A third issue is the large-scale nature of CCS leading to “concentration”. Analysing the types of facilities that could potentially use CCS (i.e., by generating a ‘supply curve’ of locations), one will rapidly come to conclude that these industries are large and often concentrated. This means that, in contrast for example to energy efficiency, the number of locations needed to generate the significant reduction in emissions is counted in the hundreds or thousands, but certainly not in millions. Arguably this may have an impact on the best strategy to promote the deployment of CCS.

Better understanding can support more acceptance

A fourth issue concerns the general level of knowledge of CCS by the public. CCS suffers in many ways from a lack of outreach and corresponding understanding. CO₂ surrounds us. It is not toxic (absent extreme levels of concentration), and yet, at the same time, it is often mistakenly equated to methane gas, or fracking, etc. Much remains to be done to inform stakeholders about what CCS involves, how the processes work, what risks are involved, and the opportunities and benefits that CCS can bring.

CCS and oil production: the potential win-win of EOR

A fifth issue concerns the role that CO₂-enhanced oil recovery (CO₂-EOR) can play, not only as a driver for first projects, but as a means to maximise the stored CO₂ in depleting oil fields. There is an increasing level of discussion on CO₂-EOR as a “win-win” technology, enabling countries to produce hydrocarbon resources while respecting climate goals. However, today’s practices are geared towards minimising the volumes of CO₂ used (for cost reasons) while maximising oil production. This paradigm would require significant changes if EOR is used for climate purposes. But a potential win-win situation does exist and it is therefore pertinent to analyse these interactions in more detail. IEA will shortly publish work in this area, quantifying the potential that CO₂-EOR can have in achieving climate goals, identifying barriers to achieving this potential and outlining policy options for the future.

The growing role of ‘negative emissions’: CCS and bio-energy

A final issue is the potential that bio-CCS, often referred to as ‘BECCS’, could hold in the global energy future. By removing atmospheric carbon during the growth of biomass, and then storing the CO₂ emissions resulting from combustion or processing of biomass, BECCS is an approach that may be applied to make deep reductions to emissions from various sources. These include: biomass power generation, combined heat and power plants, co-firing biomass with fossil fuels, flue gas streams from pulp and paper industry, fermentation in ethanol and other biofuel/synfuel production and biogas refining processes, among others. Negative carbon emissions offer a permanent removal of the greenhouse gas carbon dioxide from Earth’s atmosphere. To achieve net reductions through BECCS, it is essential that only biomass that is sustainably produced and harvested is used in a BECCS process.

BECCS projects are already reality, such as the Decatur project in Illinois, USA⁴². Several recent modelling studies indicate that CCS combined with bioenergy is a critical component if greenhouse-gas concentrations are to be stabilised at levels of 450 parts per million or below. In partnership with the International Institute of Applied Systems Analysis (IIASA), the IEA has hosted a series of BECCS workshops, including two with key emerging economies Indonesia and Brazil. Key findings of these activities will be published by IEA.

⁴² In the USA, the world’s first BECCS project is actively injecting CO₂ into the ground from a corn-ethanol production facility in Decatur, Illinois. The project has been operational since November 2011 and is the first 1 million tonne carbon capture and storage project from a biofuel facility in the US. It is scheduled to continue to inject through autumn 2014, after which it will begin post-injection monitoring under the authority of the Midwest Geological Storage Consortium (MGSC), until late 2017.

Acronyms, abbreviations and units of measure

Acronyms, abbreviations and units of measure

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BCA	border carbon adjustment
BECCS	Bio-energy with CCS
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
CCS	carbon capture and storage
CEM	Clean Energy Ministerial
CO ₂	carbon dioxide
COP	Conference of Parties (UNFCCC)
CSC	captage et stockage du carbone
ECRA	European Cement Research Academy
EOR	enhanced oil recovery
FEED	front-end engineering and design
FID	final investment decision
GHG	greenhouse gas
GCCSI	Global CCS Institute
Gt	giga-tonne, billions of tonnes
IEA	International Energy Agency
IIASA	International Institute of Applied Systems Analysis
IPCC	International Panel on Climate Change
Mt	mega-tonne, millions of tonnes
NACAP	North-American Carbon Atlas Partnership
NACSA	North-American Carbon Storage Atlas
OECD	Organisation of Economic Cooperation and Development
R&D	research and development
SAU	storage assessment unit
TASR	technically available storage resource
ULCOS	Ultra-low CO ₂ Steel
US DoE	United States Department of Energy
USGS	United States Geological Survey
WA	Western Australia
WCA	World Coal Association

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