CCS DEPLOYMENT IN THE CONTEXT OF REGIONAL DEVELOPMENTS IN MEETING LONG-TERM CLIMATE CHANGE OBJECTIVES

Report: 2015/TR3
July 2015

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA fosters co-operation amongst its 28 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 40 Implementing Agreements. These agreements cover more than 200 individual items of research, development and demonstration. IEAGHG is one of these Implementing Agreements.

DISCLAIMER

COPYRIGHT

ACKNOWLEDGEMENTS AND CITATIONS

This report describes research sponsored by IEAGHG. The report was prepared by:

- Carbon Counts (UK) Ltd

The principal researchers were:

- Greg Cook
- Paul Zakkour

To ensure the quality and technical integrity of the research undertaken by IEAGHG each study is managed by an appointed IEAGHG manager.

The IEAGHG manager for this report was:
Jasmin Kemper

The report should be cited in literature as follows:

'IEAGHG, "CCS deployment in the context of regional developments in meeting long-term climate change objectives", 2015/TR3, July 2015.'

Further information or copies of the report can be obtained by contacting IEAGHG at:

IEAGHG, Orchard Business Centre,
Pure Offices, Cheltenham Office Park, Hatherley Lane, Cheltenham, GL51 6SH, UK
Tel: +44(0) 1242 802869
E-mail: mail@ieaghg.org
Internet: www.ieaghg.org

IEA Greenhouse Gas R&D Programme

CCS deployment in the context of regional developments in meeting long-term climate change objectives

(IEA/SP/14/03)

FINAL REPORT

Carbon Counts Company (UK) Ltd

25 June 2015

Prepared by:
Gregory Cook and Paul Zakkour
Our Ref: 066

PREFACE

Carbon Counts Company (UK) Ltd ("Carbon Counts") prepared this report under contract to the IEA Greenhouse Gas R&D Programme ("IEAGHG"). The lead authors were Gregory Cook and Paul Zakkour.

The authors would like to thank Jasmin Kemper and Tim Dixon of the IEAGHG for their oversight and inputs during the development of the report.

CONTENTS

FIGURES, TABLES AND BOXES

FIGURES

TABLES

BOXES

ACRONYMS AND ABBREVIATIONS

2006 GLs	2006 IPCC Guidelines for National Greenhouse Gas Inventories
AAU	Assigned Amount Unit (the trading and compliance unit of the Kyoto Protocol, equal to 1 tCO_2e)
AB32	California Global Warming Solutions Act, 2006
ADP	Ad Hoc Working Group on the Durban Platform for Enhanced Action
AM	Approved methodology (for the CDM)
AOSIS	Alliance of Small Island States
bcm	Billion cubic metres
CCS	Carbon dioxide capture and storage
CCS M&Ps	Modalities and procedures for CCS in the CDM
CCUS	Carbon dioxide capture, utilization and storage
CDM	Clean Development Mechanism
CDM M&Ps	Modalities and procedures for the CDM
CER	Certified Emission Reduction (units issued under CDM, equal to 1 tCO_2-equivalent)
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent (based on global warming potentials of non-CO_2 GHGs)
COP	Conference of the Parties
CP	Commitment Period (under the Kyoto Protocol)
CPM	Carbon Pricing Mechanism (Australian policy)
CRF	Common reporting format (for national GHG inventories)
CSLF	Carbon Sequestration Leadership Forum
CTCN	Climate Technology Centre and Network
DECC	Department of Energy and Climate Change (UK)
DRI	Direct reduced iron
ECBM	Enhanced Coal bed Methane
EF	Emissions factor
EOR	Enhanced oil recovery
EPA	US Environmental Protection Agency
EPA	Environmental Protection Agency (US)
ERU	Emission Reduction Unit (trading unit under JI, equal to 1 tCO_2e)
ETS	Emission trading scheme
EU	European Union
EU ETS	European Union GHG Emissions Trading Scheme
EU MRR	EU ETS Monitoring and Reporting Regulation (No. 601/2012)
EUA	European Union Allowance (the trading unit of the EU ETS, equal to 1 tCO_2e)
EUR	Euro (currency)
FVA	Framework for Various Approaches
GCF	Green Climate Fund
GCCSI	Global Carbon Capture and Storage Institute
GEF	Global Environment Facility
GHG	Greenhouse Gas
GPG-LULUCF	Good Practice Guidance for Land Use, Land Use Change and Forestry
G	Giga-
GW	Giga-watt
IEA	International Energy Agency

IEA GHG	IEA Greenhouse Gas R&D Programme Implementing Agreement
IET	International Emissions Trading
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
JI	Joint implementation
lb	Pound (weight)
LCOE	Levelised Cost of Electricity
LDC	Least Developed Countries
LEDS	Low Emissions Development Strategy
M&Ps	Modalities and Procedures
MOP	Meeting of the Parties
MRV	Monitoring, reporting and verification
Mt	Mega-tonne
MW	Mega-watt
MWh	Mega-watt hour
NAMAs	Nationally Appropriate Mitigation Actions
NER	New Entrant Reserve (under the EU ETS)
NER300	300 million EUAs set aside from the NER for sale (to raise revenue to support renewable energy and CCS projects)
NMA	Non-Market Approaches
NMM	New Market Mechanism
PDD	Project design document (under the CDM)
ppm	Parts per million
QELRO	Quantified emission limitation and reduction objectives
R&D	Research and development
REDD	Reducing emissions from deforestation and forest degradation
SBI	Subsidiary Body for Implementation
SBSTA	Subsidiary Body for Scientific and Technological Advice
SNG	Synthetic natural gas
t	Metric tonne
tce	Tonne of coal equivalent
TAP	Technology Action Plan
TEC	Technology Executive Committee
TNA	Technology Needs Assessment
toe	Tonne of oil equivalent
TJ	Tera-joule
TW	Tera-watt
UN	United Nations
UNFCCC	UN Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
US	United States of America
USD	US dollars (currency)

EXECUTIVE SUMMARY

Meeting the long-term goal to limit global temperature rises to 2°C compared to pre-industrial levels requires large-scale deployment of low carbon technologies such as CCS.

According to the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC), without additional efforts to reduce emissions, global mean surface temperatures are likely to increase between 3.7 and 4.8°C by 2100 compared to pre-industrial levels. Scenarios that keep the atmospheric concentration of CO_2 to around 450 ppm by 2100 (66 per cent chance) are consistent with holding a rise in global temperatures to below 2°C – the long-term goal of the United Nations Framework Convention on Climate Change (UNFCCC). Such scenarios involve deep cuts in GHG emissions over the coming decades, requiring radical changes to energy systems and a step-change in the uptake of low carbon technologies.

Carbon capture and storage (CCS) represents a potentially important technology within a portfolio of abatement options available to help achieve the 2°C goal. The technology represents a key mitigation option in most of the emission reduction pathways described by the IPCC – as well as in other scenarios of global GHG mitigation such as the 2DS (2°C Scenario) developed by the International Energy Agency (IEA). Studies also show that both the total investment cost and the cost of emissions reduction are higher for scenarios that exclude CCS from the list of mitigation options. *(Section 1.2).* As alternative mitigation options are deployed over the coming decades, CCS will be increasingly needed to meet climate goals.

Current forecasts assume fossil-based power generation and industrial output from major emitting sectors such as cement, and iron and steel to rise globally, driven by economic growth in emerging economies *(Section 1.2)*. CCS is the only technology available that can achieve deep cuts in carbon dioxide (CO_2) emissions across fossil-fired power generation and many carbon-intensive industries - for example those where there are no realistic alternatives to using fossil fuels, or to producing CO_2 as part of the industrial process. Furthermore, CCS can be deployed with other low carbon technologies to achieve significant emissions reductions, including the potential for achieving so-called 'negative emissions', for example through the use of bioenergy combined with carbon capture and storage (BECCS or Bio-CCS).

CCS projects are technically feasible at scale and have costs that are comparable with other mitigation technologies. A number of industries routinely capture and transport CO_2 worldwide as part of their commercial activities. In North America for example, injection of CO_2 into geological formations has successfully taken place over several decades, principally for the purposes of enhanced oil recovery (EOR). CCS involves integrating the separate components of the CCS chain (capture; transport; storage) into projects deployed at scale to move beyond the technical demonstration phase. There are currently 22 large-scale CCS projects in operation worldwide, capturing up to 40 million tonnes of CO_2 per year across a range of sectors *(Section 1.3)*.

CCS presents an opportunity for many countries worldwide to reduce GHG emissions. A portfolio of technologies is available for CCS deployment depending on GHG sources and the availability of suitable geological storage sites.

CCS is not a 'one-size-fits-all' technology. Its relative importance within a country's available portfolio of climate actions will vary according to *national circumstances.* For some countries, the technology may play an integral part of their mitigation strategies, whereas for others different priorities may exist.

The evidence shows that there are significant drivers for undertaking CCS across all world regions *(Section 2)*. For many countries, the technology allows for deep cuts in national GHG emissions within the context of continued economic growth and use of fossil fuels. This applies in particular to those emerging economies whose patterns of energy use within power generation and industry are based on fossil-fuel resources, most notably coal *(Section 2.3)*. CCS technology can be applied to a wide range of sectors and sources – which also reflect national circumstances *(Section 2.4)*. For some countries, the focus will be on coal-fired power generation or carbon intensive sectors with large point sources such as cement kilns and iron and steel facilities. For others, specific options may exist in 'high purity' sectors, which already undertake the capture stage as part of project operations - such as natural gas processing and hydrogen production. Existing studies also suggest that there is sufficient storage capacity to deploy CCS on the scale needed to meet the long-term goals of the UNFCCC *(Section 2.5)*, although further work is necessary to characterise potential storage sites and to match them with suitable sources.

IEA analysis indicates that, in order to address the emissions reduction challenge, the total CO_2 capture and storage rate must grow from the tens of millions of tonnes of CO_2 currently captured worldwide to billions of tonnes of CO_2 in 2050 *(Section 2.6)*. A total cumulative mass of approximately 120 $GtCO_2$ needs to be captured and stored between 2015 and 2050, across all world regions. Deployment will take place over several decades, with differential rates of uptake across regions and countries according to their circumstances. The IEA estimates global CCS deployment potential of over 2 $GtCO_2$/yr in 2030, increasing to over 7 $GtCO_2$/yr in 2050 (of which around half of which would take place in the power sector and half in industry). Nevertheless, the scale of the challenge will be enormous. The additional investment associated with the capture stage alone is estimated at almost USD 1.3 trillion through 2050.

CCS deployment faces a broad spectrum of barriers. Some are technical, some are economic, some are institutional and regulatory, and some concern the cost effectiveness of the technology compared to alternative mitigation options.

In comparison with the progress of other GHG technologies, current uptake of CCS is far behind the levels envisaged by scenarios of global emission reduction pathways. Despite ongoing progress with technology demonstration, there are only a few large-scale projects operating worldwide and there have been a large number of project delays and cancellations (*Section 1.3*). The current pace of development must grow rapidly if CCS is to fulfil its potential.

CCS continues to face a number of challenges which will need to be overcome to achieve large-scale deployment in both developed and developing countries. These include:

- **Legal and regulatory barriers:** Many countries lack the frameworks for undertaking CCS. Suitable laws and regulations are essential to ensure safe and effective capture, transport and storage of CO_2 and to provide investors with the security for CCS deployment *(Section 3.2.1)*.

- **Policy barriers:** CCS may be overlooked within national policy priorities. It requires policy-makers to implement ambitious and well-designed support policies to encourage private sector investment and incentivise large-scale projects across a range of sectors *(Section 3.2.2)*.
- **Economic and financial barriers:** Combining CCS with industrial and power generation projects entails additional costs to project developers and consumers. Abatement costs may also be lower for other national mitigation options; so incentives are necessary to overcome investment risks and help make projects economically viable *(Section 3.2.3)*.
- **Technical barriers:** The integration of each CCS project component - capture, transport and storage - at scale gives rise to a number of potential technical and operational challenges that need to be addressed *(Section 3.2.4)*.
- **Institutional and public acceptance barriers:** Building in-country capacity within national organisations and departments and addressing societal concerns are essential for ensuring effective project deployment and gaining acceptance of CCS technology *(Section 3.2.5)***.**

Large-scale CCS deployment involves the development of a pathway establishing the necessary framework of actions and policies to incentivise projects and programmes. Countries and regions are at different stages along this pathway.

CCS faces a range of needs to ensure effective technology demonstration, investment in commercial scale projects, and safe and effective project deployment with robust regulatory oversight. Large-scale CCS deployment involves the development of a step-by-step pathway establishing the necessary framework - to overcome barriers and incentivise projects and programmes *(Section 3.3)*. This includes the following key elements:

1. **Scoping and agenda-setting:** Establishing technical potential; assessing and recognising the role of CCS within national circumstances and policy areas; identifying stakeholders and raising awareness; and developing action plans/strategies for support and deployment
2. **Strengthening institutional arrangements and legal and regulatory frameworks:** Reviewing and assessing existing institutional capacity; strengthening institutional arrangements and capacity for regulation and oversight of projects; assessing existing legal and regulatory frameworks for CCS development; and developing an enabling framework for safe and effective CCS deployment
3. **Design and implementation of effective and multifaceted policy portfolios.** Providing R&D funding and programmes to support research for early-stage projects and experimental development; supporting demonstration to show the viability of integrated CCS; developing economic and financial instruments and/or regulatory support instruments to incentivise deployment over the longer-term

The ultimate aim of such a framework is to achieve scaled-up deployment. This will require major investment from public and private sources, both for up-front project costs and ongoing costs. Investors will need the confidence that only long-term, stable and enabling frameworks can provide. Creating a market for CCS through carbon pricing and other types of policy will help wider deployment. Experiences from countries and regions worldwide leading the way in CCS development however (e.g. Norway, the USA, Canada, the EU and Australia) show that this can be a slow process.

Worldwide, different countries are at various stages along this pathway, and are therefore at varying levels of "CCS-readiness" *(Section 3.3.5; Figure 3.8)*. Some countries have begun to put in place the regulatory frameworks and policy incentives needed, whereas for others CCS remains at the scoping or assessment stage. Although several developed countries have designed far-ranging policy programs for CCS, economic and financial measures have so far proved insufficient to incentivise widespread deployment, and the use of targeted regulatory instruments is currently very limited. Many developing countries are making progress, at present mainly in scoping and capacity-building exercises supported by multilateral and bilateral funds, although several countries (e.g. Algeria, the UAE) have successfully delivered large-scale CCS projects.

Wide-spread CCS deployment will take place over several decades, and for many countries, costs present a major challenge. However, countries and regions can at this stage take specific actions along the CCS development pathway. For example, developing the regulatory and policy environment – potentially with the help of international support – may entail relatively little cost. Therefore even with the current cost of CCS, countries can take realistic steps which are essential to be ready for deployment over coming years. However, for all countries where the technology is nationally relevant, there is a real need to place CCS on the domestic policy agenda. As yet, the potential of CCS is not recognised within the energy strategies of many countries, which may, for example, be developing small-scale renewables whilst also embarking upon unabated coal-fired power generation. Despite the drivers which may be present for supporting CCS, there may be a disconnect between national climate and energy goals.

The new climate agreement being negotiated under the UNFCCC could help facilitate CCS as a mitigation option. Mechanisms within the emerging framework could support technology development in both developing and developed countries and help mobilise climate finance into projects and programs. Into this 'top-down' framework, INDCs provide the 'bottom-up' opportunity for countries to establish CCS firmly within national GHG efforts and a new international climate agreement.

Intended Nationally Determined Contributions (INDCs) submitted by Parties will collectively determine global efforts to reduce emissions under a new post-2020 agreement. The ambition of the commitments will in turn provide the demand for deploying step-change mitigation technologies including CCS to help meet them. Regions and countries worldwide are at different stages with respect to a pathway of CCS support and deployment: the focus of CCS within INDCs should therefore identify suitably ambitious and practical steps to move beyond the current stage of the pathway. For some countries at early stages along the CCS pathway, this may involve *action-based commitments* to develop an enabling regulatory and policy environment;

whereas for others at a more advanced stage, specific *outcome-based targets* may be more appropriate. For both developed and developing countries, national efforts can be assisted at the international level. The UNFCCC framework can help support CCS through the following routes:

- Providing the overall **mitigation** policy framework for CCS development and deployment
- Mobilising **finance** into CCS projects and programmes
- Addressing **technology** needs and helping to build capacity

Mechanisms are available within the evolving UNFCCC framework to help greater CCS support deployment *(Section 4)*. Modalities and procedures (M&Ps) exist for undertaking CCS projects which provide the basis for the legal and regulatory components needed to host projects under UNFCCC mechanisms. In addition, the IPCC GHG Reporting Guidelines provide a robust basis for monitoring, reporting and verification (MRV) of CCS. The UNFCCC also provide channels for mobilising climate finance into CCS support, including the Green Climate Fund (GCF) and the potential for scaled-up project development under a New Market Mechanism (NMM), a reformed Clean Development Mechanism (CDM) and potentially via the use of Nationally Appropriate Mitigation Actions (NAMAs). The potential use of bilateral crediting and other approaches accommodated under the Framework for Various Approaches (FVA) offers the potential for developed and developing countries to work together and share the benefits of CCS deployment. Furthermore, the Technology Mechanism offers the potential to provide technical and capacity support for CCS projects and activities, and to highlight its importance as a low carbon technology within the UNFCCC. Although there are ongoing uncertainties and challenges, not least regarding the future form and scale of market-based support for projects, CCS can be supported within the UNFCCC process. It is also potentially well-suited to the types of mechanisms currently envisaged under a new agreement.

There is more to be done to help support CCS at the international level, both in terms of providing the required levels of funding to achieve scaled-up deployment and also in the details of how the technology can be accommodated within the UNFCCC's specific funds and mechanisms. An international partnership for CCS could be instrumental in driving this process forward and raising awareness of the technology. However, these provide an enabling 'top-down' framework only. Progress with CCS on the scale required to meet the 2°C goal will also require a concerted 'bottom-up' effort by Parties in recognising its role as a key mitigation option within their INDCs. When compared to other mitigation options and technologies, and despite its appropriateness to many countries, national climate plans do not always adequately recognise the potential of CCS, as reflected for example in the submission of NAMAs to date. As of the end of 16 June 2015, only four Parties (Norway, the EU, Mexico and Canada) had made specific reference to CCS within their submissions. Parties should therefore seek to make CCS central to their INDCs. Parties can propose a wide range of actions and measures to help promote CCS according to their national circumstances and current stage of "CCS readiness" *(Section 4.2)*. In doing so, INDCs could become more ambitious and help move the international effort further along the low carbon pathway needed to meet the long-term goals of the UNFCCC.

1 INTRODUCTION

1.1 The UNFCCC and meeting the 2°C goal

Global anthropogenic greenhouse gas (GHG) emissions reached 49 $GtCO_2$ equivalent (CO_2eq) per year in 2010, of which CO_2 emissions from fossil fuel combustion accounted for 32 $GtCO_2$, or 65% of the total (IPCC, 2014). Almost all credible international forecasts indicate that fossil fuel use will increase by the mid-century to meet growing demand for power generation, transport, heating and industrial production. Without additional efforts to decouple GHG emissions from energy use, emissions levels will continue to grow.

According to the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC), without additional efforts to reduce emissions, global mean surface temperatures are expected to increase between 3.7 and 4.8 degrees Celsius (°C) by 2100 compared to pre-industrial levels (IPCC, 2014).[1] Scenarios in which the atmospheric concentration of CO_2 are kept to around 450 ppm by 2100 are consistent with holding a rise in global temperatures to below 2°C. Such scenarios involve deep cuts in GHG emissions to be made over the coming decades, requiring radical changes to energy systems and a step-change in the uptake of low carbon technology.

The United Nations Framework Convention on Climate Change (UNFCCC) is the principal international legal instrument to address climate change. The treaty's central objective is to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system".[2] At the 16th Session of the Conference of the Parties[3] (COP16), held in Cancun in 2010, the Parties to the UNFCCC recognised the need to limit the increase in global average temperature to below 2°C.[4] In support of the Cancun Agreements, more than 90 Parties made pledges to reduce or limit the growth in their GHG emissions by 2020. Developed countries put forward quantified economy-wide reduction targets and commitments.[5,6] Developing countries subsequently pledged to adopt so-called Nationally Appropriate Mitigation Actions (NAMAs) which recognise the need for emission reductions within a framework of sustained economic growth.[7,8]

Building on the Cancun Agreements, at the 17th Session of the Conference of the Parties (COP17), the Ad Hoc Working Group on the Durban Platform for Enhanced Action (ADP) was established with the mandate of developing a "protocol, another legal instrument or an agreed outcome with legal force under the Convention applicable to all Parties" no later than 2015 and entering

[1] Median values; the range is 2.5°C to 7.8°C when including climate change uncertainty
[2] Article 2
[3] The Conference of Parties is the supreme body of the UNFCCC responsible for deciding policy.
[4] The 2010 'Cancún agreements' state that future global warming should be limited to below 2.0 °C (3.6 °F) relative to the pre-industrial level
[5] FCCC/SB/2011/INF.1/Rev.1.
[6] Decision 1/CMP.8, Annex I.
[7] FCCC/SBI/2013/INF.12/Rev.2.
[8] FCCC/TP/2013/8.

into force in 2020.[9] Such an agreement will be sought at the COP21 to be held in Paris in December 2015.

The consideration of national priorities and circumstances is a central pillar of the UNFCCC. Article 4 of the Convention, in outlining Party commitments, recognises both that Parties have “common but differentiated responsibilities”, and that “specific national.... circumstances” should be taken into account. These considerations are central to the ongoing discussions leading into the COP21. Ahead of COP21, Parties are required to put forward so-called ‘Intended Nationally Determined Contributions’ (INDCs) towards meeting the 2°C goal (Box 1.1). National circumstances will be integral to the development of INDCs.

Box 1.1 The contribution of INDCs to an international climate change agreement

At the 19th session of the Conference of the Parties (COP 19), held in Warsaw in 2013, Parties agreed to a decision to “invite all Parties to initiate or intensify preparation of their intended nationally determined contributions”, as a key input to the preparation processes of negotiations leading towards the Paris 2015 climate agreement at COP 21.[10] The Intended Nationally Determined Contributions (INDCs) put forward by Parties through 2015 will indicate each country’s plans to address climate change and will collectively provide the basis of global mitigation efforts towards meeting the Convention’s 2°C goal.

The outcome of the COP20, the *Lima Call for Climate Action*, provides the framework for the negotiations through 2015. The text specifies that “each Party’s intended nationally determined contribution [...] will represent a progression beyond the current undertaking of that Party”[11], indicating that the ambition of the INDCs should go beyond current targets and/or reference development. The text does not however provide guidance on the level of ambition per country. In order to assess the submitted INDCs and to aggregate the global effect, the *Lima Call for Climate Action* asks for the following information to be submitted alongside INDCs, where appropriate:[12]

- Quantifiable information on the reference point (including, as appropriate, a base year)
- Time frames for implementation (e.g. target year(s) or period)
- Scope and coverage of mitigation plans (e.g. sectors and GHGs)
- Assumptions and methodology, including those for estimating and accounting for GHGs
- Information on how the INDC is fair and ambitious, given the countries’ national circumstances.
- Explanation of how the INDC contributes to the objective of the Convention
- Information on the planning processes (e.g. how the INDC was determined and how it will be implemented)

The text reiterates that the new agreement should reflect the principle of “common but differentiated responsibilities and respective capabilities, in light of different national circumstances”. Parties are invited to communicate their INDCs to the UNFCCC Secretariat well in advance of COP 21 (by the end of March 2015 – for those Parties “ready to do so”). The Secretariat will then prepare by 1 November 2015 a synthesis report on the aggregate effect of those INDCs communicated by 1 October 2015. As of 16 June, 2015, twelve Parties had submitted INDCs to the UNFCCC Secretariat.

As well as the development of INDCs which will form the basis of international mitigation efforts under a Paris 2015 agreement, the UNFCCC ‘mechanisms’ which provide an important source of financing and support for clean technology, are subject to ongoing discussion. These include the

[9] Decision 1/CP.17
[10] Decision 1/CP.19
[11] Paragraph 10
[12] Paragraph 14

Technology Mechanism (TM) and Green Climate Fund (GCF) as well as the potential evolution of future market-based mechanisms such as a reformed Clean Development Mechanism (CDM) a New Market Mechanism (NMM) and the recognition of different approaches taken by Parties worldwide, such as e.g. the use of bilateral crediting, under a common Framework for Various Approaches (FVA).

1.2 CCS as a key mitigation option

While significant, the pledges put forward so far by countries to reduce or limit their emissions will not be sufficient to meet the Convention's 2°C goal. In its *Emissions Gap Report 2014*, the United Nations Environment Programme (UNEP) estimated the size of that gap to be between 8 and 10 $GtCO_2eq$ by 2020, growing to around 14-17 $GtCO_2eq$ by 2030 (UNEP, 2014). The report also noted that while global GHG emissions will need to peak soon to stay within the 2°C limit, they are continuing to rise. UNEP further noted that, moving closer to 2020, it is becoming increasingly difficult to fully use the available GHG mitigation potential and narrow the gap. In this context, the need for decisive and urgent action to close the pre-2020 ambition gap is universally recognized by Parties.[13] The level of ambition needed by the INDCs put forward in the run up to an agreement will pose significant challenges and require a wide range of mitigation responses, reflecting national circumstances.

Carbon capture and storage (CCS) represents a potentially important technology within a portfolio of abatement options available for achieving the 2°C goal. The technology represents a key mitigation option in most of the emission reduction pathways described in the IPCC's *Fifth Assessment Report* (IPCC, 2014) as well as the most recent scenario prepared by the International Energy Agency (IEA). In the latter scenario, known as 2DS (which aims for an 80% probability of limiting the average global temperature increase to 2°C; IEA, 2014a) and published in the IEA's *Energy Technology Perspectives 2014*, CCS contributes 14% of the cumulative emissions reductions needed through 2050 (Box 1.2). The IEA estimates global deployment of CCS capable of capturing and storing over 2 $GtCO_2$/yr in 2030, increasing to over 7 $GtCO_2$ in 2050 – around half of which would take place in the power sector and half in industry. Although the deployment rates vary over time and across sectors, the analysis shows a significant contribution from all world regions over the coming decades (IEA, 2009; 2013).

Studies show that both the total investment cost and the cost of emissions reduction are higher for various scenarios when CCS is excluded from the list of mitigation options (Global Energy Assessment (GEA), 2012); IEA, 2012a, 2014). The IPCC's *Fifth Assessment Report* estimates that without CCS the cost of climate mitigation by 2100 would increase by between 29% and 297%), while the IEA estimates that without investment in CCS, total mitigation costs in the power sector alone would increase by USD 2 trillion by 2050 (IEA, 2012a). Costs of CCS projects differ significantly by project type, location and application: costs in the power and industry sectors range from around USD 30/tCO_2 to USD 150/tCO_2 avoided (IIASA, 2012; IPCC, 2014). However, low-cost opportunities exist in some niche cases in those industry sectors where purer streams of CO_2 can be captured at relatively low cost.[14]

[13] FCCC/TP/2013/8.

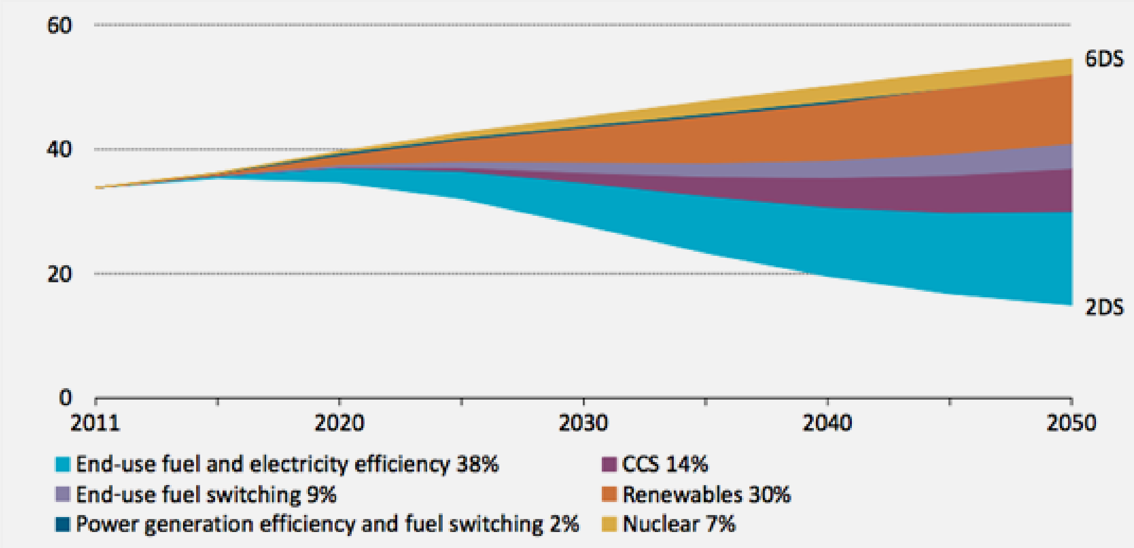
[14] FCCC/TP/2014/13; see for example Zakkour and Cook, 2010.

Box 1.2 CCS deployment under the International Energy Agency's 2DS scenario

The International Energy Agency's (IEA) latest *Energy Technology Perspectives 2014* (ETP 2014) assesses the outlook for global energy over the next 35 years. EPT 2014 analyses three possible energy futures to 2050:

- **6°C Scenario (6DS),** where the world is now heading with potentially devastating results
- **4°C Scenario (4DS)** reflects stated intentions, including pledges, by countries to cut emissions and boost energy efficiency
- **2°C Scenario (2DS)** offers a vision of a sustainable energy system of reduced greenhouse gas and carbon dioxide (CO_2) emissions, consistent with meeting global agreements to limit temperature increases to 2°C

Under 6DS, global energy demand is projected to grow by 70% compared to 2011 levels; associated emissions are projected to grow by more than 60%, resulting in total emissions in 2050 of 55 $GtCO_2$ (see below). According to the same projections for population and economic growth through 2050, radical climate policy action and deployment of low carbon energy technology under 2DS results in global emissions cuts of more than 50% - resulting in total emissions of around 15 $GtCO_2$ in 2050. Energy efficiency accounts for 38% of cumulative emissions reductions needed to move from 6DS to the 2DS; renewables account for 30%, and CCS accounts for 14% with fuel-switching and nuclear making up the difference. The IEA estimates that USD 44 trillion in additional investment is required to decarbonise the energy system in line with 2DS by 2050.



Fossil fuel use decreases by 2050 in the 2DS, but its share of primary energy supply remains above 40%, reflecting its important role for use in industry, transport and electricity generation. ETP2014 indicates that CCS will be vital in reducing emissions from continued use of these fuels in both the electricity generation and industry sectors. Fossil fuel power plants will increasingly need to be equipped with CCS, not only for coal (growth in coal-fired generation since 2010 has been greater than that of all non-fossil sources combined, continuing a 20-year trend) but also for base-load natural gas plants which will also require CCS to meet 2DS targets by 2050.

Between 6DS and 2DS, CCS is required to contribute annual emission reductions within industry and electricity generation of around 7$GtCO_2$ by 2050 - several orders of magnitude above current levels. However, the IEA finds that, contrary to the significant progress made with renewable energy deployment over recent years, CCS remains far from where it needs to be, citing high costs and lack of political and financial commitment as the key factors for the technology's slow development. ETP2014 concludes that near-term progress in CCS research, development and demonstration is necessary to ensure long-term and cost-competitive deployment towards meeting climate goals.

Source: IEA, 2014a

CCS deployment also allows for the delivery of a broad range of low-carbon energy options, which allows Parties to maintain a diversity of energy supply (UNFCCC, 2014). Despite climate concerns, power generation from coal is expanding faster than ever: capacity additions reached record growth of more than 350 GW over the last five years. (IEA, 2012a) For those countries that are heavily reliant upon continued use of fossil fuels for economic growth, particularly the use of coal in power generation in emerging economies such as China and India, CCS represents a means of ensuring continued growth and energy security whilst enabling deep cuts in domestic emissions. Furthermore, when combined with the use of CO_2 for enhanced hydrocarbon recovery (EHR), CCS technology offers those countries whose economies are based on oil and gas production a viable option for contributing to global mitigation efforts.

Another reason that CCS is important within mitigation efforts is that, for some industrial applications, there are no realistic alternatives to using fossil fuels or to producing CO_2 as part of the industrial process – the use of CCS is necessary in order to reduce CO_2 emissions from such applications and processes (e.g. iron and steel, cement, refining and fertiliser production). With increasing deployment of renewable energy sources such as wind and solar under an emissions constrained pathway, CCS also allows for valuable base-load low-carbon power generation. Additional flexibility is also possible through the simultaneous capture of CO_2 with hydrogen production from coal or natural gas. The hydrogen produced can be used directly in power generation (or chemicals production) or stored for flexible power generation in gas turbines, gas engines or fuel cells (*ibid*). Furthermore, CCS can be deployed with other low-carbon technologies to achieve significant emissions reductions, including the potential for so-called 'negative emissions'. For example, the use of bioenergy combined with carbon capture and storage (BECCS or Bio-CCS) offers the opportunity of removing CO_2 emissions from the atmosphere on a net basis (IEA, 2009, 2011; IEAGHG, 2014; IPCC, 2014).

1.3 Progress to date

Despite its potential, the uptake of CCS remains significantly behind other low carbon technologies. The IEA's latest *Energy Technology Perspectives 2014* contains a 'report card' on the status of global technology efforts to meet long-term climate change targets. Their analysis indicates that only renewable power alone, among all clean energy technologies, is on track to meet the 2DS targets; CCS is among a raft of technologies considered far behind what is currently needed.

The latest version of the Global Carbon Capture and Storage Institute's (GCCSI) *Global Status of CCS 2014* publication indicates that there are currently 55 large-scale CCS projects in different stages of development worldwide. These include 22 'active' CCS projects, of which 13 are operational and 9 are under construction. The total CO_2 capture capacity of these 22 projects combined is around 40 million tonnes per year (GCCSI, 2014a). The majority of these are located in North America, where most projects involve the commercial use of CO_2 for enhanced oil recovery (EOR). There is at present only one operational power project (SaskPower's Boundary Dam coal-fired power station located in Saskatchewan, Canada). While progress is being made in demonstrating elements of capture, transport and storage, the current pace of development must grow rapidly if CCS is to fulfil its potential: the rate of capture and storage must increase by two orders of magnitude in the next decade to achieve 2DS targets.

A number of jurisdictions worldwide have introduced wide-ranging R&D programmes, policy support and financial incentives for CCS, and there is ongoing progress in the development of the legal and regulatory frameworks needed to ensure the safe and permanent storage of CO_2 in the sub-surface. Furthermore, at the UNFCCC level, the role of CCS as a clean technology has been recognised through the agreement of Modalities and Procedures (M&Ps) for undertaking CCS projects under the CDM[15]; effectively establishing a set of rules by which CCS projects undertaken in developing countries can earn emissions reduction credits (see Section 4).

1.4 Report aims and structure

This study aims to characterise key countries and regions worldwide where CCS could play an important part of mitigation efforts, based on national circumstances and priorities.[16] Given the need to reach an international climate agreement based upon national circumstances, the study provides a basis for understanding the relevance of CCS within this process, especially with respect to INDCs.

Policy makers will need to take a range of ambitious actions to overcome the various barriers and challenges to deploying CCS on the scale and timeline required to meet the 2°C goal. The study therefore also looks at how barriers can be addressed and needs met, and aims to characterise key countries and regions' current progress against a framework of key indicators (policies and actions) for CCS support and deployment.

Support for CCS will be required at the international as well as the regional, national and local level. The policy architecture under the UNFCCC is under discussion, including issues around support for low-carbon technology, funding and the use of market-based instruments. Mechanisms under the UNFCCC could provide an important source of financing and technical learning to support uptake of CCS, for both developed and developing countries. The study therefore also aims to identify how CCS can be supported through the international framework.

The issues described above set the backdrop for the analysis described in this report, which is structured as follows:

- **Section 2** describes the drivers for CCS as a mitigation option in the context of national circumstances, including an assessment of where the technology can play a key role within the climate policy objectives of regions and countries worldwide;
- **Section 3** considers the barriers facing CCS deployment, and draws upon best practises and experiences to date to describe a framework of policies and actions for government level CCS support and deployment, including an assessment of the current progress made by different regions and countries worldwide;
- **Section 4** sets out a range of options and recommendations on how CCS could be incorporated and promoted at the international level within the framework of the UNFCCC in support of meeting long-term climate change objectives.

[15] UNFCCC (2011) *Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities*. Decision 10/CMP.7
[16] FCCC/TP/2014/13

2 CCS WITHIN NATIONAL CIRCUMSTANCES

2.1 Introduction

CCS has a significant role to play in the future of climate change mitigation. However, its relative importance within a country's available portfolio of climate actions will vary; for some countries, CCS may play an integral part of their mitigation strategies, whereas for others different priorities may exist. The 195 plus the EU (196) Parties to the UNFCCC vary across a wide range of factors relating to patterns of energy use, national resources, CO_2 emissions, and policy objectives. Such factors have a bearing on the potential interest of countries in CCS deployment as a suitable national climate change mitigation technology.

This chapter assesses the potential for CCS deployment within the context of those national priorities and circumstances. Drawing upon a large evidence base, a number of national drivers for undertaking CCS are described, and an assessment made of how these apply across key regions and countries worldwide.

2.2 Drivers for CCS at a national level

Factors indicating that CCS could be relevant to national circumstances and priorities include the following:

- The ability to reduce CO_2 emissions from industry and power generation as part of national climate policy plans/strategies (e.g. within INDCs under a UNFCCC agreement);
- Continued and emerging use of fossil fuels in a carbon-constrained economy;
- Continued and emerging use of indigenous energy resources, especially coal;
- Opportunities as part of upstream energy activities (natural gas production including contaminated gas; tertiary oil production using EOR; enhanced coal-bed methane);
- Alignment with R&D objectives and technology development

National circumstances which suggest countries could be in a position to take advantage of these factors form a set of potential drivers for supporting and developing CCS within their emissions mitigation efforts. These include:

- Large economic dependence on fossil fuels (energy production, energy exports, industry and power sector reliance on fossil fuels), particularly on coal;
- Energy security (ability to use indigenous resources, especially coal; ability to prolong oil and gas assets; potential for CO_2-EHR with storage);
- High national CO_2 emissions, CO_2 intensity of economy, projected CO_2 increases;
- Sufficient storage potential (access to suitable storage site(s), including mature oil & gas producing provinces);
- High capture potential (CO_2 sources viable for CCS projects and/or suitable to capture technologies);
- Availability of adequate in-country capacity and technology capabilities (capture technology development, storage development technology and know-how; expertise in sub-surface aspects)

The remainder of this section presents a comparative assessment of these factors across key regions and countries worldwide.

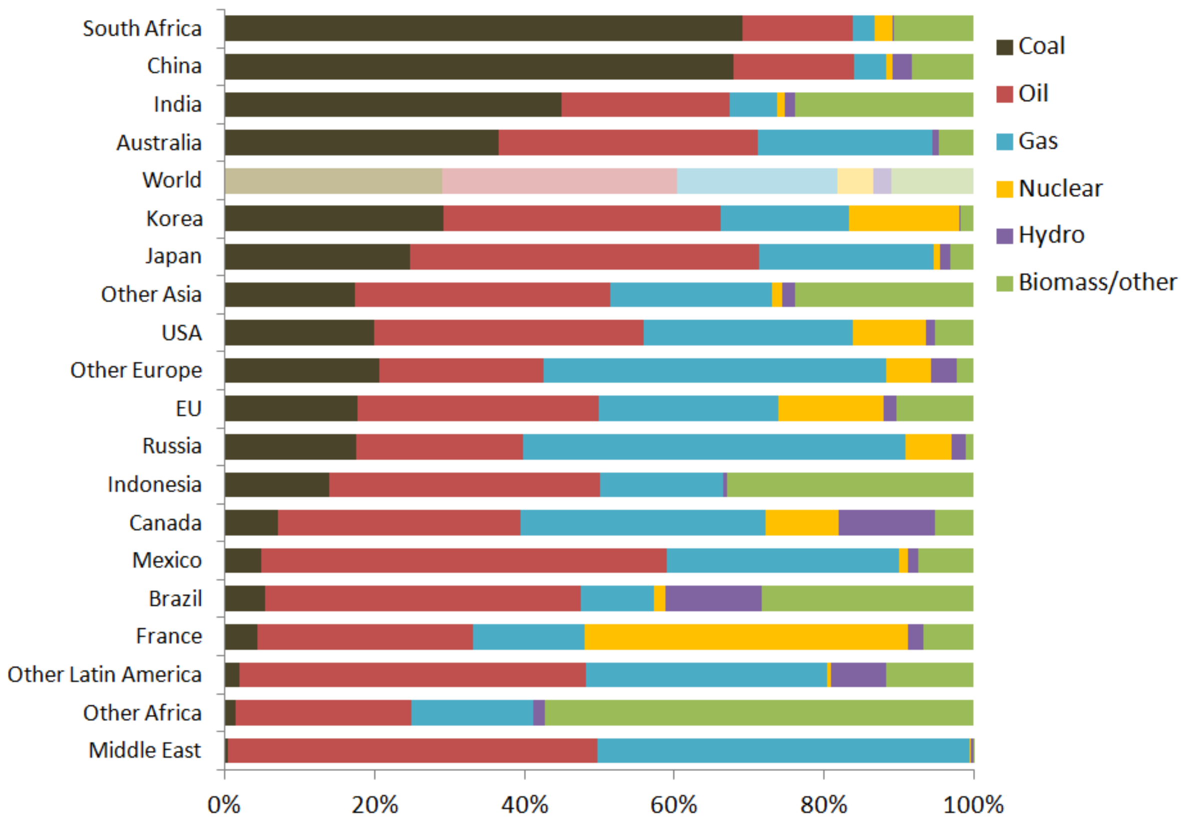
2.3 Energy and CO_2 emissions

2.3.1 National energy supply and fossil fuels

Among the many human activities that produce greenhouse gases the use of energy represents by far the largest source of emissions, accounting for almost 70% of global anthropogenic GHG emissions in 2010 (IEA, 2014c). CO_2 resulting from the combustion of fossil fuels accounts for some 90% of these energy sector emissions, and growing demand for fossil-based energy plays a key role in the upward trend in global emissions.

Figure 2.1 illustrates how energy supply varies by fuel type across different regions and countries, indicating the relative importance of different energy sources to national economies. It can be seen that China, India, and South Africa are highly reliant on coal for their energy supply, whereas the economies of the Middle East and some African and Latin American countries are heavily dependent upon oil and natural gas. While fossil fuels dominate global energy supply and use, and those of most regions worldwide, energy from nuclear and renewables represents a significant share of energy supply in many countries worldwide (e.g. France, Brazil). Energy from biomass remains important in some countries, notably the least developed economies of Asia and Africa; some countries in these regions are almost wholly reliant on biomass for their domestic energy supply (e.g. cooking stoves) giving rise to health and local pollution issues.

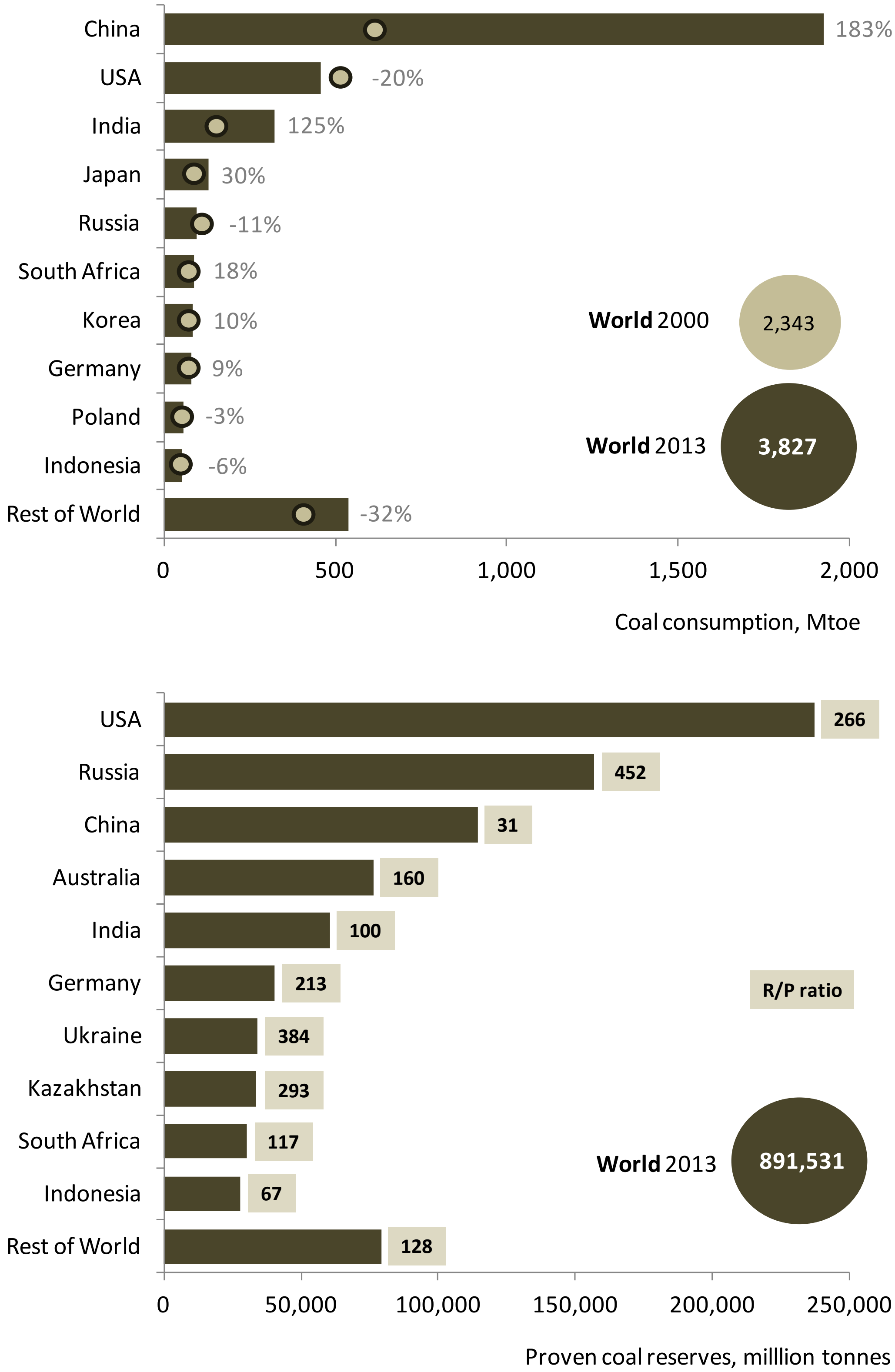
Figure 2.1 Total primary energy supply by country/region in 2012



Note: Coal includes peat and peat products; oil includes crude, NGL, feedstocks, oil products, oil shale and oil sands; biomass/other includes biofuels and waste, geothermal, solar and wind
Data source: IEA, 2014d

With the exception of some countries that are heavily reliant on energy imports (for example, Korea, Japan and many smaller countries with no energy resources), national energy use largely reflects the availability of domestic resources. Figure 2.2 shows the world's top ten countries according to coal consumption and resources. The largest three consumers, China, India and the USA, accounted for 70% of total world coal consumption in 2013; the same countries accounted for around two thirds (66%) of proven coal reserves in the same year. The graphs also illustrate the rapid change in coal consumption seen across world regions over the past decade. Global coal consumption increased 63% between 2000 and 2013, a growth rate driven largely by an increasing demand from just one country, China, followed by India and several other developing Asian economies. Growth in coal consumption has been much lower across other world regions, with some countries such as the USA and Russia seeing modest decreases over recent years. The ratios of proven coal reserves to production demonstrate that while some countries such as Russia, the USA and Australia have sufficient resources to meet domestic demand and/or exports over the coming decades, others face the challenge of securing adequate supplies to meet their rising demand - most notably China which has introduced wide-ranging plans to reduce national coal consumption and diversify its energy supply (Box 2.1).

Figure 2.2 World top ten countries by coal consumption and proven reserves, 2013



Note: Percentages indicate relative increase between 2000 and 2012; R/P = reserves to production ratio in 2013
Data source: BP, 2014; WEC, 2013

Box 2.1 China's Energy Development Strategy Action Plan (2014-2020)

China is the world's largest producer and consumer of coal, accounting for around one-half of all global consumption. It overtook the USA as the world's largest energy consumer in 2010 because of high coal consumption.

The State Council of China unveiled a new Energy Development Strategy Action Plan (2014-2020) focussing on the development of renewables and capping primary energy consumption at 4.8 Gtce (tonnes of coal equivalent) per year until 2020 – equal to limiting the primary energy consumption growth rate to 3.5%/year until 2020. China aims to limit coal consumption to 4.2 Gt/year until 2020, a 16% increase over 2013 levels. China will also target a reduction of coal in the primary energy mix to under 62% by 2020, to the advantage of non-fossil fuels (15% by 2020 and 20% by 2030, from about 10% in 2013) and gas (10% by 2020). By 2020, the installed nuclear power capacity is expected to reach 58 GW, with an additional 30 GW under construction; inland nuclear power projects will be studied, while the construction of nuclear reactors on coastal areas will begin "at a proper time". China has a target to reach an installed hydropower capacity of 350 GW by 2020, with wind and solar reaching 200 GW and 100 GW respectively. Shale gas and coal-bed methane production are targeted to reach 30 bcm by 2020.

The consequence of its high coal consumption is that China is also the world's leading energy-related CO_2 emitter, releasing 8,251 million tCO_2 in 2012. China's government plans to reduce carbon intensity (carbon emissions per unit of GDP) by 17% between 2010 and 2015 and energy intensity (energy use per unit of GDP) by 16% during the same period, according to the country's 12th Five-Year Plan. China also intends to reduce its overall CO_2 emissions by at least 40% between 2005 and 2020.

Source: Xinhuanet, 2014; EIA, 2014; IEA, 2014b

2.3.2 Carbon intensity

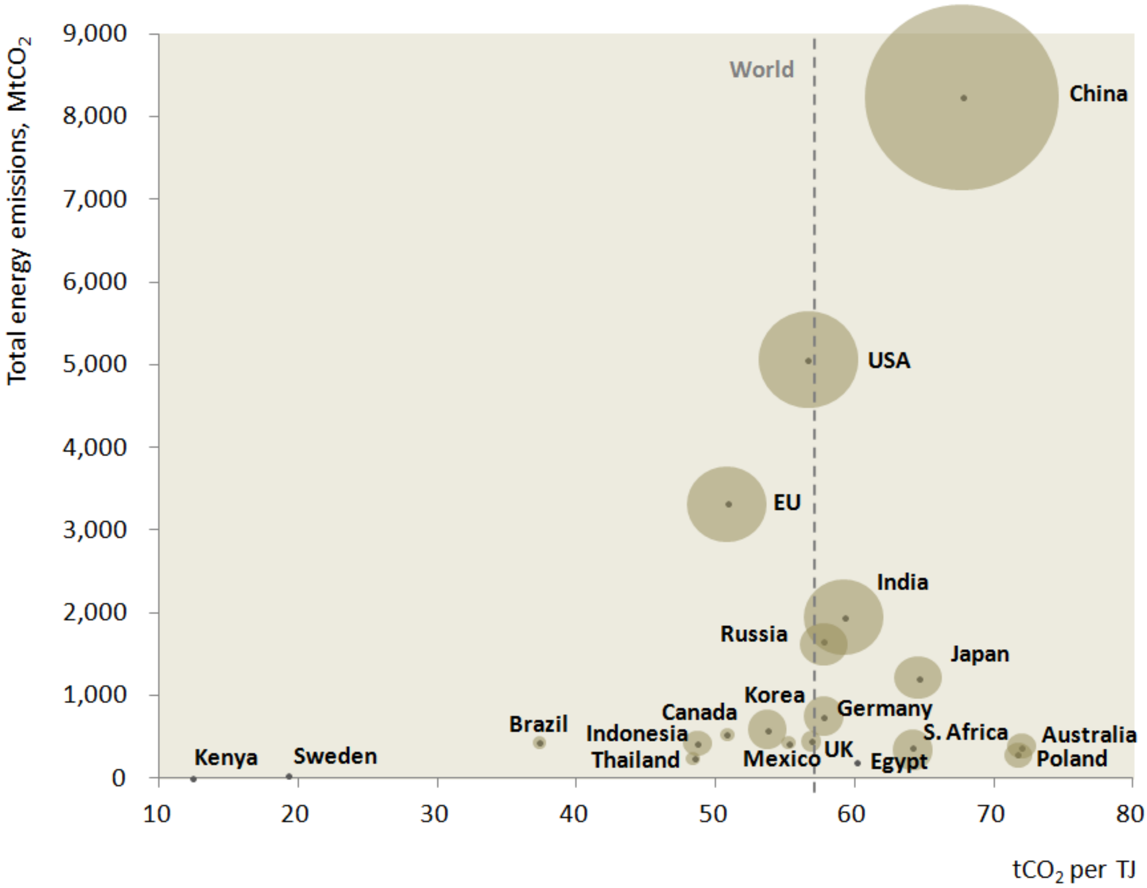
National patterns of fossil fuel use are highly linked to countries' emissions intensity.[17] Figure 2.3 shows emissions intensity of energy supply (tCO_2 per TJ) plotted against CO_2 emissions for a range of countries worldwide including the world's largest emitters in 2012. The circular areas shown indicate each country's relative coal consumption in the same year. The plot shows a clear correlation between coal use and national emissions intensity - for example the relative high carbon intensity in emerging economies such as China, India and South Africa where domestic coal resources currently fill much of the growing energy demand. The plot also shows that most of the world's largest CO_2 emitters (including China, USA, India, Japan, the EU and Russia) have largely fossil-based energy mixes whose carbon intensity values are similar to, or above, the world average value of around 57 tCO_2 per TJ.[18]

Figure 2.3 also illustrates the wide range in emissions intensity between countries and regions, closely reflecting the patterns of national energy use. Countries as diverse as Kenya and Sweden, in which non-fossil energy play a significant role, have relatively low carbon intensities; others whose economies are highly reliant on fossil energy, and particularly coal, such as Australia, Poland and China have much higher carbon intensities. Unsurprisingly, the former group are

[17] Coal has the highest carbon content per unit of energy released within the key fossil fuels: coal when combusted, emits 68% more CO_2 than natural gas for the same energy-equivalent amount of fuel, while this emissions ratio is 42% more for coal relative to oil.
[18] World carbon emissions intensity of energy (TPES) has remained relatively stable since 2000; IEA statistics indicate a value of 56.3 tCO_2 per TJ in 2000 and a value of 56.7 tCO_2 per TJ in 2012; most world regions and large GHG emitting countries have similarly demonstrated relatively stable emissions intensity values over this period.

typically small emitters in terms of global CO_2 emissions.[19] Countries whose energy use is highly carbon intensive cover a wide range of large, medium and small emitters.

Figure 2.3 CO_2 intensity of energy versus total energy emissions, 2012



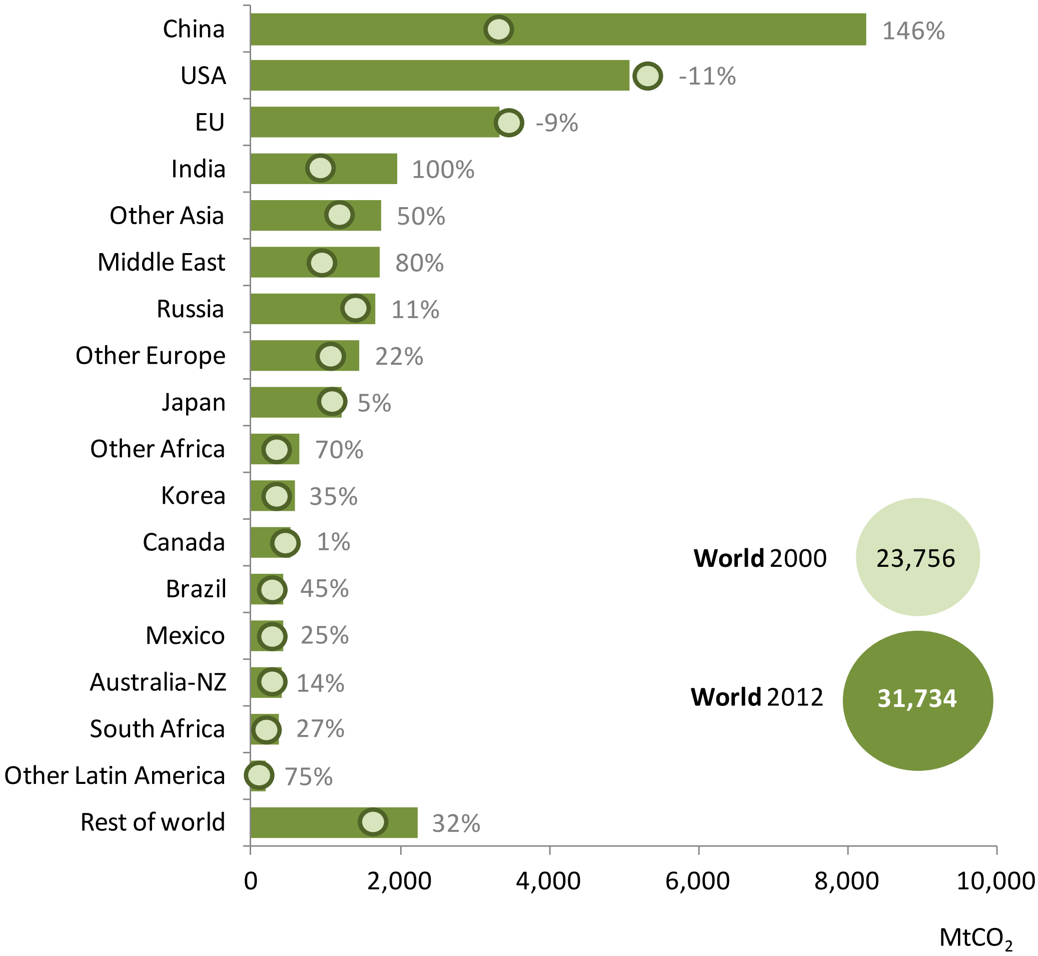
Note: Circles show the relative size of coal consumption in 2012 (energy basis)
Data source: IEA, 2013b, 2014e; BP, 2014

2.3.3 National CO_2 emissions

Figure 2.4 shows the change in CO_2 emissions between 2000 and 2012 for key regions and countries worldwide. Whilst global emissions rose by 34% between 2000 and 2012, some countries have seen far large growth rates over the same period, driven largely by increased economic growth based on fossil fuel use. For example, China's emissions have increased by 146% to reach around 8.3 $GtCO_2$. Latin America, Southeast Asia and the Middle East have also seen large emissions growth over the past decade. The rapid growth rates shown in the figure represent the key overriding driver for undertaking CCS: as a key abatement option within national strategies to curb fossil-based CO_2 emissions.

[19] With national energy emissions of 440 $MtCO_2$ in 2012, Brazil is a notable exception due in part to the large size of its its population and economy

Figure 2.4 Increase in global CO_2 emissions by region, 2000-2012



Note: Percentages indicate relative increase between 2000 and 2012
Data source: IEA, 2014b

2.4 Suitability of emissions sources to CCS

2.4.1 Overview

The potential to undertake CCS as part of national efforts to reduce emissions is dependent upon the suitability of countries' emissions sources to the technology. CCS, as currently envisaged, involves capturing CO_2 from large stationary sources of anthropogenic emissions such as power generation plants and industrial facilities (e.g. cement kilns, iron and steel works and chemical production plants) for subsequent transport and geological storage.

Three approaches are possible for capturing CO_2 from **fossil-fuel power plants**:

- **Post-combustion capture** uses chemical solvents such as amines to separate CO_2 from gas streams and is a commercially available, mature technology. Upon heating, a high-purity CO_2 stream is produced which can then be compressed and transported to a suitable storage site. The post-combustion approach can be applied in principle to any source of CO_2, and is generally viewed as the most viable option to be applied to gas- and dual-fired power stations. It is also simple, relatively easy to retrofit and does not need large supporting processes like integrated gasification combined cycle (IGCC) or oxy-fuel retrofits.
- **Oxy-fuel capture systems** involve combusting fossil fuels in a recycled flue gas stream enriched with oxygen. The resulting combustion products are mainly water and CO_2 produced at much higher concentrations than air combustion. The water (steam) is then separated from the CO_2 stream. Like the other alternatives to post-combustion, oxy-fuel technology remains at the development stage with the focus firmly on coal fired generation in the near term.
- **Pre-combustion capture** involves a partial conversion of hydrocarbon fuels into a mixture of hydrogen and CO_2 (or syngas) through gasification (for solid fuels such as coal or biomass) or steam methane reforming (SMR) (for natural gas). This is then followed by a shift conversion of carbon monoxide (CO) to CO_2, which can be separated and treated for subsequent transport and storage. Pre-combustion capture in the power sector has focused on the use of IGCC technology as a clean coal technology.

Because of the high carbon content in coal, CO_2 capture technology is highly suitable to capture from coal-fired power generation; the lower concentration of CO_2 emissions within the flue gases of other fuels including natural gas require additional processing to produce a high purity CO_2 stream suitable for transport and storage. However, capture from both coal- and gas-fired installations has been demonstrated to be technically feasible and will be required under the 2DS (as described in Chapter 1). A range of factors including the relative costs and availability of coal and gas across regions drives the comparative costs and viability between the two options. Capture from oil-fired plants is not generally considered feasible: most existing units are relatively small and/or ageing and in most regions are being replaced with other type of generation. The capture of CO_2 from zero-emission rated biomass units offers the potential for so-called 'negative emissions' on a net emissions basis.

A growing number of studies have assessed the technical and economic feasibility of capturing emissions from large **industrial sources** using some of the same capture technologies outlined above. The capture of high-purity CO_2 source streams is routinely undertaken on a commercial basis worldwide for purposes other than geological storage (e.g. in the production of urea), representing a potential source for early-stage CCS projects. Industrial sectors and processes potentially suitable for CCS include the following:

- **Refining**. Large oil refining complexes offer a number of CO_2 sources potentially suitable for post-combustion capture, including heaters, furnaces, boilers, crackers and utilities. Depending on the refinery configuration and product slate, the largest sources of CO_2 are typically combustion emissions from large utility boilers and process furnaces, the catalytic reformer and the fluidised catalytic cracker (FCC) unit regenerator.[20] Energy use and CO_2 emissions vary depending on what type of crude oil is being processed and on the mix and quality of the final products (Rootzen *et al.* 2009). Between 5% and 20% of CO_2 emissions from a refinery are linked to the production of hydrogen (UNIDO, 2010), representing a high-purity low cost capture source.
- **Iron and steel**. Blast furnaces at iron and steel plants represent significant sources of fuel combustion CO_2 that could be captured either pre-combustion or post-combustion. Neither approach captures all of the CO_2 from integrated iron and steel plants, since large volumes are also emitted from non-core processes such as sinter plants, basic oxygen furnaces and rolling mills. However, CO_2 reductions in the core process (i.e. emissions from blast furnaces) could amount to 75% of total emissions (see Borlee, 2007).
- **Cement**. The manufacture of cement results in the generation of large volumes of CO_2 from both fuel combustion and the calcination of limestone in cement kilns. Two types of emission source are therefore potentially available for capture at a cement plant. Furthermore, the production process means that typically the two source streams are co-mingled in the off-gas from the kiln, and can therefore be captured together. The application of post-combustion technology has received most attention and is potentially suitable for both new-build and retrofit plants.
- **Pulp and paper**. Several studies have assessed the potential for post-combustion capture of fuel combustion emissions from boilers (black liquor, other biofuels, CHP, natural gas) at large-scale integrated pulp and paper mills. Although CCS is not considered economically viable at many pulp and paper facilities in the EU and elsewhere, due to their limited production size and emissions volume, capture from large integrated Kraft pulp and paper mills is considered feasible (Hektor and Berntsson, 2007; Möllersten *et al*, 2003).
- **Chemicals**: Certain chemicals production processes which produce large volumes of CO_2-rich flue gases, or pure CO_2, offer opportunities for relatively low cost CO_2 capture. These include the production of ammonia, hydrogen, ethanol, ethylene and ethylene

[20] Given this diversity of processes, all three key capture routes – pre-combustion (pre-process) capture from syngases, post-combustion from diluted flue gas streams and oxyfuel combustion for concentrating CO_2 in flue gases – could be relevant (UNIDO, 2010).

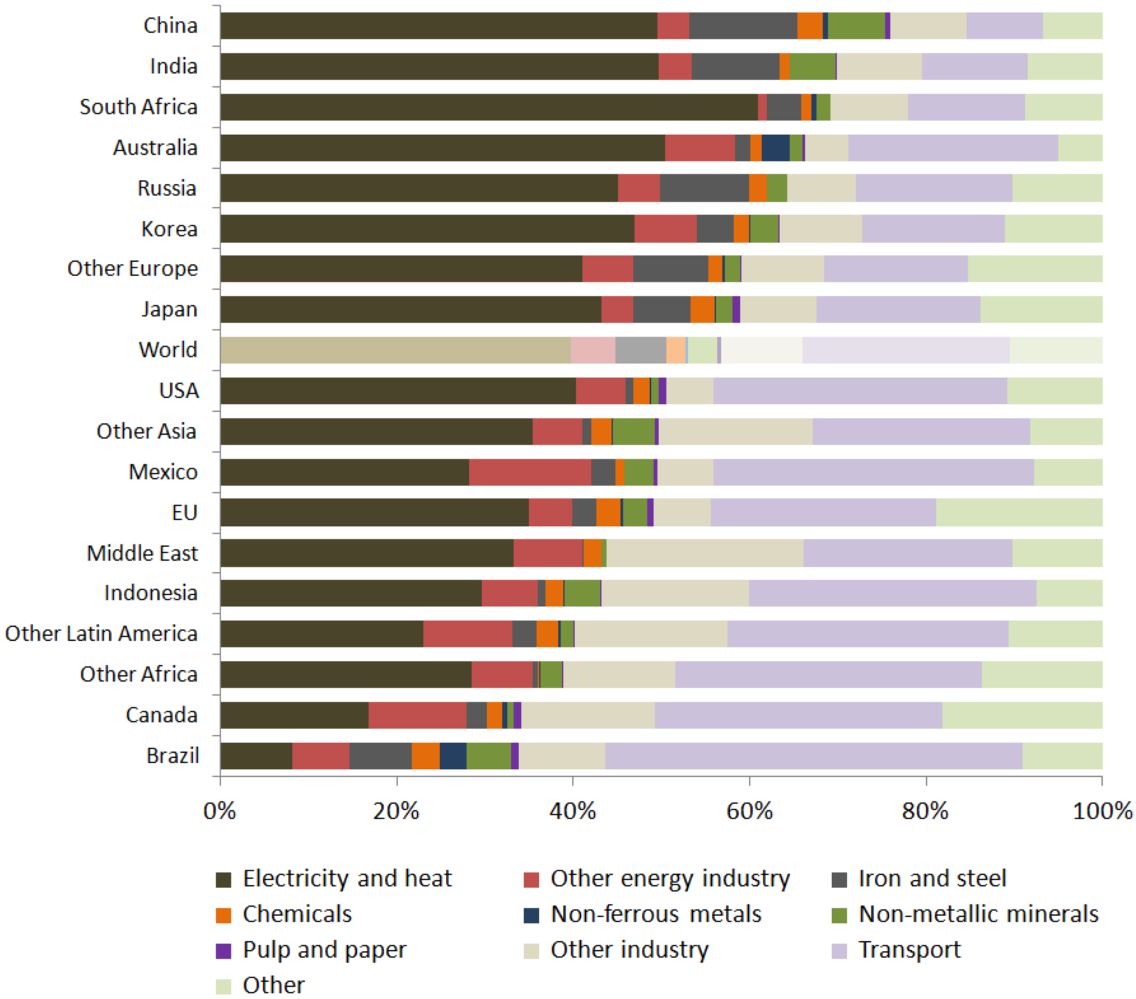
oxide. Capture from large volume high-CO_2 concentration sources such as ammonia and steam methane reforming (SMR) hydrogen plants can be achieved at relatively low cost, as only compression and drying are required as major additional equipment, as well as pumps, coolers and separators.

In addition, within the upstream energy sector CO_2 emissions are routinely captured from **natural gas processing**. Natural gas in commercial operations worldwide include varying amounts of CO_2 - ranging from sweet (CO_2-free) gas in Siberia to high-CO_2 content gas (e.g. as high as 90% in the Platong and Erawan fields in Thailand; IEA, 2008). CO_2-content specifications for gas pipelines and sales specification are typically about 2% by volume: where gas supplies have a higher CO_2 content than this, the CO_2 therefore has to be removed. This is often referred to as “gas sweetening”, although this term typically refers to both the removal of CO_2 and/or hydrogen sulphide. CO_2 removal may occur at the well-head, and/or downstream at one or more processing facilities. As this type of installation is typically located in or nearby a gas producing region, there may often be suitable storage sites in close proximity to the CO_2 source. Low-cost capture from such activities are likely to represent important ‘early opportunity’ projects enabling important lessons to be learned and successful technology demonstration ahead of wide-scale CCS deployment over the coming decades. Other energy supply facilities such as liquefied natural gas (LNG) and coal-to-liquids (CTL) plants may also represent significant point sources of CO_2 emissions suitable to capture.

Figure 2.5 shows the sources of CO_2 emissions across key world regions and countries in 2012, shown as shares of national emissions. In the context of the above description, the graph highlights those sources to which CCS can be most readily applied: these are shown by the full colours whilst the sectors shown by the pale colours are unsuitable for capture. Note however that in addition to the (fuel combustion) emissions shown, additional process and vented CO_2 source from sectors such as cement, fertiliser, and chemicals production and natural gas processing offer significant capture potential for many countries worldwide (and are discussed further below). As is the case with power generation, many of these industry sectors are forecast to expand over the coming decades - with associated emissions increases, in the absence of mitigation efforts.

The graph shows how the share of CO_2 emissions to which CCS can potentially be applied varies significantly across regions and countries. The variation reflects different national circumstances in terms of those sectors and activities giving rise to CO_2 emissions. For example, China and India’s economies are highly reliant on carbon-intensive heavy industry sectors such as iron and steel and cement production as well as coal-fired power production. In other regions, sectors less readily suitable to CCS account for a larger share of national emissions. For those countries, energy efficiency and low-carbon fuel development may be prioritised within national climate plans. The relative importance of different sectors suitable to CCS across regions and countries worldwide is described in more detail below.

Figure 2.5 CO_2 emissions by region and sector in 2012

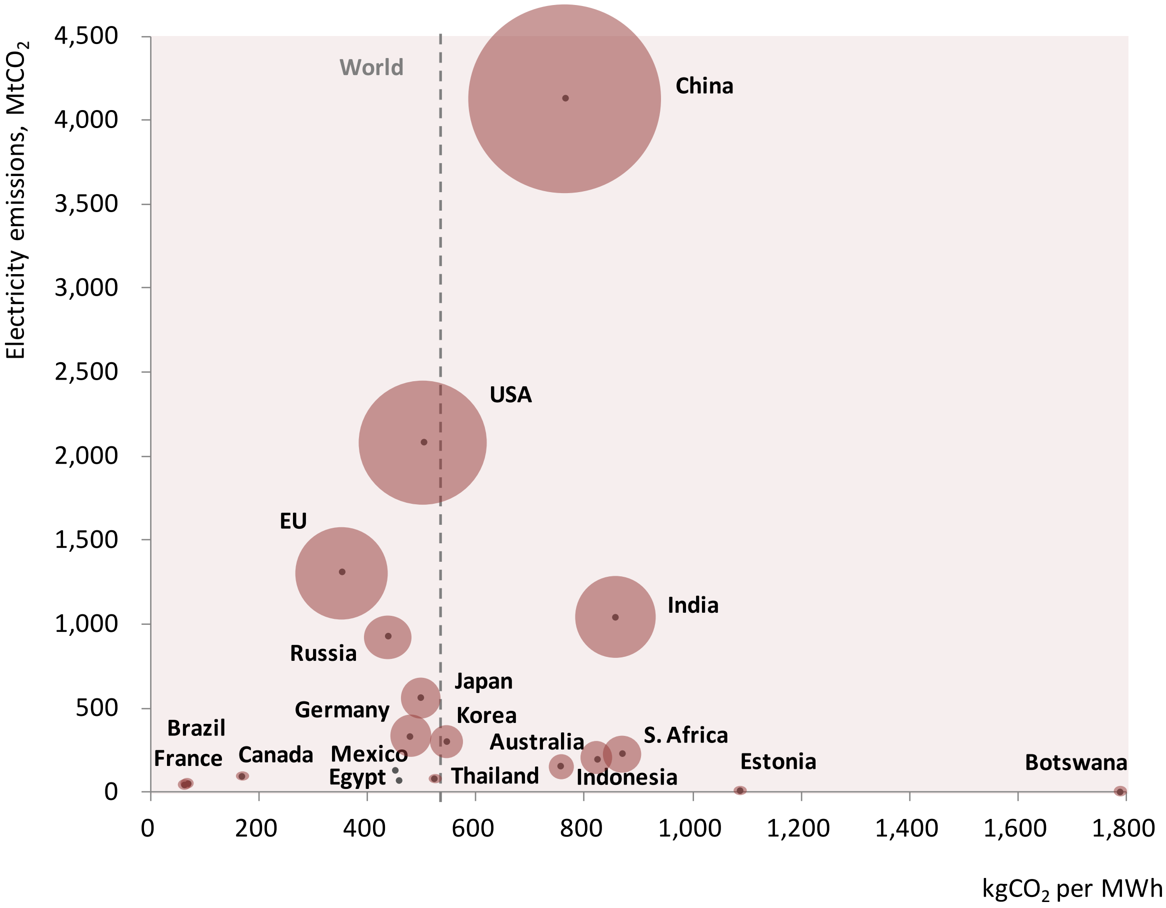


Note: 'Other energy industry' includes emissions from own use in petroleum refining, manufacture of solid fuels, coal mining, oil and gas extraction and other energy-producing industries. 'Non-metallic minerals' comprises mainly cement, but also ceramics and glass; 'Other industry' includes manufacturing and construction.
Data source: IEA, 2014b

2.4.2 Power generation

It can be seen from Figure 2.5 that electricity and heat generation (from fossil-fuel power stations and combined heat and power, CHP, plants) offers the largest share of emissions for CO_2 capture across most regions. As such, CCS offers many countries worldwide the opportunity to make deep cuts in their power sector emissions. As shown in Figure 2.6, the electricity supply of many key countries worldwide is highly carbon intensive, reflecting the high use of fossil fuels in the generating mix, in particular the dominance of coal in the electricity grids of countries such as China, India, Indonesia and South Africa. Other factors influencing carbon intensity include the technology, efficiency, and age of the generating fleet; an important issue facing coal-reliant Botswana, for example, which has an extremely carbon-intensive power supply. For these countries, CCS potential represents a major abatement option to reduce power sector (and total national) emissions, whereas for others such as Brazil, France, Canada and many smaller developing countries, the potential may be limited to a smaller number of specific projects, if at all.

Figure 2.6 CO_2 intensity of power generation versus CO_2 emissions, 2011

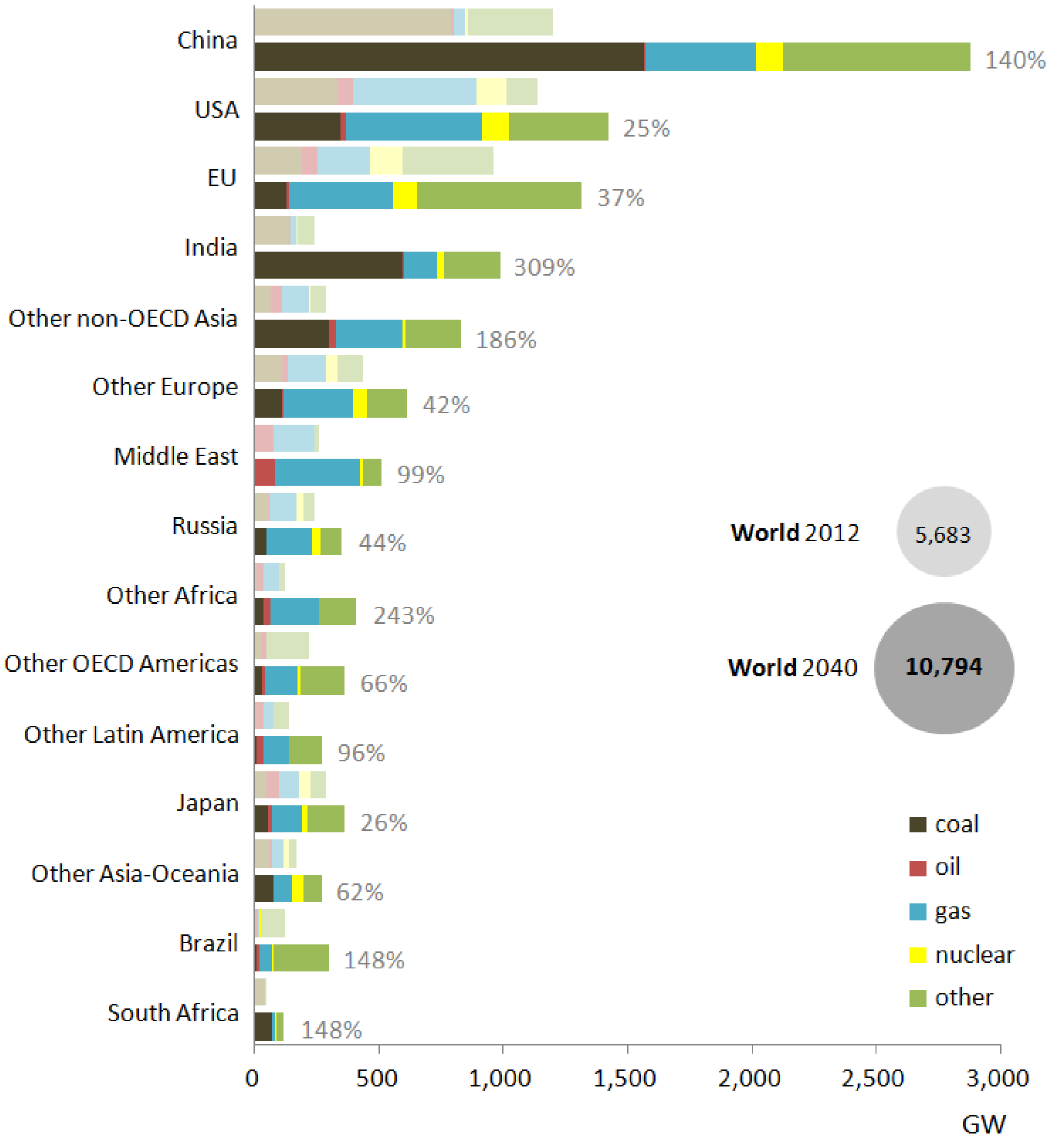


Note: Circles show the relative size of coal-fired power capacity in 2012
Data source: IEA 2013b; 2014b; 2014c; various

Figure 2.7 highlights the importance of power sector CCS deployment in ongoing national emission reductions efforts. The graph shows forecast increase in electricity generation capacity through 2040 based upon analysis of currently known national policies and plans. Under this scenario, world generation capacity doubles to 10,794 GW (IEA, 2014c) while many regions and countries worldwide see significantly higher growth rates. These include China, Africa, and the emerging economies of Southeast Asia - most significantly India which is undergoing an unprecedented programme of rapid power capacity expansion wholly based on coal (Box 2.2).

Associated emissions are forecast to rise from around 15 $GtCO_2$ in 2012 to over 21 $GtCO_2$ globally in 2040 (*ibid*), representing some 47% of total forecast emissions in 2040. Several countries have accordingly recognised the need to reconcile continued fossil fuel use with curbing power sector emissions within their national energy plans, including both OECD and non-OECD countries (Box 2.3).

Figure 2.7 Electricity capacity outlook under the IEA Current Policies Scenario, 2012-2040



Note: Percentages indicate relative increase between 2012 and 2040

Data source: IEA, 2014c

Box 2.2 India's Ultra Mega Power Projects

The Government of India has embarked on an ambitious programme to build a series of coal-fired 'Ultra Mega Power Projects' (UMPPs) to meet the country's rising power demand. The UMPPs are an expansion of the MPPs (Mega Power Projects) undertaken through the 1990s which met with limited success. The Ministry of Power, in association with the Central Electricity Authority (CEA) and Power Finance Corporation Ltd., has launched an initiative to develop the UMPP's, with projects awarded to developers based on competitive bidding.

Based on supercritical technology, 16,000 MW of capacity has so far been contracted through the competitive bidding process for UMPPs. Nine projects are currently at various stages of construction, including five coastal sites (Mundra in Gujarat, Krishnapatnam in Andhra, Pradesh, Tadri in Karnataka, Girye in Maharashtra, and Cheyyur in Tamil Nadu) and four coal pit-head sites (Sasan in Madhya Pradesh, Tilaiya in Jharkhand, Sundergarh District in Orissa and Akaltara in Chhattisgarh). The first UMPP, developed by Tata Power at Mundra, Gujarat has been commissioned and contributes 4,000 MW in power to the Western grid.

Source: Government of India Ministry of Power, 2015

Box 2.3 Reducing CO_2 emissions from power generation in South Africa

South Africa has developed an Integrated Resource Plan (IRP) for the electricity sector that describes the expected generation investment by fuel type over the period 2010 to 2030. The IRP is updated every two years and was last updated by the Department for Energy Affairs in 2013. The plan expects that in 2030 coal-fired power plants will provide 48% of South Africa's power generation capacity, or 36,000 MW . This includes 45% of the capacity provided by coal-fired power plants that exist today, and 3% provided by new coal-fired plants planned or under construction. The balance of the capacity comprises a mix of gas-fired plants, nuclear, solar PV, concentrated solar power, wind and other technologies. Though coal-fired power plants will provide only 48% of capacity, they will typically operate in base load and their contribution to energy and national CO_2 emissions will be substantially greater than 48%. Eskom, South Africa's state-owned power utility, states that 93% of its electricity currently comes from coal-fired power plants.

The government has developed a peak-plateau-decline (PPD) strategy for CO_2 emissions[21], with the peak targeted to occur around 2025. The IRP shows a peak in CO_2 emissions from the power sector of a little over 300 $MtCO_2e$, with the majority originating from coal- fired power plants. The government expects that the main reductions in CO_2 emissions will come in the period after 2030, which is the horizon for the IRP. By 2050, the government expects CO_2 emissions from power to have fallen to between 100 and 200 million tonnes per year. One of the elements of the Government's strategy to reduce emissions is the establishment of the South African Centre for Carbon Capture and Storage (SACCCS) whose mission is to investigate the feasibility of CCS in South Africa. SACCCS has developed a roadmap for the development of CCS in South Africa. The first and second steps of the roadmap i.e. assessment of the CCS potential and the development of a CO_2 storage atlas have been completed. SACCCS is currently experimenting with CO_2 storage to test the suitability of local geological structures as a medium for safe storage of CO_2. The roadmap indicates that a small pilot plant will be developed in 2017, a demonstration plant by 2020 and that commercial scale CCS will be introduced by 2025.

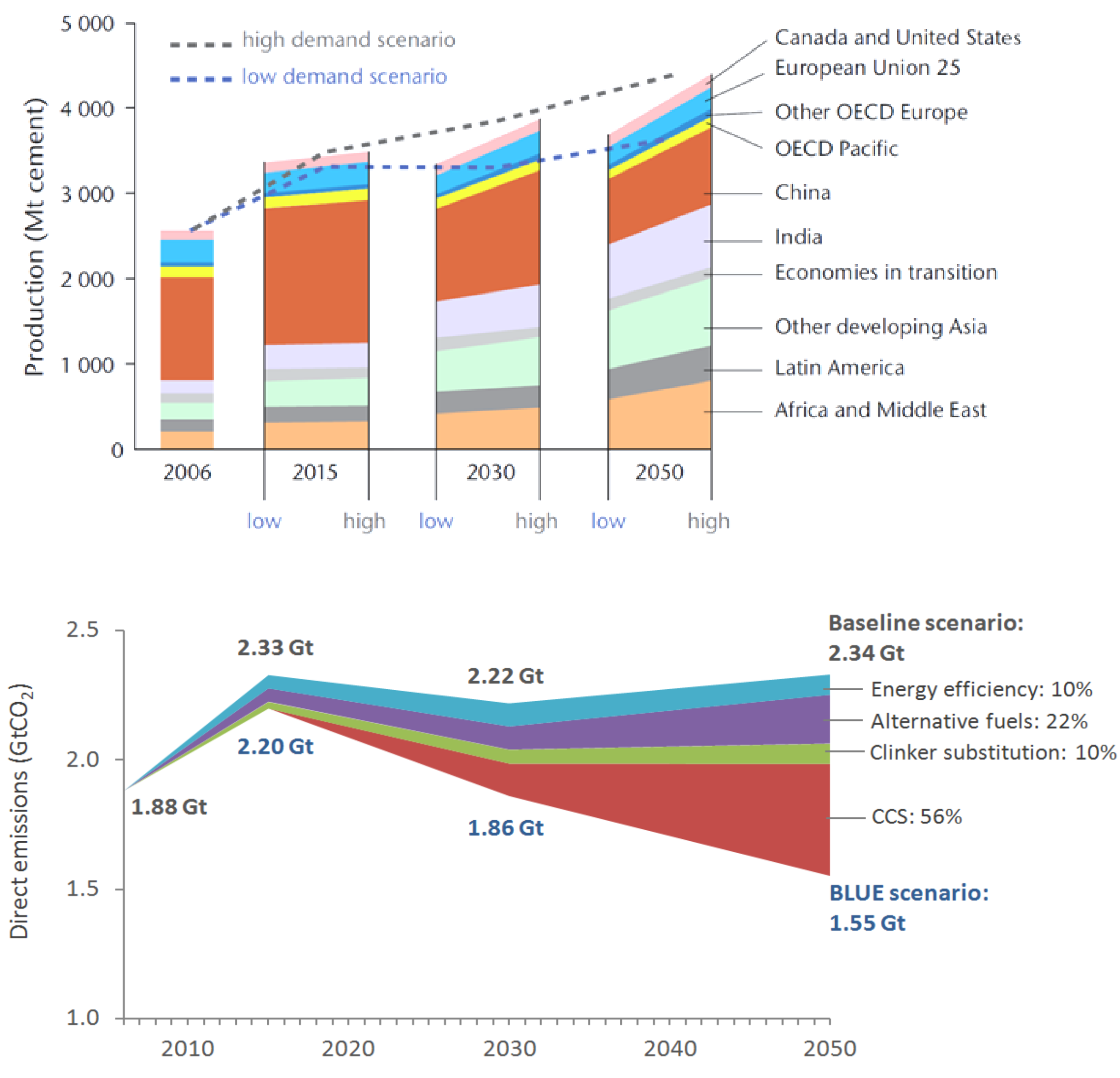
Source: South African Department of Energy, 2013; Eskom, 2011; South Africa Centre for Carbon Capture and Storage (SACCS).

[21] In August 2011, the Department of Environmental Affairs published an explanatory note "Defining South Africa's Peak, Plateau and Decline Greenhouse Gas Emission Trajectory".

2.4.3 Cement

Figure 2.8 shows a forecast of cement production by region, and associated CO_2 emissions pathways, based on analysis by the World Business Council for Sustainable Development (WBCSD) and the IEA (WBCSD/IEA, 2009). Between 2006 and 2050, cement production is projected to reach between 3,700 Mt and 4,400 Mt in 2050, representing a 43-72% increase compared to production in 2006 (*ibid*). Cement consumption in China, which in 2006 accounted for almost half of total world production, is expected to peak between 2015 and 2030, as per capita cement consumption declines towards more developed country levels. After 2030, global cement production will be fuelled by strong demand growth in India and other developing Asian countries, and in Africa and the Middle East (*ibid*). Indeed many countries in these regions such as Egypt, Saudi Arabia and Algeria have significantly expanded their cement production capacity over recent years, aimed at both export and domestic markets.

Figure 2.8 Forecast of cement production by region and CO_2 emissions scenarios



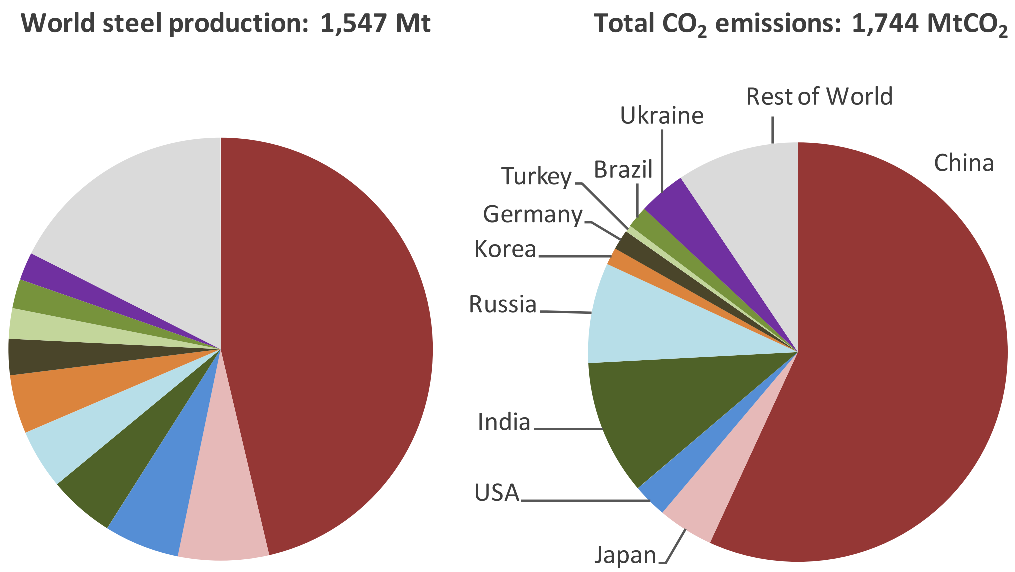
Source: Adapted from WBCSD/IEA, 2009

Under a baseline scenario, CO_2 emissions associated with this rise in cement production are forecast to reach 2.34 $GtCO_2$, rising from 1.88 $GtCO_2$ in 2006. These include both fuel combustion and process emissions from calcination.[22] According to the WBCSD/IEA analysis, CCS will be required to achieve significant cuts in cement emissions through 2050, contributing 56% of the sector's emissions reductions required under the IEA BLUE scenario (consistent with a global rise in temperatures of 2°C to 3°C, and the more recent IEA 2DS scenario). As described above, both fuel combustion and calcinations emissions can be captured for CCS using post combustion technology.[23]

2.4.4 Iron and steel

According to IEA and the World Steel Association statistics (IEA, 2014b; World Steel Association, 2013), steel production totalled 1,547 Mt in 2012 with associated emissions of 1,744 $MtCO_2$ (Figure 2.9). As with cement production, production from emerging and developed economies has overtaken developed country production over the past decade, a trend expected to continue with strong ongoing demand and production expected in China, India, other emerging Asian economies and the Middle East. A number of studies and R&D programmes, such as e.g. the European steel industry Ultra-low CO_2 Steel-making programme (ULCOS), have demonstrated the potential for large-scale CO_2 capture from blast furnaces; gas based direct reduced iron (DRI) production could allow CO_2 capture at a lower cost, although DRI facilities are concentrated in relatively few countries and are comparatively small in scale (IEA, 2008). Steel production is projected to grow to between 1,800 and 2,700 Mt by 2050 (UNIDO, 2010). With the expected rapid growth in DRI production in the Middle East and elsewhere, the potential for CO_2 capture could however be significant.

Figure 2.9 Steel production and CO_2 emissions in 2012



---

[22] Process CO_2 emissions associated with limestone calcination account for around 60% of direct sector emissions (Cook, 2009).

[23] Other abatement options such as energy efficiency measures, alternative fuel use and the substitution of clinker for alternative materials are limited, and for some regions offer only marginal emissions reduction potential.

Data source: World Steel Association, 2013; IEA, 2014b

2.4.5 Refining

Global refining capacity was around 92.6 million barrels per day (mb/d) in 2013 with Europe, North America and China together accounting for around half of the total (IEA, 2014c). The capacity of the world's refining sector is in general closely related to world oil demand, with oil primarily being converted to transportation fuels. As such, the majority of future refining capacity expansions through 2040 will likely be in the emerging economies of Asia (10.6 mb/d out of a global total of 16.1 mb/d) where expansions are dominated by China and India *(ibid)*. The second largest capacity additions are projected in the Middle East; some 4 mb/d through 2040 (*ibid*). Over the same period, demand is forecast to decrease in OECD regions such as Europe, North America and Japan, resulting in the closure of older refining capacity. Globally, refining capacity projections indicate an increase to 108.7 mb/d by 2040 (Figure 2.10).

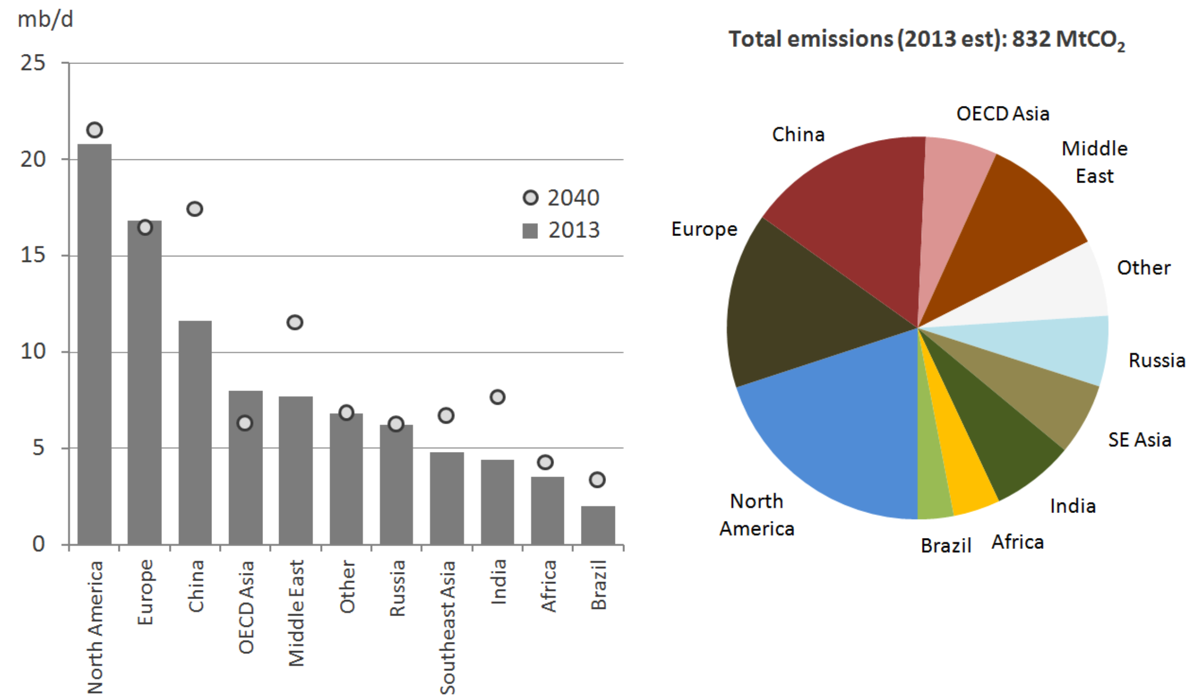
There is at present no comprehensive database of CO_2 emissions for the world's refining industry. Emissions estimates provided by the (formerly available) IEA Greenhouse Gas Program (IEAGHG) CO_2 Emissions Database were based on the daily production capacity operating for 8,300 hours per year with an average emissions factor of 0.219 kg CO_2 per kg of product (IEAGHG, 2008a)[24]. IEAGHG (2008) reports that refineries produced 818 Mt CO_2 per year based on data available in 2008; based on historic throughputs data[25], and assuming no change in carbon intensity over the period, global emissions in 2013 can be estimated at around 832 $MtCO_2$. Assuming no regional variation in carbon intensity, regional distributions of refining sector emissions can also be estimated.[26] Based on IEA projections of increased global throughputs, global emissions in 2040 are likely to increase to around 948 $MtCO_2$ (Figure 2.10).

[24] The assumptions made in these estimates lead to uncertainty in the final estimates, and a number of different sources would suggest that the uncertainty is great. For example, Gary and Handwerk (2001) state that typically for a 300,000 bbl/d refinery, CO_2 emissions range from 0.8 million tCO_2/y to 4.2 million tCO_2/y. However, as noted by DNV (2010), despite the large uncertainty involved others support the figure of 0.219 kg CO_2/kg

[25] BP, 2014 (74.99 mb/d in 2008; 76.28 mb/d in 2013)

[26] This is necessarily a crude assumption, given multiple factors such as product slate, refinery age, environment controls etc which vary across regions, countries and installations.

Figure 2.10 World refining capacity and associated CO_2 emissions 2013-2040



Source data: IEA, 2014c; various

As described above, refineries offer multiple sources of fuel combustion and process emissions available for CO_2 capture, which will vary according to refinery layout, product slate etc. Given the strong forecast growth for transport fuel demand and associated refinery capacity additions in China, India and much of the rest of developing world including Middle East, Africa and Latin America, there is significant potential for new build CCS deployment in these regions. The potential for CCS deployment in the more established OECD markets over the coming decades is likely to be as retrofits of brownfield refinery sites (DNV, 2010).

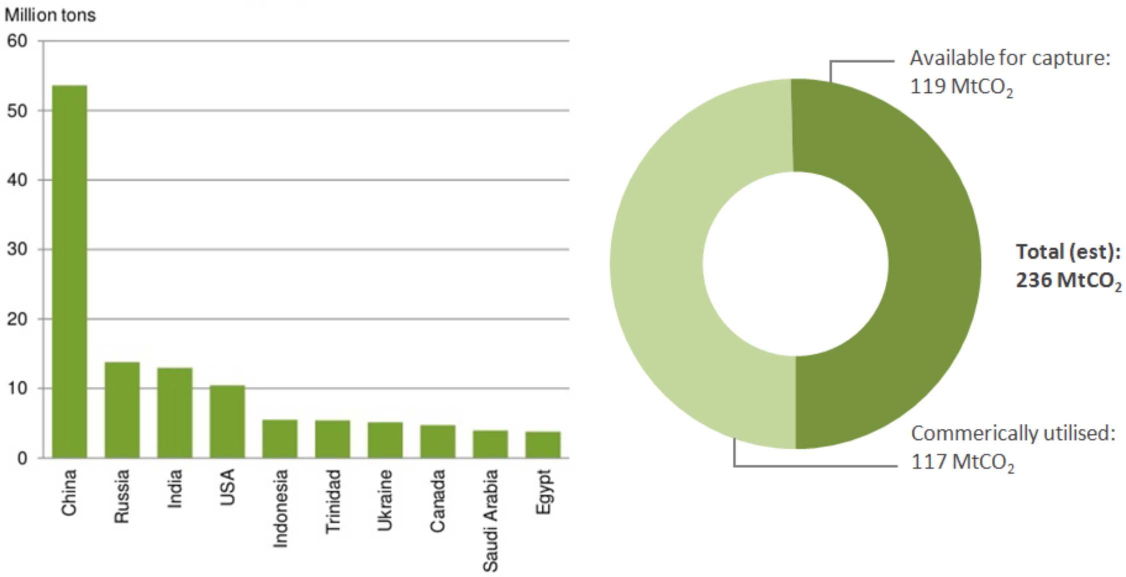
2.4.6 High-purity CO_2 sources

Several processes in industrial applications result in a high-purity CO_2 vent stream, which can be readily dehydrated, compressed, transported and stored, providing a lower-cost option for CCS (IEA/UNIDO, 2011). These include the production of ammonia, hydrogen (often within refinery complexes), ethanol, ethylene and ethylene oxide, as well as natural gas processing and coal-to-liquids (CTL). The potential for capturing CO_2 from these sources across world regions and countries is summarised below.

Presently around 140 million tonnes of **ammonia** are produced globally (IFA, 2015). The main producing regions are East, Central and South Asia, where more than half of global ammonia production is located. The Middle East has increased its production of ammonia in recent years, and is likely to be a major source of ammonia in the future as production in OECD areas such as Europe and North America continues to decline (Zakkour and Cook, 2010). For many countries, the industry is strategically important either because of the importance it plays in national food security (e.g. India) or because of its role in raising foreign direct earnings through valorisation of natural gas resources (e.g. the Middle East) (*ibid*).

The International Fertiliser Association (IFA) reports that the industry already utilises around 36% of the CO_2 removed from the syngas in the gas clean-up step of the production process (IFA, 2010). Of this, around 33% goes into the synthesis of urea, whilst the remaining 2.2% is sold on to other uses. Analysis suggests that the total amount of CO_2 generated in ammonia production globally is around 236 $MtCO_2$ per year (Zakkour and Cook, 2010). Based on the stoichiometry of urea production and IFA reported utilisation rates of CO_2 from ammonia production, almost 50% of current CO_2 production is utilised for other purposes (approximately 117 $MtCO_2$) meaning that some 119 $MtCO_2$/yr of produced CO_2 is vented directly to the atmosphere and could be available for capture (Figure 2.11).

Figure 2.11 Top ten ammonia producing countries in 2012, and estimated CO_2 emissions



Source data: IFA, 2015; Zakkour and Cook, 2010.

There are presently no publicly available data sources that provide information on the levels of CO_2 vented from **natural gas processing** operations. Privately held data on estimated CO_2 concentrations in gas reservoirs around the world do exist (e.g. IHS database, see Bakker *et al.* 2010). However, much of the information is proprietary and commercially sensitive. Further, no gas producers provide detailed reporting of vented emissions from gas production. The picture is further complicated by the production profiles for gas reservoirs, which may produce varying levels of CO_2 across their operational life, whilst the distribution of fields with CO_2 contamination is highly heterogeneous making generalised estimates difficult and subject to large uncertainty (Zakkour and Cook, 2010).

A range of estimates have however been developed, including both top-down estimates (e.g. Metz *et al*. 2005; Philibert *et al.*, 2007) and bottom-up estimates (e.g. IEAGHG, 2008b) of CO_2 emissions vented from gas processing/sweetening operations (Table 2.1). The IEAGHG study provides a detailed estimate of vented emissions through 2020 based on country- and publicly available field-level data for known high-CO_2 gas fields worldwide (Figure 2.12). The analysis shows the dominant potential contribution of Southeast Asian countries due to the occurrence of high-CO_2 gas in the Gulf of Thailand, South China Sea provinces, and in onshore and offshore Indonesia (e.g. Java Sea, Flores Sea, Banda Sea, Timor Sea), and also due to energy security issues in the region driving the development of these fields (*ibid*).

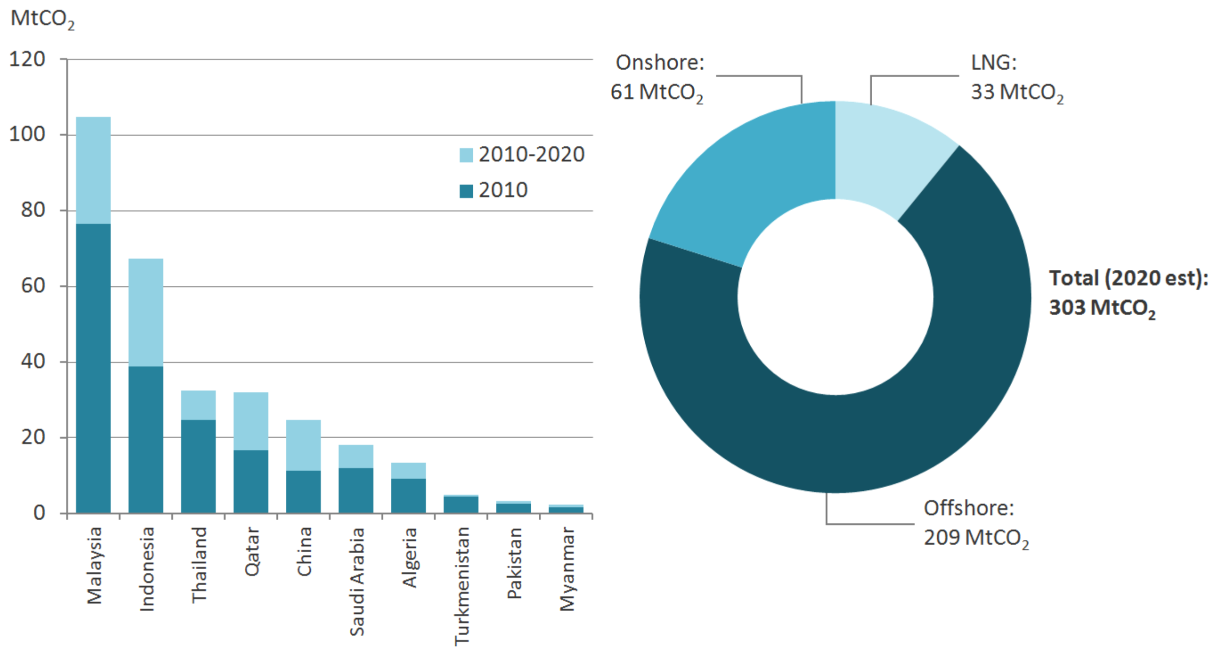
Table 2.1 Estimates of vented CO_2 emission from natural gas processing

Source of estimate	$MtCO_2$/yr	Year	Assumptions
IPCC (Metz *et al*, 2005)	50	2005	2600 bcm/y gas production worldwide; half containing 4% CO_2 that needs to be sweetened to 2%.
IEA (Philibert *et al*, 2007)[a]	167 324	2007 2020	98 bcm/y in developing countries; various new fields means increase to 324 $MtCO_2$/yr by 2020
IEA GHG (IEA GHG, 2008)[a]	219 313	2010 2020	Bottom-up estimate based on published field data and extrapolation
ECN (Bakker *et al*. 2010)[a]	174 (146-222)	2020 (range)	Bottom-up, IHS database
Average (excl IPCC)	*193* *270*	*2010* *2020*	-

Notes: [a] Analysis covered developing countries only

The IEAGHG study is subject to many uncertainties, not least ongoing exploration and production developments worldwide. For example, although Brazil is not included within the study, the Brazilian state oil company Petrobras' Lula project became operational in June 2013 (Box 2.4). The IEAGHG study is limited in scope to developing countries only. Although these countries represent the largest share globally, a number of other high-CO_2 content gas fields are producing elsewhere worldwide, including the capture of CO_2 for CCS and/or enhanced oil recovery (EOR) purposes. CO_2 can be captured from both onshore (e.g. In Salah, Algeria) and offshore (e.g. Sleipner, Norway) gas processing facilities, as well as LNG facilities (e.g. Barrow Island, Australia). It is difficult to ascertain the number of points sources for CCS application in the natural gas processing sector as gas processing operations vary significantly in size. Assuming average emissions of a single operation of around 2-3 $MtCO_2$ per year, these data suggest that around 50-80 locations worldwide could potentially utilise CCS (Zakkour and Cook, 2010).

Figure 2.12 Estimated CO_2 emissions from gas processing in developing countries



Source data: IEAGHG, 2008b

Box 2.4 Petrobras Lula Oil Field CCS Project

Brazil's state oil company Petrobras and JV partners' Lula project became operational in June 2013. Once operating at full capacity, the project aims to capture of 700,000 tCO_2 per year from an offshore gas processing facility for EOR injection in the Santos Basin, around 300 km off the coast of Rio de Janeiro. The Lula oil field was discovered in 2006 and is one of several oil fields that have been discovered in an area of the South Atlantic Ocean known as the Santos Basin Pre-Salt Cluster (SBPSC). It is one of the largest oil field discoveries in Brazil, with estimated recoverable reserves of 8.3 billion barrels of oil equivalent.

The main drivers for developing the project were the high naturally occurring CO_2 content in the hydrocarbon resource and the strategic decision not to vent this CO_2 to the atmosphere (Pizarro and Branco, 2012). The thick salt column traps a light, 28-30 degree oil and a high solution gas ratio, with solution gas containing between 8-15 per cent CO_2 which must be removed.

The project consists of a floating production, storage, and offloading (FPSO) facility with CO_2 separation, and a 2 km injection riser delivering the CO_2 for injection. The depth of the oil reservoir varies from 2 to 5 km below the ocean floor. The ultra-deep waters make the Lula field a pioneer in CO_2-EOR development, with the deepest CO_2 injection well in operation. Injection commenced at a smaller scale in 2011 and used tracers and pressure monitors to assess the CO_2 behaviour. In July 2013 contracts were executed for the construction of two new FPSOs (for charter by Petrobras and its partners) to support production development at Lula Alto and Lula Central. Each FPSO will be connected to 18 wells – 10 production wells and eight injector wells.

Source: GCCSI, 2014b

There are presently only a few **CTL** plants in operation in the world, the most well-known ones being at Secunda, South Africa and Ordos Basin, China. Several plants have been built in the United States, and a large number have been planned but most have since been delayed or cancelled. China, Indonesia, India, Australia and Mozambique are currently planning for CTL plants. Emissions from the coal gasification process at existing plants have been estimated to be around 28 $MtCO_2$ per year (Metz *et al*., 2005; Sun, 2008; Zakkour and Cook, 2010). All of this CO_2 is available for CCS as it is presently vented to the atmosphere.

Ethylene oxide is produced in a number of countries worldwide, notably the USA, Canada, Venezuela, Saudi Arabia and China (SRI consulting, 2009). Global demand for ethylene oxide is forecast to grow at a rate of around 3% per year from 2014 to 2019 with strongest demand growth from emerging economies (SRI Consulting, 2010). Several studies have estimated associated CO_2 emissions, including Zakkour and Cook (2010), who calculate a figure of around 6.3 $MtCO_2$ based on known production plants worldwide.

The same study has estimated that worldwide, high-purity sources - ammonia, gas processing, CTL and ethylene oxide - accounted for around 340 $MtCO_2$ of vented emissions in 2010, rising to around 800 $MtCO_2$ in 2030 and almost 1,200 $MtCO_2$ by 2050 (in the absence of CCS). These estimates exclude ammonia sector CO_2 used for other purposes and CO_2 from hydrogen production, considered within the scope of the refinery sector.

2.5 CO_2 storage availability

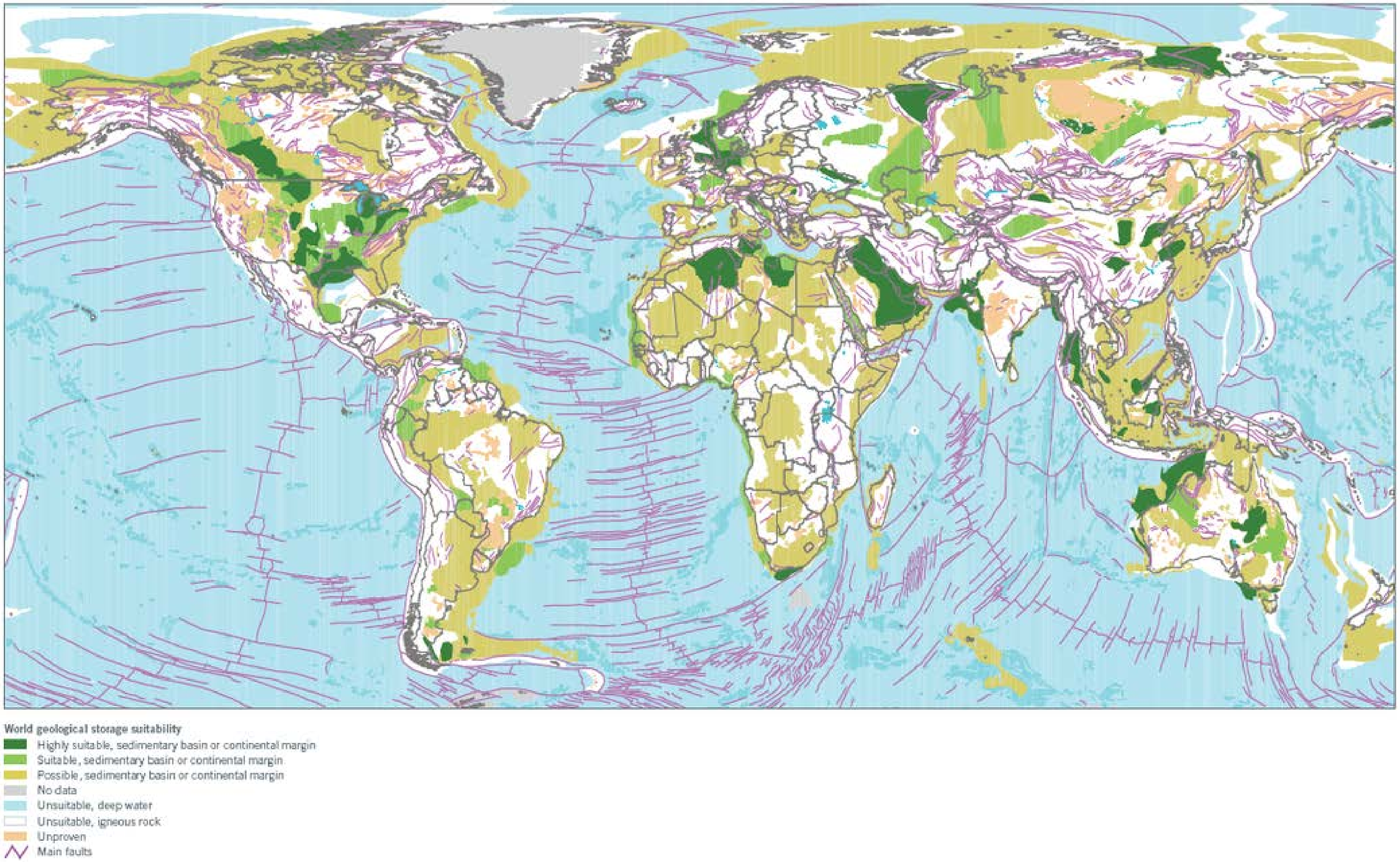
2.5.1 Overview

A key limiting factor determining the potential for CCS deployment within national climate plans is the availability of suitable CO_2 storage. There have been many efforts at global, basin, regional and national scales to characterise the amount of CO_2 that can be geologically stored. As scientists work to refine methodologies, estimates of global geological storage capacity can be highly variable (CSLF, 2011).[27] Nevertheless, numerous studies suggest there is extensive worldwide potential for permanently storing large quantities of CO_2 in geological formations such as deep saline aquifers and depleted oil and gas reservoirs. The IPCC has identified a technical potential of at least 2 trillion tonnes of worldwide CO_2 storage capacity (Metz *et al*., 2005); this is around fifty times larger than current global emissions of CO_2, meaning that there is enough technical storage potential to store fifty years' of CO_2 if held at the current annual level.

Figure 2.13 shows an interim update of the international IPCC 2005 assessment of global geological potential 'suitability' for storage prepared for the GCCSI by the IEAGHG R&D Programme and Geogreen. The figure shows that many key world regions are likely to possess suitable or highly suitable storage capacity: in particular, large areas of North America, Australia, Europe, North Africa, the Middle East and parts of Asia. In recent years, more detailed regional and country-level assessments have been undertaken, as summarised below.

[27] Considerable work is in progress to develop and build consensus on an international classification system for estimates of geological storage capacity for CO_2 involving the Carbon Sequestration Leadership Forum (CSLF), the United States Department of Energy (DOE) and the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) that consider factors such as the scale of the assessment and technical, economic and regulatory factors.

Figure 2.13 Global geological storage suitability



Source: IEAGHG, Geogreen and GCCSI, 2011

2.5.2 Europe

Within Europe, the GeoCapacity project has mapped CO_2 point sources, infrastructure and geological storage within 25 countries in order to assess the European capacity for geological storage of CO_2 in deep saline aquifers, oil and gas structures and coal beds.[28] The assessment comprises most European sedimentary basins suitable for geological storage of CO_2 and identifies a total storage capacity of 360 Gt, of which some 117 Gt is considered to represent a conservative estimate of Europe's viable storage potential (EU GeoCapacity, 2009). Some 82% of this potential is in deep saline aquifers; with 17% is depleted oil and gas fields and 1% in unmineable coal beds. These figures are compared to a total of 1,892 Mt emitted annually from large point sources in Europe, thereby corresponding to around 62 years of storage capacity (if held at the same annual emissions rate).

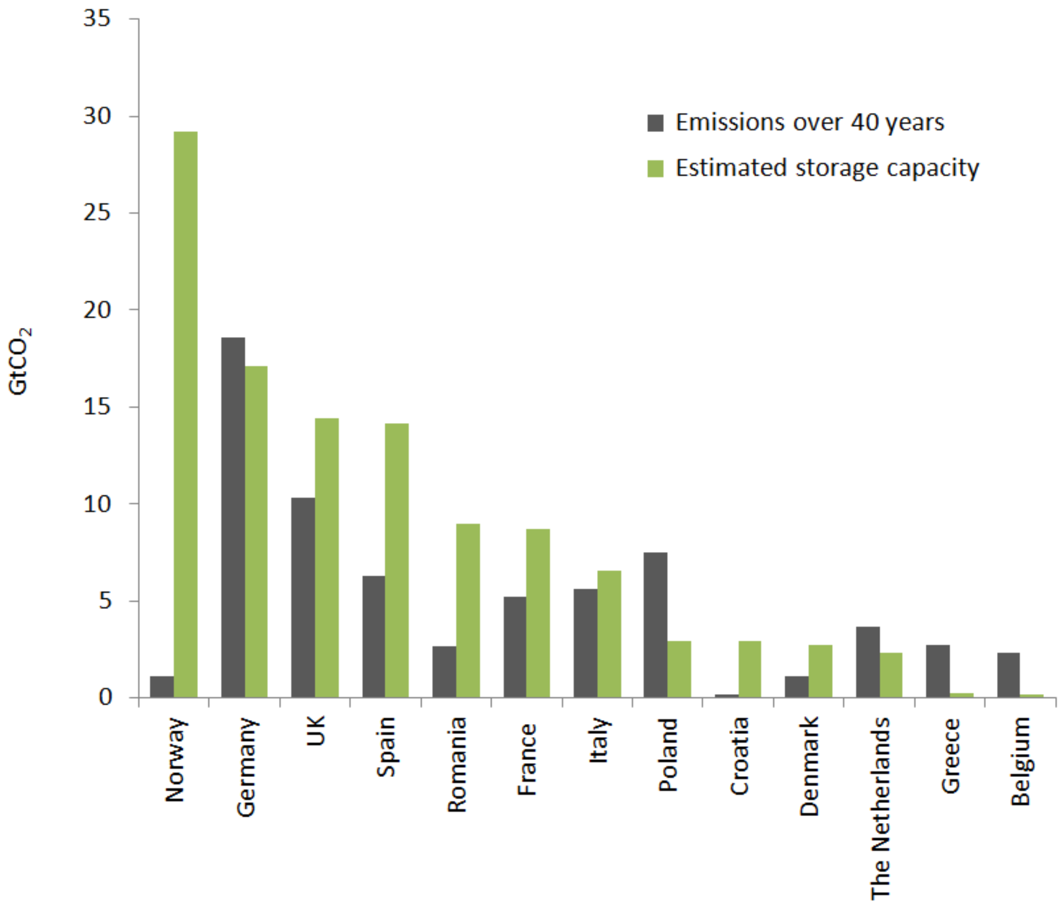
The GeoCapacity project generates regional source-sink maps, based on GIS mapping of large emissions point sources, storage options and pipeline infrastructure: these indicate storage capacity to be highly variable across Europe. Figure 2.14 shows the results across a range of key European countries, comparing estimated storage capacity with 40 years' emissions at current levels. In common with several other studies (UK SAP, 2011; Norwegian Petroleum Directorate, 2011; Holler and Viebahn, 2011; Bentham *et al*., 2014)[29], the assessment shows that many of the most promising storage formations are located offshore in the North Sea of **Norway** and the **UK**. In this context, the assessment suggests the longer-term potential for these countries to develop CO_2 storage services, or hubs.

For example, the Wuppertal Institute (Holler and Viebahn, 2011) notes that the offshore North Sea areas of Norway and the UK provide sufficient potential to import CO_2. They conclude that especially **Germany**, Europe's biggest emitter, with possibly limited storage capacity to sequester the desired amount of CO_2, the North Sea space of Norway and the UK could be part of a pipeline infrastructure for CO_2 storage (*ibid*). A number of European countries (e.g. **Greece**, **Belgium**) are thought to have relatively low storage capacity whilst others may have no or negligible capacity (e.g. **Finland**, **Estonia**, **Lithuania**).

[28] The European Commission has since initiated the CO_2StoP project in 2011 to establish a database of publicly available data on CO_2 storage potential in Europe. The CO_2StoP database may be the first step towards a European storage atlas.

[29] The Norwegian Petroleum Directorate estimates storage capacity of 72 $GtCO_2$ in the Norwegian sector of the North Sea.

Figure 2.14 Estimates of CO_2 storage capacity and 40 year emissions in Europe



Source data: EU GeoCapacity, 2009

2.5.3 North America

The USA National Energy Technology Laboratory (NETL) published the first Carbon Sequestration Atlas of the **United States** and **Canada** in 2007, and in 2012, the fourth version was published as *The North American Carbon Storage Atlas*, which also includes **Mexico**. The conservative (low range) estimates of storage capacity across the three countries is 1,751 Gt for saline reservoirs, 140 Gt for depleted oil and gas fields, and 15 Gt for coal-beds, collectively representing 600 years of storage assuming 2011 emissions rates (Table 2.2). High theoretical estimates are also given, resulting in estimated potential of up to 6,700 years. The atlas identifies additional locations for EOR. By matching EOR storage locations with specific sources of CO_2, the atlas provides a more comprehensive view of the outlook and potential for carbon storage through EOR as an early mover for CCS deployment in North America. Additional storage capacity assessments have been made by the United States Geological Survey (USGS) (Brennan *et al.*, 2010, Blondes *et al.,* 2013).

Table 2.2 Estimated CO_2 storage capacity in North America

Country	CO_2 emissions		Oil and gas storage resource	Unmineable coal storage resource		Saline formation storage resource		Total storage resource	
				Gt		Gt		Gt	
	Mt per year	No. of sources	Mt	lower	upper	lower	upper	lower	upper
Canada	218	254	15.6	3.6	8.2	38.3	295.9	47.6	319.7
Mexico	205	188	-	-	-	100.8	-	100.8	-
USA	3,014	1,811	124.4	11.8	12.2	1,613	20,138	1,796.5	20,382
North America	**3,437**	**2,253**	**140.1**	**15.5**	**20.4**	**1,752**	**20,435**	**1,945**	**20,702**

Source data: North American Carbon Storage Atlas, 2012

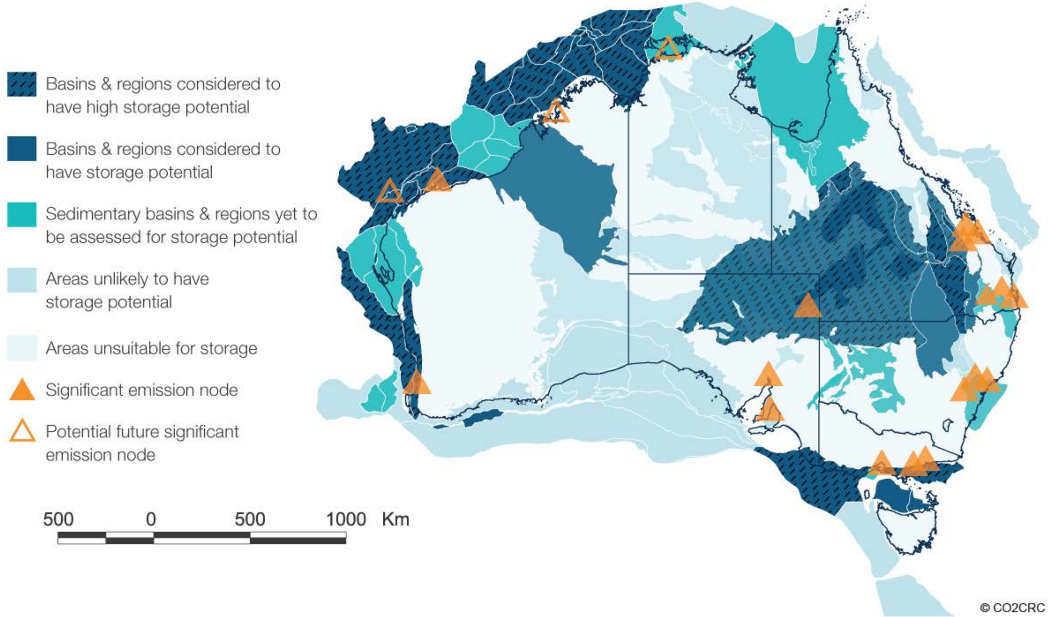
2.5.4 Asia-Pacific

Australia has undertaken a range of storage assessment activities at both the federal and state level, and in 2009, the Australian Carbon Storage Taskforce reported on its assessment of national storage capacity (Carbon Storage Taskforce, 2009). The report concluded that there is a 'high confidence' that the east of Australia has aquifer storage capacity for between 70 and 450 years at an injection rate of 200 Mt per year (i.e. 14-90 Gt capacity), and that the west of Australia has capacity for between 260 and 1,120 years at an injection rate of 100 Mt per year (i.e. 26-112 Gt capacity). The assumptions made on storage efficiency are highly conservative, and the authors conclude that far greater capacity is possible as basins and their CO_2 storage behaviour become better known (*ibid*). Figure 2.15 shows another recent national-level assessment illustrating the considerable potential for source-sink matching between significant CO_2 emission centres and potential storage areas.

A national saline-aquifer storage capacity assessment has also been carried out in **Japan** (Ogawa et al. 2011). Candidate saline aquifers were classified in terms of the type of geological structure and the amount of data available. CO_2 storage capacity for the entire country was then estimated based upon oil and gas exploration data, at 146 Gt. The areas considered were however located mostly offshore and far from large CO_2 emission sources. A second stage involved storage capacity estimation in 27 areas near large CO_2 emission sources. A preliminary assessment was performed, and promising sedimentary regions were selected for more detailed examination. Earlier studies by the Research Institute of Innovative Technology for the Earth (RITE) and Suekane et al. (2008) suggest a total national storage capacity of around 102 Gt.

South Korea's storage potential appears limited to three candidate basins all located offshore: Ulleung basin in the east/southeast, Kunsan Basin in the west and the Cheju-Fukue area in the south. The capacity and seal suitability of these basins require further characterisation (IEA, 2008).

Figure 2.15 Mapping of Australian CO_2 storage potential

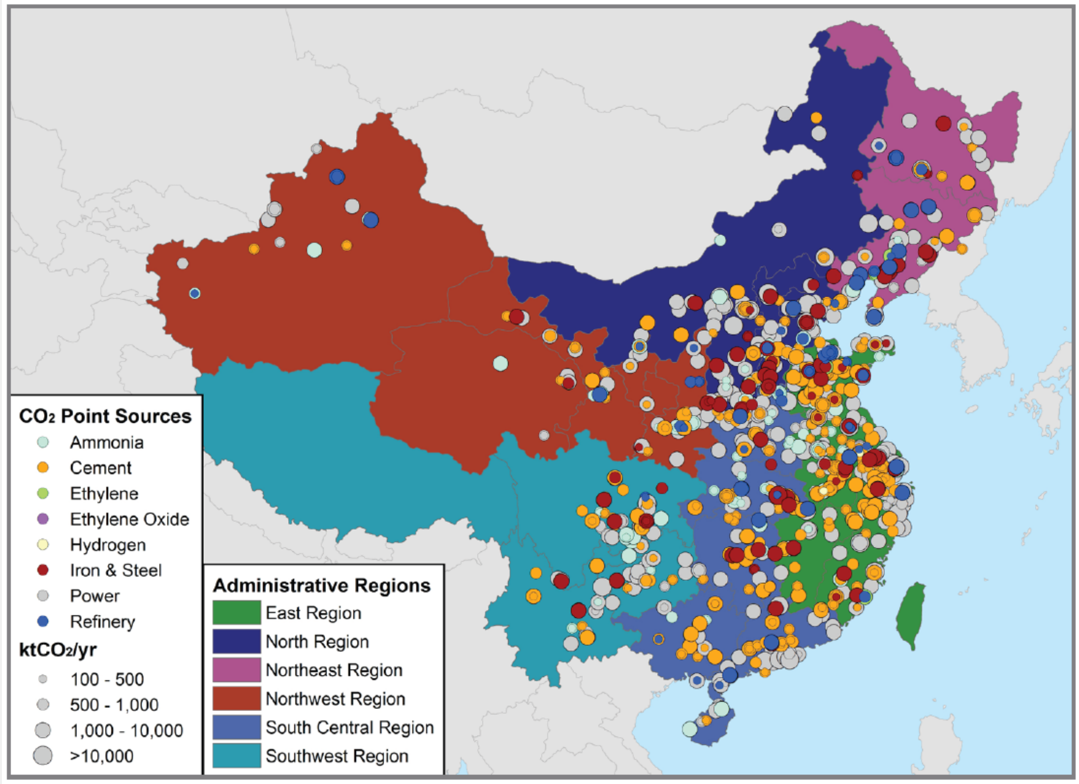


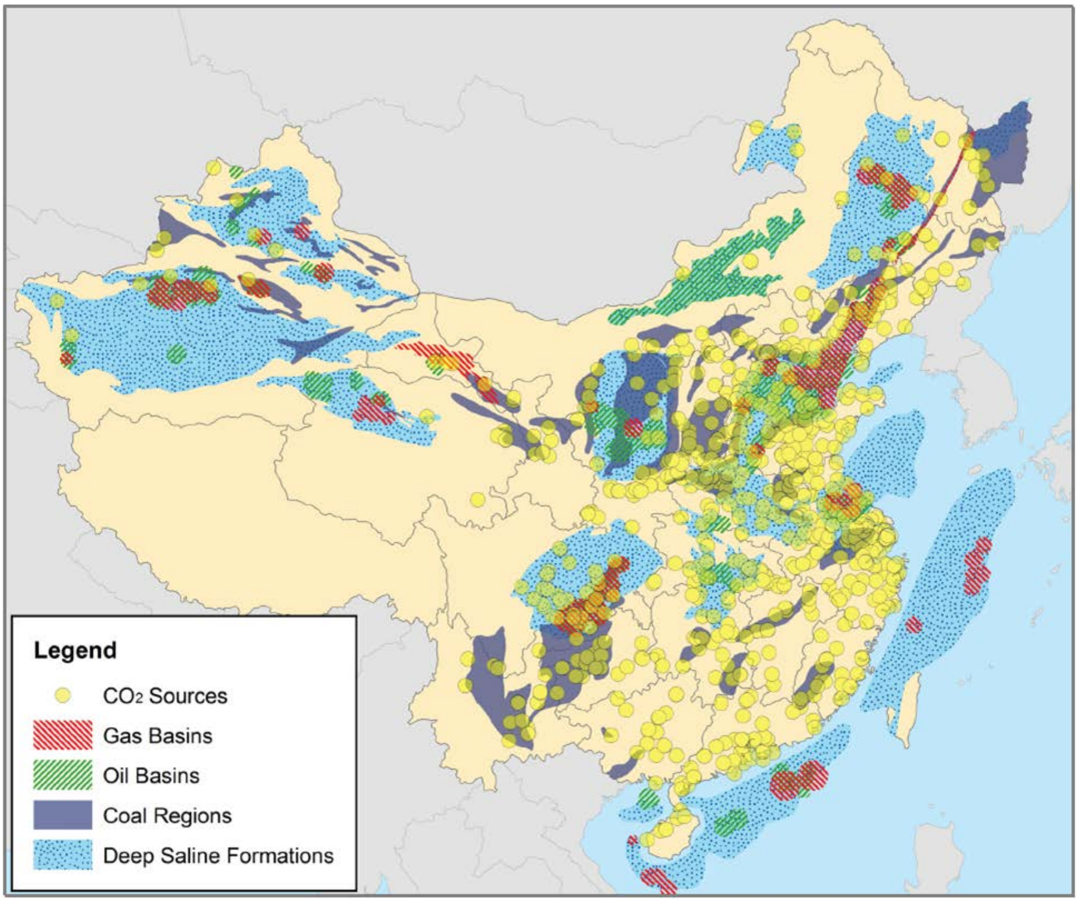
Source: CO2CRC, 2012

2.5.5 China

In 2009, the United States Department of Energy published its five-year joint Chinese-American study (Dahowski *et al.* 2009) providing a preliminary assessment of CO_2 storage capacity in **China.** The study found that China has a large theoretical and geographically dispersed storage capacity in excess of 2,300 Gt located in 90 onshore basins, with deep saline-filled sedimentary basins accounting for over 99 percent of the total. The assessment indicated a high level of source-sink matching (Figure 2.16) which shows that there are over 1,620 large stationary CO_2 point sources emitting a combined 3,890 Mt CO_2 per year, of which 91 percent are within 161 km of a candidate deep geologic storage formation (*ibid*). The team also identified an additional 780 Gt capacity in 16 offshore geologic formations along mainland China's heavily developed coastal regions, which could prove immensely valuable in this part of China where there is strong potential demand for storage (*ibid*). The Ministry of Science and Technology (MOST) have since begun a national level capacity assessment and a number of recent programmes and studies have assessed China’s storage potential at the regional, province and basin-level demonstrating significant potential (Fang and Li, 2011; Zhou *et al.*, 2013; Wang *et al.,* 2014).

Figure 2.16 CO_2 storage capacity assessment of China



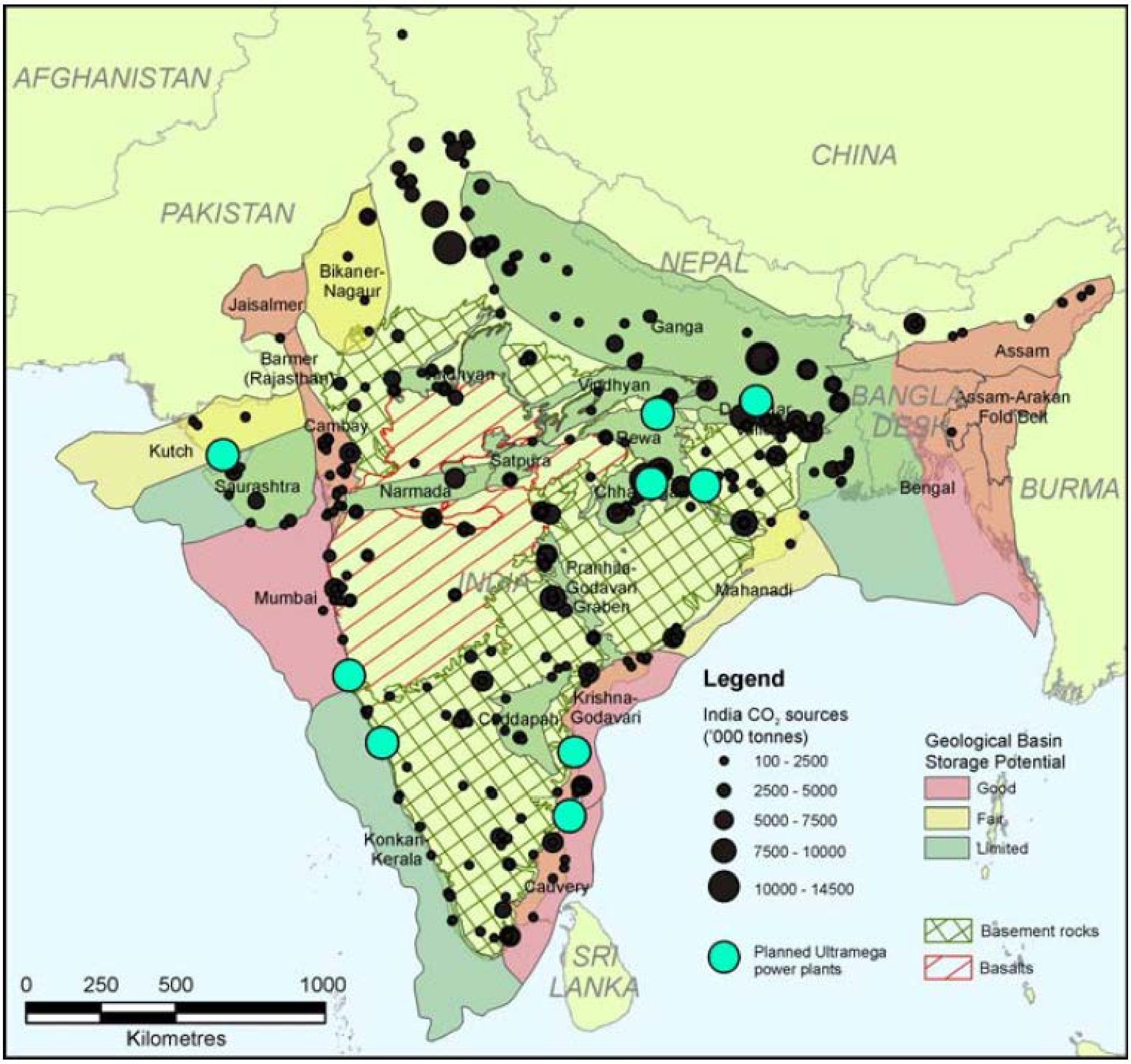


Source: Dahowski *et al.* 2009

2.5.6 Other Asia

In 2008, the IEAGHG completed a regional assessment of the potential for CO_2 storage in the Indian subcontinent, pointing to significant potential storage, particularly in parts of near shore area in **India** - specifically in the shallow offshore areas, in Gujarat and Rajasthan (IEAGHG, 2008c) (Figure 2.17). The Deccan flood basalts in northwest India have also been assessed as a storage target; the capacity at a depth below 800 m is tentatively estimated to range between 150 and 300 Gt (Jayaraman, 2007; Sonde, 2007). A pilot study by the National Thermal Power Corporation (NTPC) in collaboration with Pacific Northwest National Laboratories (PNNL) and the National Geophysical Research Institute (NGRI) plans to investigate whether CO_2 injection into basalts is technically feasible in India.

Figure 2.17 Preliminary assessment of CO_2 storage potential in India

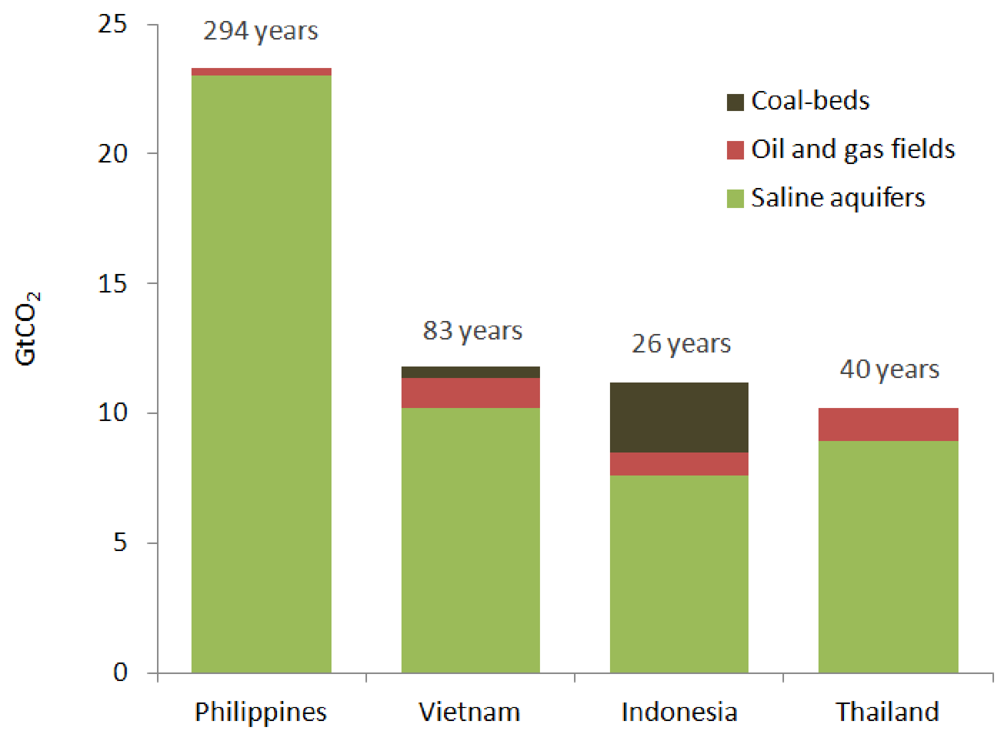


Source: IEAGHG, 2008c

The 2008 IEAGHG study also notes the reasonably good matching of large CO_2 sources with good potential for saline aquifer storage in **Pakistan** and highlights the storage capacity in natural gas fields. This is estimated at 1,602 Mt, resulting in the potential to store 35 years of CO_2 in the gas fields alone (IEAGHG, 2008c). Although relatively small in scale, estimates of storage potential from gas fields in **Bangladesh** are in the order of 65 times the annual emissions from large point sources. Similarly, although **Sri Lanka** is considered to have limited storage potential, a saline aquifer on the Sri Lankan side of the Cauvery basin classed as "good" is thought to be sufficient to store all national CO_2 emissions (*ibid*). The study concludes that there is good potential for CCS on the Indian sub-continent.

A programme supported by the Asian Development Bank (ADB), the GCCSI and the UK Government is assessing prospects for CCS development in Southeast Asia (ADB, 2013). As part of its initial assessment, it has estimated theoretical storage potential for **Vietnam**, **Indonesia**, **Thailand** and the **Philippines** (Figure 2.18). The assessment indicates large storage potential and opportunities for enhanced hydrocarbon recovery with good source-sink matching opportunities across the region. Based on IEA estimates of national energy emissions in 2012, the estimated capacity for the region as a whole (57 Gt) is equivalent to around 62 years of CO_2 storage.[30] Within **Malaysia**, the largest concentration of CO_2 emissions is in the Malay basin (76% of the total). Despite good permeability and porosity, the area has limited CO_2 storage potential. High CO_2 gas fields in Malaysia represent a significant CCS and CO_2-EOR opportunity; CO_2 content from Malaysian gas fields varies from 28% to 87% (Darman, 2006).

Figure 2.18 Theoretical storage capacity assessment of Southeast Asia



Note: figures above columns indicate equivalent years of geological storage based on energy CO_2 emissions estimated in 2012.
Source data: ADB, 2013; IEA, 2014b

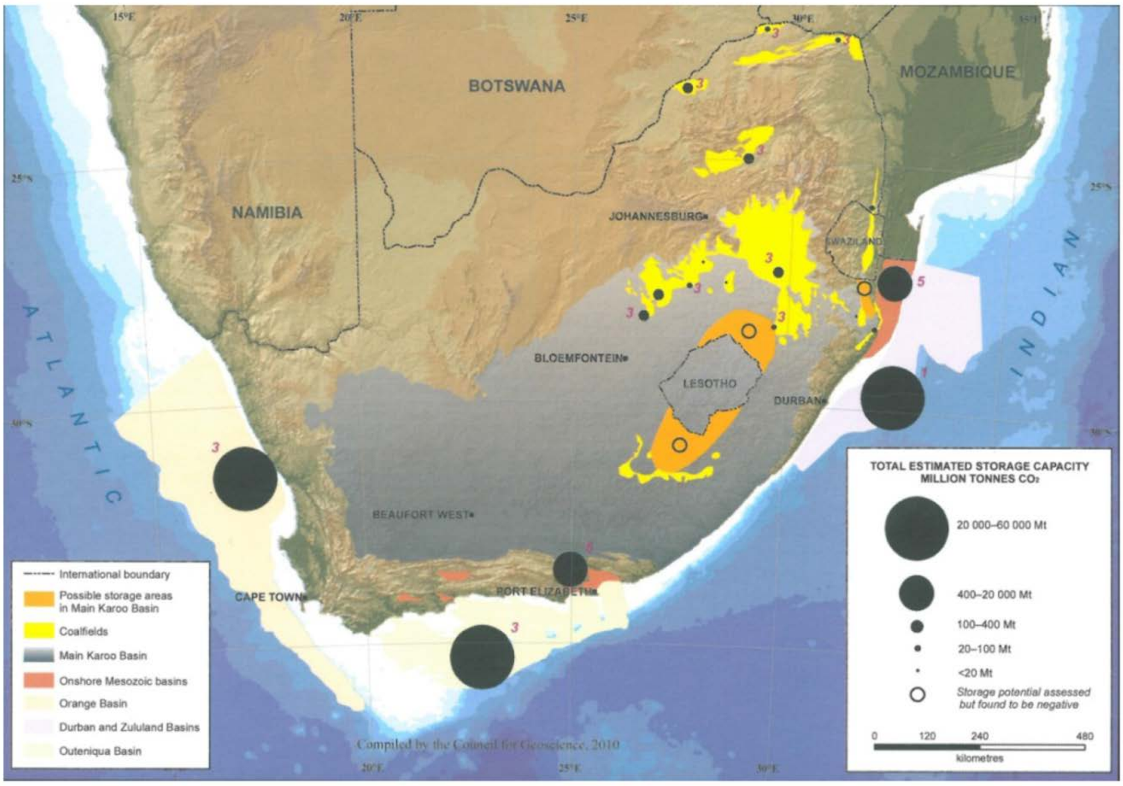
[30] These data include emissions sources of all sizes and the estimated years should therefore be seen as highly conservative as an indication of viable storage potential

2.5.7 Africa and Middle East

While estimates for storage capacity in **Africa** vary widely, Hendriks, et al. (2004) indicate that the best prospects are in aquifers (6-220 Gt) and oil & gas fields (30-280 Gt). North and West Africa represent the highest potential for oil and gas fields, while all areas except for East Africa have significant storage space in aquifers (15-60 Gt each).

A CO_2 Storage Atlas of **South Africa** was released in September 2010 (Council for Geosciences, 2010). The report estimates a national storage capacity of around 150 Gt, and indicates that most of the potential for storage lies in offshore sediments of the Western Cape and Orange Basin regions (Figure 2.19). Less than 2% of the estimate capacity lies onshore; up to 40 Gt may be available for enhanced coal bed methane (ECBM). A national CCS assessment commissioned by the World Bank under its CCS Trust Fund programme surveyed CO_2 storage options in **Botswana** (Carbon Counts, ERM, Wellfield Geosciences, 2015). The assessment indicates significant potential in the Kalahari-Karoo sediments of up to 1.8 Gt across several basins, sufficient to store the whole of Southern Africa's emissions for several decades.

Figure 2.19 Deep saline storage opportunities in South Africa



Source: Council of Geosciences, 2010

Given the size of the sedimentary basins in the area, there is very significant potential storage in the **Middle East**. Hendriks, et al. and the Very Long-Term Energy and Environment Model (Hendriks, *et al.,* 2004; VLEEM, 2003) provide the following preliminary ranges:

- 105 Gt to 1,000 Gt in onshore oil and gas fields;
- 75 Gt to 200 Gt in offshore oil and gas fields; and
- 1 Gt to 500 Gt in aquifers.

Work undertaken by Stevens *et al.* (2001) identifies oil and gas sites of greatest potential storage capacity as the Qatar dome (53 Gt), Zagros Fold Belt (42 Gt), Mesopotamian Foredeep (42 Gt), Greater Ghawar (36 Gt) and Rub Al Khali (24 Gt) formations. Much of the potential for CCS in **North Africa** is related to the capture of CO_2 from produced gas and its re-injection for storage or enhanced hydrocarbon recovery. The gas fields in **Algeria**, **Tunisia** and **Libya** seem to offer the greatest potential. Further work is however required to characterise the suitability of deep saline formations in the Middle East for CO_2 storage (IEA, 2008).

The World Bank CCS Trust Fund programme has commissioned nine country-level programmes to date at various stages of development: in addition to Botswana and South Africa, these include Egypt, Jordan, Kosovo, Indonesia, China, Mexico and the Maghreb region (Algeria, Morocco and Tunisia). Although some of these include storage capacity assessments, the majority of the study reports are not publicly available. The **Jordan** study indicates that two areas of the country, underlain by deep saline formations, appear to be favourable for storing CO_2.[31] The **Egypt** study assessed only depleted oil and gas fields and indicated limited storage potential of around 400 Mt, principally located in the Nile Delta and Western desert, offering some potential for low cost storage and EOR projects taking CO_2 from nearby gas processing installations (Carbon Counts, ERM and Environics, 2013).

2.5.8 Latin America

The CARBMAP project aims to assess stationary emission sources in **Brazil** and estimate CO_2 storage capacity on a country- to basin scale. Preliminary results suggest that sedimentary basins may provide as much as 2,000 Gt of effective storage capacity in saline aquifers (Ketzer *et al.*, 2007). Source-sink analysis suggests that the basins in the southeast of the country are particular well located, whereas large effective capacity in the northern part of the country are likely to be too far away from large source to prove viable as storage site.

Most of the potential CO_2 storage capacity in **Venezuela** is in the eastern offshore areas and in the Lake of Maracaibo, relatively close to a number of sources (IEA, 2008). Bradshaw's (2006) storage retention analysis estimates 2.7 Gt storage space in the lake in oil and gas fields. Opportunities for EOR also exist as reservoirs are depleting. The Venezuelan national oil and gas company, PDVSA, has embarked on an EOR screening project for a number of maturing fields.

2.5.9 Summary

Table 2.3 shows a non-exhaustive summary of national and regional storage estimates. Even the most conservative assumptions suggest that most world regions have access to storage capacity significantly in excess of their likely total cumulative CO_2 emissions over the next few decades. Those regions with major oil and gas production fields (e.g. Middle East, North Africa, Malaysia, Vietnam, Brazil, and Mexico)are likely to have significant capacity available in depleted reservoirs, with high-CO_2 gas resources and EOR potential offering particularly interesting early opportunities. Elsewhere, studies suggest considerable capacity from saline aquifers (e.g. China, North America, Australia) and ECBM storage (South Africa, Indonesia). Others countries e.g. South Korea, have few proven suitable storage sites in close proximity to large CO_2 sources.

[31] These are the Hamad Basin in northeast Jordan and the Wadi Sirhan Basin in east-central Jordan; the study estimates the CO_2 storage capacity of the Hamad Basin at approximately 7 Gt billion metric tons and the capacity of the Wadi Sirhan Basin at approximately 2.7 Gt (World Bank, 2012).

Table 2.3 Recent estimates of geological CO_2 storage capacity for key countries

Country/region	$GtCO_2$	Years of storage*	Sources
Europe			
EU25	117 - 360	62 - 200	EU GeoCapacity, 2009
Norway	21 - 45	750 - 1,600	Holler & Viebahn, 2011; NPD, 2011
UK	14.4 - 78	56 - 170	EU GeoCapacity, 2009; Bentham *et al.*, 2014
Germany	5 - 17.1	11 - 37	EU GeoCapacity, 2009; Holler & Viebahn, 2011
Spain	14.2	90	EU GeoCapacity, 2009
France	1 - 8.7	8 - 66	EU GeoCapacity, 2009; Holler & Viebahn, 2011
Italy	6.6	47	EU GeoCapacity, 2009
Poland	2.9	15	EU GeoCapacity, 2009
North America			
USA	1,797 - 20,382	600 - 6,700	NETL, 2012
Canada	47.6 - 319.7	215 - 1,450	NETL, 2012
Mexico	100.8	490	NETL, 2012
Asia Pacific			
Australia	40 - 202	130 - 670	Carbon Storage Taskforce, 2009
Japan	146	120	Ogawa *et al.,* 2011
China	2,300	590	Dahowski *et al.,* 2009
Other Asia			
India	150-300	220 - 450	IEAGHG, 2008c
Pakistan	1.6	35	IEAGHG, 2008c
Bangladesh	1.1	65	IEAGHG, 2008c
Philippines	23.3	294	ADB, 2013
Vietnam	11.8	83	ADB, 2013
Indonesia	11.2	86	ADB, 2013
Thailand	8.9	40	ADB, 2013
Africa	44-540	40 - 525	Hendriks, *et al.,* 2004
South Africa	150	400	Council for Geosciences, 2010
Botswana	1.8	400	Carbon Counts, ERM, Wellfield, 2015
Middle East	181 - 1,700	100 - 1,000	Hendriks *et al.*, 2004
Jordan	9.7	450	World Bank, 2012
Egypt	0.4	-	Carbon Counts, ERM, Environics, 2014
Latin America			
Brazil	2,000	4,500	Ketzer *et al.*, 2007
Venezuela	2.7	15	Bradshaw, 2006

Note: *Where data is available within the studies, figures are based on annual emissions from large point sources only held at constant annual levels; otherwise total annual energy CO_2 emissions are used, based on IEA data (2014) and as such the estimated years should be viewed as highly conservative. Where existing storage estimates are highly limited/restricted (e.g. just to oil and gas fields) figures are not provided.

2.6 Conclusions

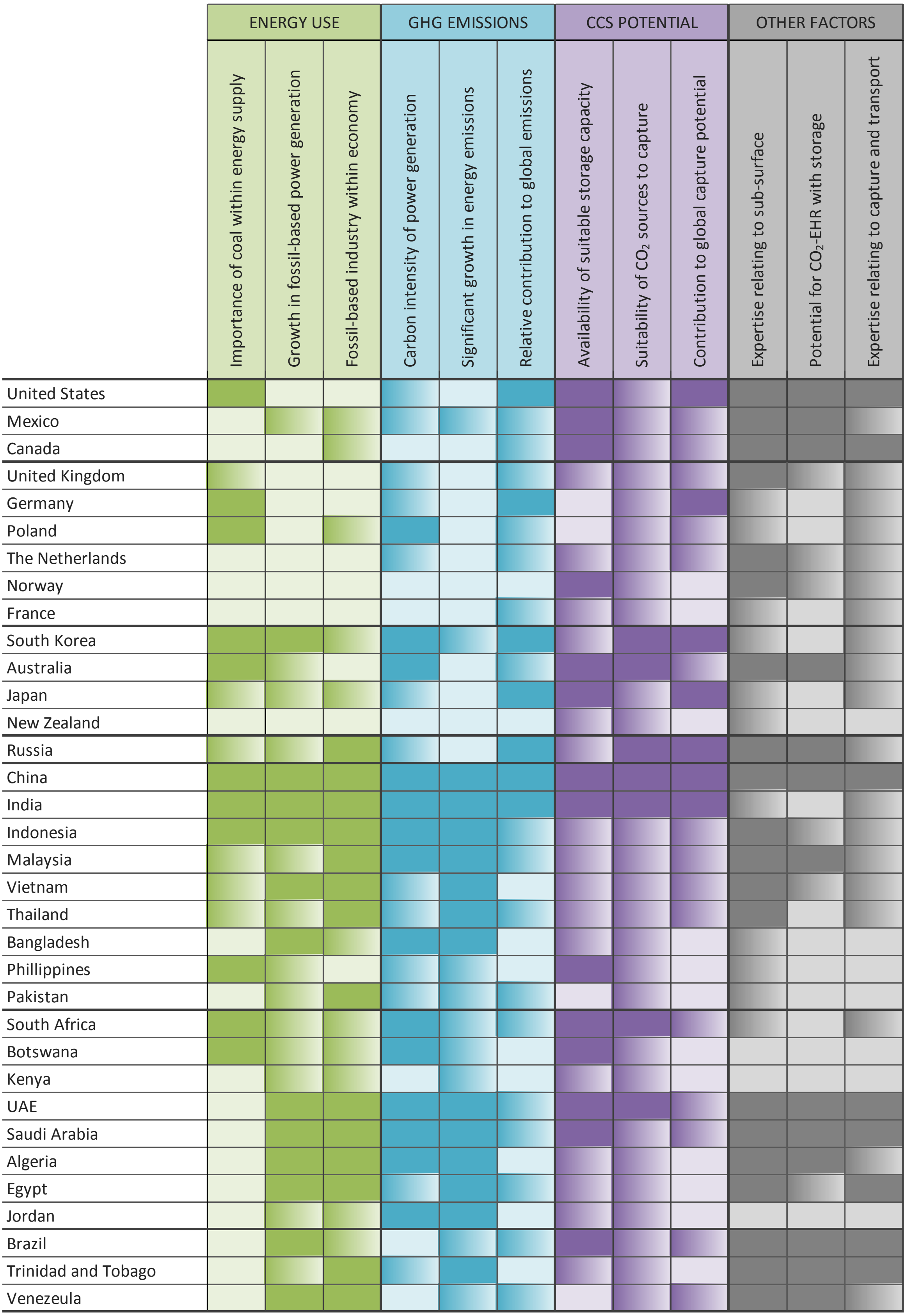
2.6.1 Summary of national drivers for CCS

Figure 2.20 shows a summary of the drivers for supporting and deploying CCS as a key abatement option for a range of key countries worldwide.

Two broad conclusions can be made. Firstly, there are clearly significant drivers for undertaking CCS across all world regions. For many countries, the technology allows for deep cuts in national GHG emissions within the context of continued economic growth and use of fossil fuels: this applies in particular to those emerging economies whose patterns of energy use within power generation and industry are based on fossil-based resources, most notably coal. Existing studies suggest that for the countries shown - which together contribute over 80% of total global CO_2 emissions - there is sufficient storage capacity and eligible emissions sources to deploy CCS on the scale needed to meet the long-term goals of the UNFCCC. Secondly, drivers for CCS may vary significantly between countries, reflecting *national circumstances*:

- **North America:** Although coal use and fossil-based power generation are relatively stable, the United States, Canada and Mexico have large energy and industrial sectors suitable for capture, and significant CO_2 storage potential. There is significant expertise across all stages of CCS technology, with the United States and Canada having undertaken commercial-scale CO_2-EOR for several decades.
- **Europe:** National circumstances are extremely diverse: countries such as Germany and Poland have large coal-based industries whilst energy use in others such as France and Norway is largely based on non-fossil fuel resources. The availability of suitable storage capacity is also varied, with the North Sea oil and gas producing countries (Norway, UK) having significant potential as well as in-country expertise relevant to CO_2 storage.
- **OECD Asia-Pacific:** The heavily industrialised fossil-based mature economies of Australia, Japan and South Korea have significant potential to meet national climate goals using CCS within a portfolio of clean technology and abatement measures.
- **Non-OECD Asia:** China, India and the other emerging economies of Asia account for almost 40% of global emissions, with strong growth in coal-fired power generation and carbon-intensive industrial sectors such as cement, iron and steel and chemicals production. Several countries in the region have mature oil and gas sectors with the potential for CO_2-EHR and/or low-cost capture from contaminated natural gas fields.
- **Africa and Middle East:** Coal-based economies such as South Africa and Botswana have large emissions sources suitable for CO_2 capture along with adequate storage capacities. Many countries in the Middle East have fast growing emissions with enormous geological storage and CO_2 utilization potential, as well as in-country expertise.
- **South America:** There is significant potential for industrial CO_2 capture and storage within energy producing countries such as Brazil, Venezuela, and Trinidad and Tobago. The region also has considerable in-country expertise relating to sub-surface aspects of CCS with likely potential storage combined with CO_2-EHR.

Figure 2.20 National drivers for CCS



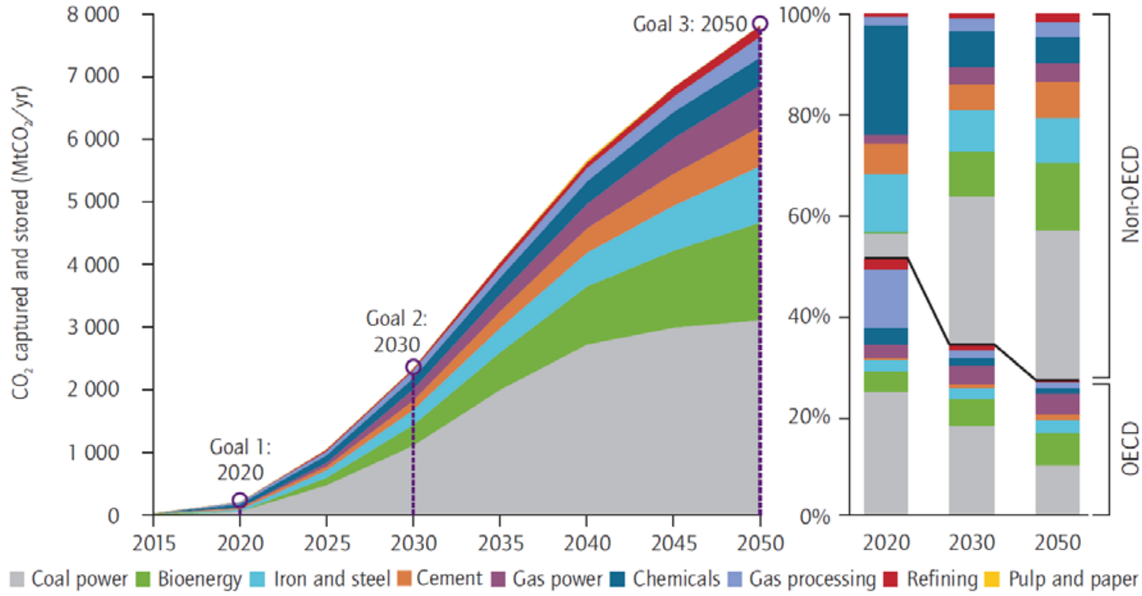
Notes: Partially coloured areas indicate only partial drivers relative to other countries. Drivers for CCS (low, medium, high) are determined as follows: (1) *Importance of coal within energy supply*: coal share of energy mix > world average = high; Coal share between 10% and world average = medium; (2) *Growth in fossil-based power generation*: fossil-based power generation increase 2000-2012 >10% = low; >100% = high: 10-100% = medium; (3) *Fossil-based industry within economy*: (sum of industry sector and energy sector energy emissions (MtCO_2) / GDP (billion USD) in 2012) > 0.25 = high; > 0.1 = medium; < 0.1 = low; (4) *Carbon intensity of power generation*: Carbon intensity of power generation (gCO_2/kWh) > world average = high; >300g/kWh = medium; <300g/kWh = low; (5) *Significant growth in energy emissions*: CO_2 growth (2000-2012) > 50% = high; >20% = medium; <20% = low; (6) *Relative contribution to global emissions*: >2% of world total = high; > 0.5% = medium; <0.5% = low; (7) *Availability of suitable storage capacity*: high-level relative assessment based on published studies; (8) *Suitability of CO_2 sources to capture*: Share of national CO_2 emissions falling within sectors considered suitable/viable for capture (e.g. power and industry); <60% = medium; >60% = high; (9) *Contribution to global capture potential*: global share of CO_2 emissions falling within sectors considered suitable/viable for capture (e.g. power and industry); >2% of world total = high; >0.5% = medium; <0.5% = low; (10) *Expertise relating to sub-surface*: significant and active national O&G industry = high; some O&G exploration/production and/or significant mining or other geophysical activity = medium; otherwise = low; (11) *Potential for CO_2-EHR with storage*: high-level relative assessment made on basis of public studies and assessments of theoretical potential for undertaking CO_2-EHR; and existing/planned activities; (12) *Expertise relating to capture and transport*: High-level relative assessment of industrial activity in sectors where CO_2 is routinely captured (e.g. hydrogen, ammonia, gas processing, fertilizers).

2.6.2 Regional CCS deployment required under the 2DS

This section has provided an evidence-based description of the drivers for undertaking CCS across key regions and countries worldwide, highlighting the role of national circumstances. National circumstances determine both the level of CCS potential and the type of projects which can be deployed. Relevant factors include patterns of energy use, carbon intensity, CO_2 sources (power; industry; upstream), and CO_2 storage capacity. The assessment shows that there is significant potential for undertaking CCS in most world regions and countries, although the relative potential - in terms of total CO_2 abatement – may vary along with the choice of specific sectors and project types.

As described in Section 1, analysis by the IEA shows that CCS is an integral part of any lowest-cost mitigation scenario. In the 2DS, CCS is widely deployed in both power generation and industrial applications. The IEA *Technology Roadmap for Carbon Capture and Storage* (IEA, 2013a) indicates that the total CO_2 capture and storage rate must grow from the tens of millions of tonnes of CO_2 currently captured worldwide to billions of tonnes of CO_2 in 2050 in order to address the emissions reduction challenge. A total cumulative mass of approximately 120 GtCO_2 needs to be captured and stored between 2015 and 2050, across all regions of the globe (Figure 2.21). The associated investment costs will be significant. The additional investment associated with the capture stage alone is estimated at almost USD 1.3 trillion through 2050 (IEA, 2009).

Figure 2.21 CCS deployment under the 2DS



Source: IEA, 2013a

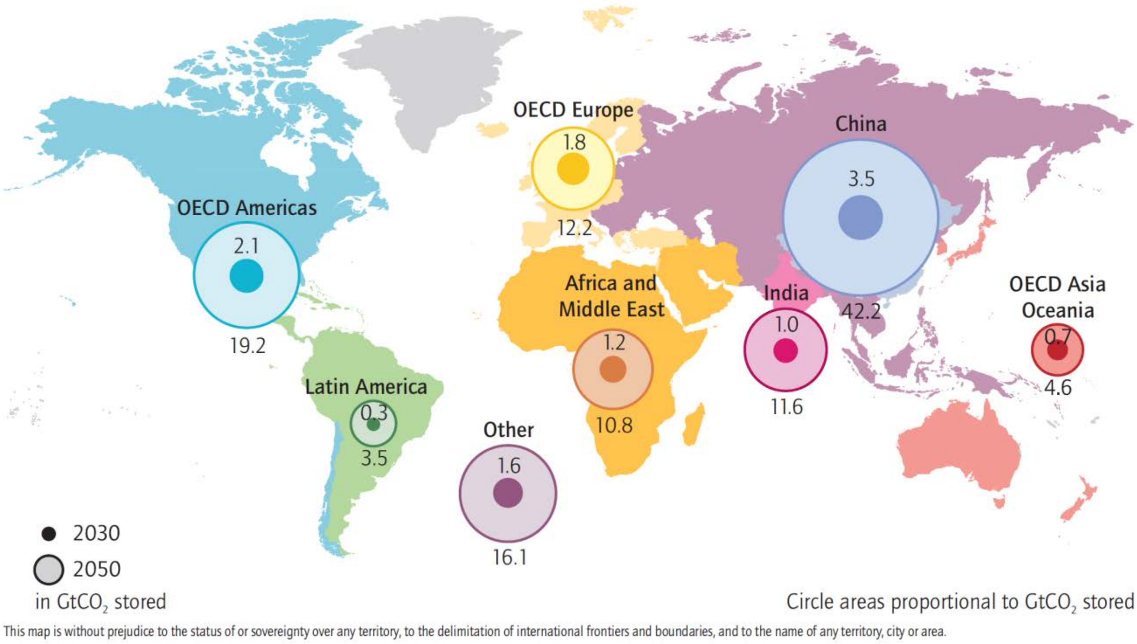
As shown in the figure, the IEA roadmap identifies three specific goals for CCS deployment:

- **Goal 1**: By 2020, the capture of CO_2 is successfully demonstrated in at least 30 projects across many sectors, including coal- and gas-fired power generation, gas processing, bioethanol, hydrogen production for chemicals and refining, and direct reduced iron (DRI) steel production, leading to over 50 $MtCO_2$ safely and effectively stored per year.
- **Goal 2**: By 2030, CCS is routinely used to reduce emissions in power generation and industry, having been successfully demonstrated in a large range of industrial applications. This level of activity will lead to the storage of over 2 $GtCO_2$/yr.
- **Goal 3**: By 2050, CCS is routinely used to reduce emissions from all applicable processes in power generation and industrial applications at sites around the world, with over 7 $GtCO_2$ annually stored in the process.

While the 2DS sees fossil fuel generation considerably reduced by 2050 compared to current levels, the largest single application of CCS in the 2DS is in coal- and gas-fired power generation. By 2050, a total of 964 GW of power generation capacity needs to be equipped with capture, or 8% of all power generation capacity globally. This includes about two-thirds of all coal capacity and one-fifth of gas. Nonetheless, industrial applications of CCS are just as important in the 2DS (IEA, 2013a).

The IEA assesses the contribution towards these goals from different world regions (Figure 2.22). As described in Section 2.5, existing estimates of regional storage capacity are significantly in excess of the volumes of CO_2 captured and stored under the 2DS.

Figure 2.22 Cumulative CO_2 captured 2015-2030 and to 2050 by region under the 2DS

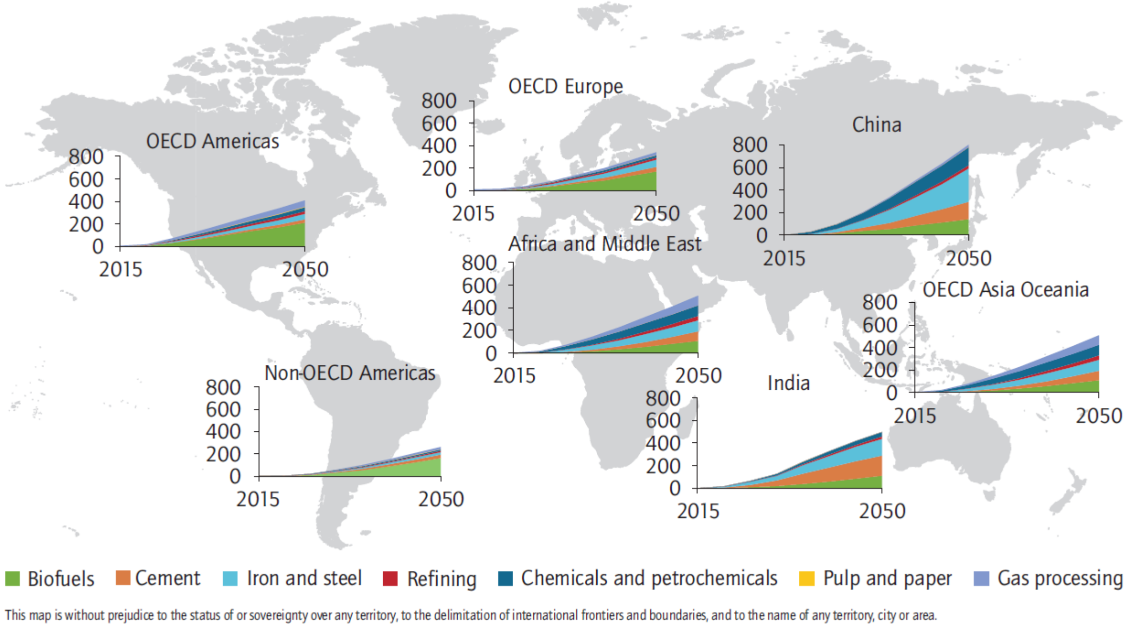


Source: IEA, 2012a

As illustrated in this section, regions and countries vary in terms of which sectors and technologies can contribute most towards CCS deployment. Within power generation, of the total 964 GW equipped with capture in the 2DS in 2050, over 60% (586 GW) are located in **China** and the OECD Americas (principally the **United States**). However, in China more than 90% of this capacity is coal-fired, while in the United States only about half of capture-equipped capacity is coal-fired, the remainder being mainly gas-fired capacity (*ibid*). Other regions of the world where a substantial amount of gas-fired capacity is capture-equipped include the **Middle East**, **OECD Europe** and **Southeast Asia**. In the Middle East, it is particularly noteworthy that over 90% of capture-equipped capacity under the 2DS is gas-fired (*ibid*).

Regional variations are also significant within CCS applied to industrial sectors in the 2DS (Figure 2.23). The relative importance of CO_2 capture from gas processing is shown within **OECD Americas**, **Africa** and **Middle East** and **OECD Oceania**, whereas for **India** and **China** heavy carbon intensive sectors such as cement and iron and steel contribute the largest share of CCS potential. The increasing contribution of biofuels through 2050 is most significant in OECD regions supported by ongoing policy incentives, but most significantly in non-OECD America, where countries such as **Brazil** are developing large biofuels industries.

Figure 2.23 CO_2 captured from industrial applications in the 2DS



Note: individual graphs show million tonnes of CO_2 captured by world region
Source: IEA, 2013a

3 SUPPORTING AND DEPLOYING CCS

3.1 Introduction

The previous chapter assessed the range of drivers for undertaking CCS across different regions and countries worldwide as part of efforts to mitigate GHG emissions. The analysis demonstrated the significant potential for CCS deployment: CO_2 can be captured from a variety sectors and sources and even the most conservative estimates of geological CO_2 storage capacity indicate that, for most regions, there is likely to be sufficient potential to permanently sequester several decades' of CO_2 emissions from large point sources. The IEA, IPCC and others accordingly recognise CCS as a key mitigation technology.

Policy makers will however need to take a range of ambitious actions to overcome a number of barriers and challenges currently facing the technology. The introductory chapter of this report (Chapter 1) described how CCS deployment has so far fallen significantly behind that of other low carbon technologies, and also the levels required according to recent analysis. Despite ongoing efforts to increase the rate of project deployment, the technology faces a range of technical, institutional, economic, regulatory and financial barriers which may be hindering its wider development.

This chapter describes how to support and achieve wider deployment of CCS within national climate policy plans. It begins by considering the barriers and challenges hampering progress to date. The chapter then presents a framework or 'pathway' for national CCS support and deployment, covering key elements, or indicators, of what is needed to overcome these barriers and move towards ambitious and effective CCS deployment. In so doing, the analysis draws upon experiences worldwide to describe a range of potential approaches and options. Finally, the chapter assesses key countries and regions' current progress against this framework.

3.2 Barriers to widespread deployment

It is widely acknowledged that a number of barriers need to be overcome in order to achieve large-scale CCS deployment in both developed and developing countries (World Bank, 2011). Some of these are common to many pre-commercial or emerging technologies (low carbon, or otherwise) whereas others are more specific to CCS. They can be broadly grouped as follows:

- **Legal and regulatory barriers:** Many countries lack the legal and regulatory frameworks needed to ensure the safe and effective capture, transport and storage of CO_2 and to provide investors with the security for CCS deployment.
- **Policy barriers:** CCS requires policy-makers to address policy concerns with the technology and to implement ambitious, well-designed support policies to encourage private sector investment and incentivise large-scale projects across a range of sectors.
- **Economic and financial barriers:** Combining CCS with industrial and power generation projects entails additional costs to project developers and consumers; economic and financial incentives are therefore necessary to overcome investment risks and help make projects economically viable.

- **Technical barriers:** The integration of each CCS project component - capture, transport and storage - at scale gives rise to a number of potential technical and operational challenges.
- **Institutional and public acceptance barriers:** Building in-country capacity within national organisations and departments and addressing societal concerns are essential for ensuring effective project deployment and gaining acceptance of CCS technology**.**

Each of these key areas is discussed further below.

3.2.1 Legal and regulatory barriers

The development of robust legal and regulatory frameworks for CO_2 capture, transportation and storage activities - and associated tools, models and guidelines - are critical to promoting wider CCS deployment. The main regulatory gaps within national/regional frameworks typically lie with the storage component of CCS projects, particularly in relation to CO_2 storage liability. Fewer issues tend to arise in regulating the capture and transport stages, which usually fall within existing regulations. In many cases, proposed storage provisions within national regulations may be insufficiently robust and may need further development.

Box 3.1 highlights the key requirements of a regulatory framework for geological storage of CO_2 identified in the impact assessment of the EU CCS Directive. Several of these issues are briefly described further below.

Box 3.1 Key requirements of a regulatory framework for CO_2 storage

- Requiring storage sites to be permitted, based on an assessment of the characteristics of the geological storage site, and its suitability for long-term storage of CO_2 based on appropriate risk assessment procedures
- Imposing conditions on the safe use and selection of a site
- Ensuring that the assessment of whether the above conditions are met is robust. The main way of achieving this is via competent authority approval but other options may also be considered
- Imposing conditions on the composition of CO_2 accepted for storage
- Imposing monitoring requirements
- Imposing verification/inspection requirements
- Requiring corrective measures in the case of CO_2 leakage
- Establishing measures for dealing with liability, including possible insurance
- Establishing closure and after-care procedures for the storage site, including provisions on transfer to the state
- Ensuring equal access to the transport and storage network

Source: Impact Assessment for EU Directive 2009/31/EC on the geological storage of carbon dioxide.

CCS Permitting and Licensing Framework

Permitting and licensing CO_2 capture and transport activities are typically accommodated under existing arrangements within the regulatory frameworks of most jurisdictions. CO_2 storage may however give rise to new requirements which must be met for safe and robust CCS project deployment. Issues may include various provisions for interactions between CO_2 storage and petroleum licences (e.g. operating criteria for CO_2 storage licensees and existing petroleum licensees in the same geographical area; licensing of existing petroleum licence areas for CO_2 storage), suitable time periods for storage permit application; public consultation arrangements; and other special license provisions, (e.g. in the event of transfer of license, discovery of petroleum reserves).

There are two broad approaches to regulating CCS exploration and storage activities:

- Integrated exploration and storage licensing frameworks that interact with CO_2 storage legislation, as has been the case in the EU; or
- Legislative amendments or decisions usually associated with existing oil and gas exploration legislation, as has been the case in Australia, Canada, and (partially) in the USA.

Property Rights

A number of property rights issues must be addressed when undertaking CCS projects, including (after Carbon Counts, ERM and Environics, 2014):

- **Ownership of the CO_2 across the CCS chain.** Where the operational phase of a project involves different operators responsible for each stage of the CCS chain i.e. capture, transport and storage, allocation of CO_2 ownership must be achieved. This can often be undertaken based on existing commercial contractual practices, allocating clear responsibility for CO_2 ownership (or 'custody') and associated project risks.
- **Property and access rights associated with surface infrastructure.** Property rights for surface facilities and related access rights are typically governed through existing property law and other access and permitting laws and should not pose major issues to CCS projects unless certain rights have been granted to specific development projects - in which case it may be necessary to review the extension of such rights to CCS projects.
- **Property rights associated with sub-surface geological pore space in which the CO_2 is stored**. Pore space is typically owned by the state, particularly where there is oil and gas exploration, although this is not always specified clearly within existing legislation. With the introduction of CCS, national laws may be required to recognise an ownership interest in subsurface pore space. This should clearly include rules on how these rights should be recognised and protected as well as a process for assuring that storage operators secure the legal property right to store CO_2.

Monitoring, Reporting and Verification

Because CCS involves the storage of CO_2 to avoid its emission to atmosphere rather than to avoid its production, it poses the risk that it could remerge to the atmosphere at some point in the future. This creates problems associated with the issue of 'permanence' if for example carbon credits are awarded for not emitting CO_2, thereby potentially undermining the objectives of its use, and also the integrity of any emission trading scheme into which the credits have been used. The issue is particularly pertinent to emission trading but any robust policy approach supporting CCS projects will similarly need to demonstrate environmental integrity. For example, accurate and robust data are required in the event of establishing liability in the event of leakage from or disruption to the CO_2 storage site. Guidelines or standards for the monitoring, reporting and verification (MRV) of injected CO_2 are therefore crucial to any regulatory or legal framework for CCS. Such arrangements must be in conformity with relevant international reporting guidelines and requirements e.g. IPCC reporting guidelines for UNFCCC Parties.

Liability Issues

CCS projects give rise to different liabilities across the project chain and cycle. There are two broad types, depending on the phase of the project:

- Liabilities associated with capture, transport and injection activities during the operational phase of the project; and
- Liabilities associated with the storage site during the post-closure period (often referred to as 'long-term liability')

The various legal liabilities and other responsibilities which may occur during the operation of a storage site (e.g. monitoring, remedial measures, environmental or property damages) can typically be dealt with by existing common law and are likely to be adequately covered by contract arrangements and traditional risk transfer. The long-term liability associated with geological leakage of stored CO_2 and major loss of containment is however less well understood and poses challenges to regulators, in part due to the long timeframes after the life of the project's assets or possibly the storage site operator itself. A CCS liability regime must therefore be developed clearly defining *inter alia* any liability transfer arrangements (e.g. from the project operator to the state) and provisions in the event of seepage (e.g. insurance; funds).

Liability for CO_2 storage has been identified as a key issue within international discussions on CCS under the UNFCCC. Where projects are liable to seek support under UNFCCC mechanisms, regulators are likely to need to ensure host country compliance with the modalities and procedures (M&Ps) for CCS activities undertaken as CDM projects.[32] For example, the M&Ps include specific liability provisions indicating the minimum length of the liability period, performance criteria and other considerations such as for example financial provisions that need to be in place to cover against monitoring and possible CO_2 seepage costs.

3.2.2 Policy barriers

Because CCS is undertaken for the sole purposes of emissions reduction, it requires well-designed and robust policy frameworks providing adequate incentives for global deployment across world regions. The incentives provided under many policy frameworks worldwide are at present insufficient to drive large-scale CCS deployment. Most noticeably, carbon prices signals provided under emissions trading schemes, carbon taxes and other instruments are not yet providing project developers with sufficient incentives to overcome the additional costs and various risks associated with early stage project development (see 3.2.3 below). Support is needed across the project cycle from investment through to operation and (potentially) after project completion.

[32] UNFCCC (2011) *Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities*. Decision 10/CMP.7

The broader energy, climate change and other strategic policy objectives influencing national and regional policy decisions will shape the development of CCS policy. Policy objectives that may drive or pose barriers to CCS include the need to transition to low-carbon energy systems and preferred emission reduction technology options. For example, policy-makers may focus upon low carbon technology options such as renewable energy and energy efficiency that can deliver co-benefits beyond GHG mitigation such as energy security and industrial development at a relatively low cost. Both renewable energy and energy efficiency measures can result in reduced consumption of energy resources, including domestic fossil fuels. In contrast, CCS projects require additional energy because of the 'energy penalty' associated with the capture, transport and storage of CO_2; this can accelerate the depletion of local energy resources and exacerbate energy security concerns.

As well as favouring alternative GHG reduction technologies according to national circumstances and priorities, policy-makers may view CCS as unsafe, unproven, or liable to give rise to *unintended outcomes*, notably promoting fossil fuels and subsidising oil production (in the case of CO_2-EOR projects obtaining policy support). The issue of unintended outcomes associated with CCS was for example a strong element of the negotiations on CCS eligibility within the CDM. Potential issues raised by Parties and observers to the UNFCCC in this context include (after Zakkour *et al*, 2011):

- **Increased production and consumption of fossil fuel.** CCS prolongs the use of fossil fuels, which is incompatible with the goals of the UNFCCC. The energy penalty for CCS results in greater fossil fuel use for same output with attendant impacts on the environment.
- **Creation of new emissions through combustion of fossil fuels produced using EOR.** EOR potentially leads to increases in global fossil fuel production, which may be contrary to the objectives of the UNFCCC.
- **Diversion of investment away from other low emission technologies**. CCS diverts scare financial resources away from other more sustainable activities, promotes investment into large projects in limited number of countries, and restricts investment in small-scale projects.
- **Enhancing CO_2 generation to maximise carbon asset potential**. For power plants, this could involve installing CCS at inefficient plants in order to increase CO_2 generation. Risk also of "gaming" for projects which involve capture and storage of CO_2 process off-gas streams (could modify underlying process to enhance amounts of off-gas produced).
- **Constraining bioenergy with CCS (BECCS or Bio-CCS).** Storing CO_2 from fossil fuels, i.e. most CCS projects capturing fossil CO_2 from power stations and industrial facilities, could restrict storage capacity for BECCS in future.

These views have acted to restrain the development of CCS policy in some jurisdictions worldwide. In designing CCS incentives, policy-makers need to make use of a range of policy, methodological, legal and regulatory decisions and guidance to minimise or eliminate the risk of such unintended outcomes arising.

3.2.3 Economic and financial barriers

The additional costs of undertaking CCS, coupled with the lack of support to offset such costs, is typically cited as the major overriding challenge facing widespread deployment of the technology at present. For large-scale projects, the capture stage usually represents the largest cost component, comprising approximately 70% of total costs. Costs for CO_2 transport (assuming a 200 km pipeline) and storage components are approximately 15% each, depending upon the specific of the project (IEA ETSAP, 2010). The cost of capturing CO_2 consists of three main components:

- the cost of additional capture equipment;
- the cost of additional fuel;
- increased operating and maintenance (O&M) costs, including chemicals e.g. amines

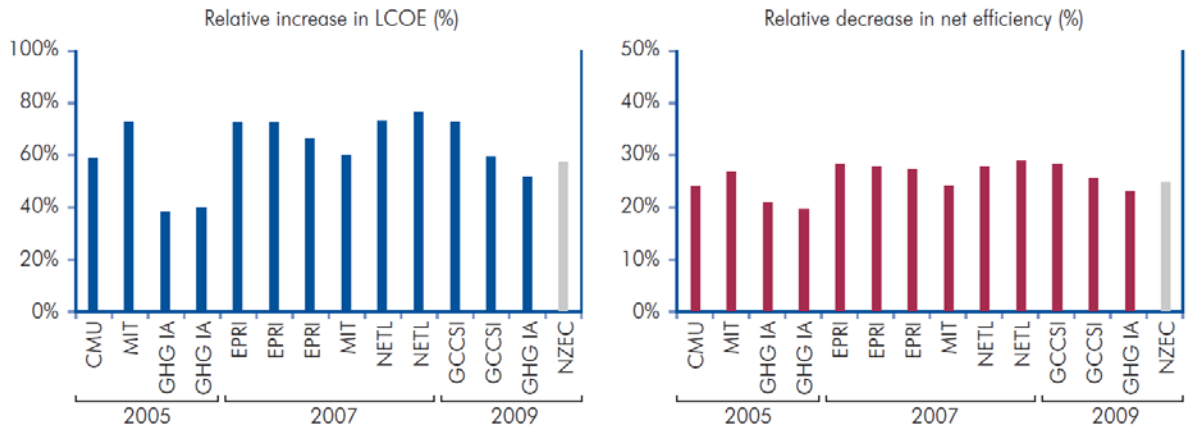
For CCS applied to power generation plants, not only do the capital and O&M costs increase, but there is also a loss in power output since some of the energy generated is used in the capture process. This factor – the energy penalty – plays a major role in contributing to higher electricity generation costs for units with CCS compared to those without. The cost of equipping power plants with CCS capture and compression units is considered an incremental cost increase, as opposed to gas processing facilities, for example, where the cost of a CO_2 capture unit is a standard part of the plant capital expenditure (World Bank, 2011).

A large number of cost studies exist for CCS applied to power generation. The IEA published a report in 2011 reviewing a range of engineering studies over the previous five years providing cost estimates of CO_2 capture in power generation. The report was largely based upon technical studies from the US and Europe and focused the scope of its review on 'early commercial installations' of CO_2 capture from power generation that would be operational around 2020 - rather than early stage 'first of a kind' demonstration plants considered unrepresentative of subsequent wider CCS deployment.[33]

Figure 3.1 shows the variation in estimates for the increase in levelised cost of electricity (LCOE) and decrease in efficiency for pulverised coal plants over 300 MW net power output with an without post-combustion capture. The review finds that on average, in OECD countries, the relative increase in LCOE for a coal-fired power plant with post-combustion CO_2 capture is around 60%, compared to a plant without CCS equipped. The net decrease in power available to the grid because of the energy penalty associated with the capture unit is 25%. The report finds that in OECD countries, overnight capital costs for coal-fired power plant with CCS of any technology is on average around USD 3,800 per kW, which is 74% higher than for reference plants without CCS. A recent report by the GCCSI (2011) estimates the overall cost of capture from coal-fired power generation to range between around 44-78 USD per tCO_2 avoided depending upon the technology used.

[33] In order to allow for comparative analysis between the studies, the IEA review applied common financial and operating boundary conditions and fuel prices. This included in all cases updating cost data to 2010 USD levels, applying a real discount rate of 10%. More detailed information can be found in IEA (2011b).

Figure 3.1 LCOE increase and net efficiency decrease for power plants with PC-CCS



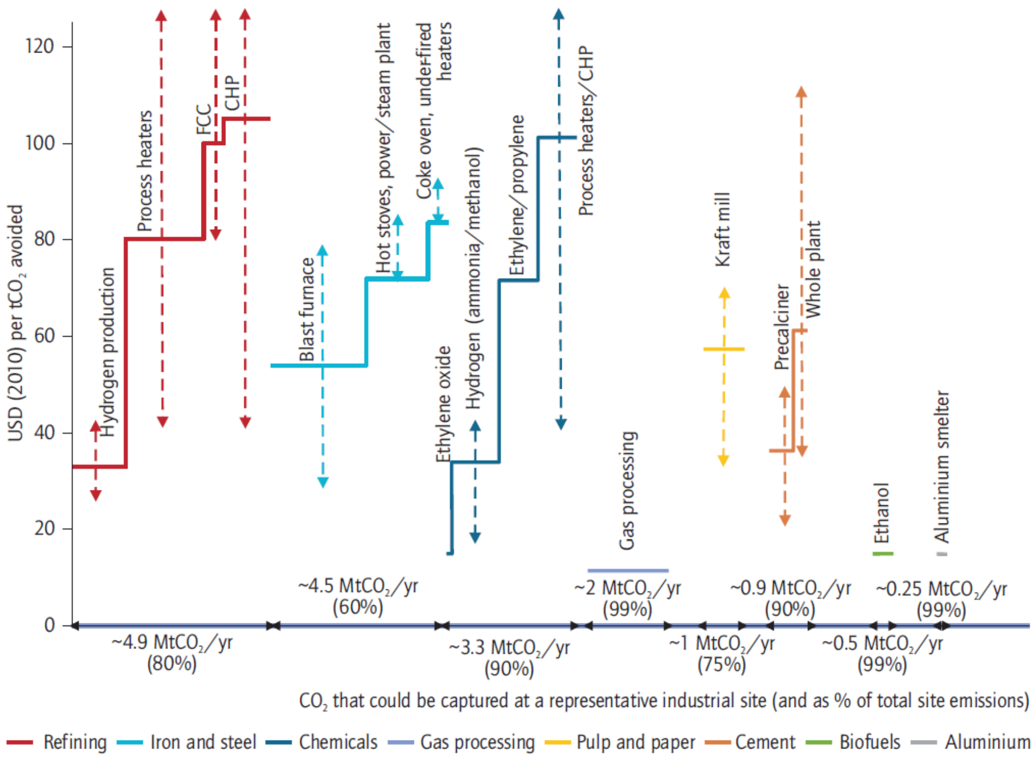
Note: PC=post-combustion; dates shown refer to the year of cost data; years of source publication are shown below. Multiple results shown within each source reflect different assumptions and parameters e.g. different coal types.

Source: IEA, 2011b, based on Rubin (2007) of Carnegie Mellon University, CMU; NZEC (2009); Melien (2009); EPRI (2009); GCCSI (2009); Davidson (2007), GHG IA (2009); NETL (2008; 2010a-f); MIT (2007); Hamilton and Parsons (2009).

Such cost increases would have significant impacts if passed onto industrial and domestic consumers. Competitiveness issues could arise for those industrial sectors where electricity cost forms a significant part of their cost base (e.g. non-ferrous metals, electric arc steel production, fertilizer, paper and pulp, refining and certain manufacturing and chemical sectors). Economic impacts may be particularly adverse for export-oriented sectors that are unable to pass cost increases through to consumers without affecting their international competitiveness. For many countries worldwide, these industries may be critical to future economic growth and employment.

Techno-economic studies of CCS applied to industrial sources indicate a far wider range of cost estimates than for power generation, depending upon the source and sector (Figure 3.2). As described in Chapter 2, CO_2 can be captured from certain high-purity sources such as gas processing, ammonia and hydrogen production facilities at relatively low cost e.g. below 30 USD per tCO_2. Although these so-called 'early opportunity' project types can represent important CCS deployment options for certain countries over the coming decade, particularly when combined with EHR, wider deployment will require CO_2 capture from higher cost carbon-intensive sectors such as cement and iron and steel production. While CCS deployed in high purity sectors may result in only marginal production cost increases (1% in gas processing; 3% in fertilizer production); for other sectors such as blast furnace steel (10-14%) and cement production (39-52%) the cost increases are significant (*ibid*). These higher costs may be in addition to any increased costs passed on from power generators implementing CCS.

Figure 3.2 Estimated costs and sizes of CO_2 capture at industrial sites

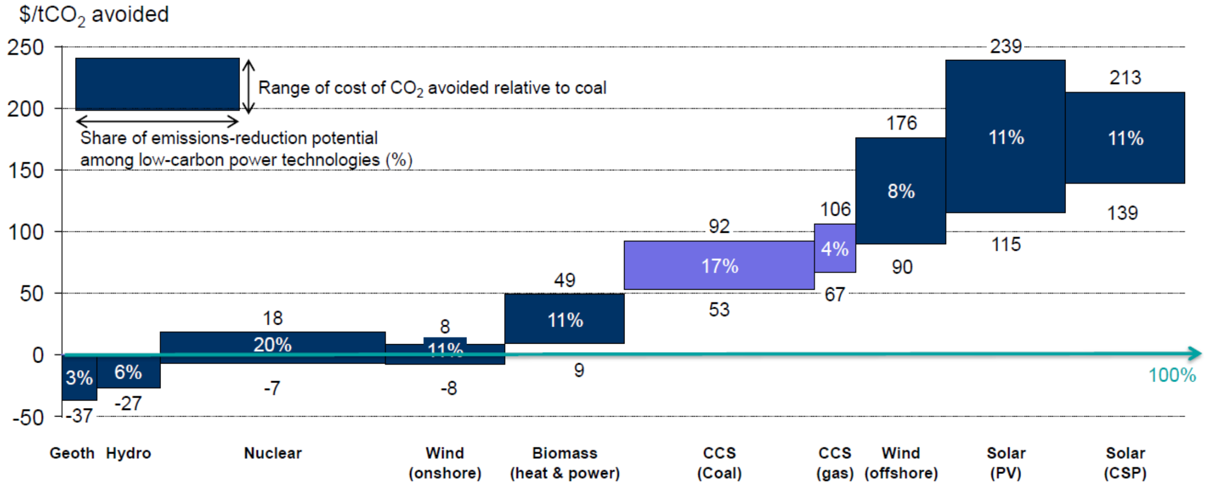


Source: IEA, 2013a, based on various studies

Note: Arrows represent data given by literature data. Dotted lines are ranges from selected studies.

In this context, a key factor determining the appropriateness of CCS within national circumstances is the relative cost and abatement potential offered by CCS technologies versus other GHG reduction options. Figure 3.3 shows cost estimates of CCS compared to other emissions reduction technologies within the power sector, as well as their relative potential to contribute towards the 2°C pathway. The figure shown is just one example; the relative position, and abatement potential, of CCS will vary according to the sector and country. For some countries with large carbon-intensive industries and existing fossil-based power generation, for example, CCS may represent a large share of the national mitigation potential. For others, it may be of less importance overall, and perhaps significant only within certain sectors.

Figure 3.3 Costs and CO_2 reduction potential for low carbon power technologies in 2050



Note: avoided costs shown are for current technology relative to coal-fired power generation in the US only, except for CCS (gas) which is relative to gas-fired power generation. The reduction potential shown is that of each technology to contribute, at the global level, to the lowest-cost pathway to limiting global warming to 2°C compared with business-as-usual projection by 2050 (IEA‟s 2DS and 6DS scenario in Energy Technology Perspective, 2012)
Source: SBC Energy Institute, 2013

As noted earlier, with the exception of certain niche circumstances where captured CO_2 can be used as an input to production processes (e.g. for EHR, urea manufacture, in greenhouses for vegetable growing or in the beverage industry), the benefits of deploying CCS are limited to that of climate change mitigation. This sets CCS apart from most other types of mitigation technologies, such as renewable energies, which deliver clean energy benefits and fuel cost reductions as well as mitigation benefits. This means that CCS requires the establishment of incentive mechanisms that provide a sufficiently high and long-term price signal to assure operators of avoided costs – or revenue streams that adequately cover ongoing commercial costs of operating and maintaining capture, transport and storage facilities (*ibid*). In the absence of sufficient incentive mechanisms, the prospects for securing appropriate levels of finance to support the investment needs for CCS will be limited.

Over the medium and long-term, costs associated with certain components of CCS projects are expected to decrease with ongoing R&D efforts and wider deployment. During the early stages of deployment however, the large additional costs associated with implementing CCS across power generation and industry will need to be met through enhanced policy incentives (e.g. carbon pricing, fixed tariffs, capital grants, loans and fiscal measures) and/or additional revenues from EHR or other commercial uses of CO_2.

An associated set of challenges concerns the financing of CCS projects. Commercial CCS projects are large in scale compared to most other carbon reduction projects, and may involve a wide range of disciplines and expertise (e.g. chemical engineering, pipeline construction and operation, geological storage). The risks to project developers and lenders are therefore proportionately large, and project success is based on relatively high levels of uncertainty. In addition to the sheer scale of the engineering and project integration challenges, the large up-front investment requirements pose a major challenge. Furthermore, although the separate components of the CCS chain have been proven at a reasonable scale, integrated systems have not yet been demonstrated at commercial scale - presenting potential lenders with an unattractive ‘first of a kind’ risk when compared to other more mature, technically proven projects also competing for project finance.

Three broad categories of risk can be identified across the CCS project cycle, each of which impacts the overall commercial risk of the project as a whole (after Element Energy and Carbon Counts, 2010):

1. **Regulatory and policy risks.** Risks associated with the regulatory and policy framework for both CCS support and project development, which creates uncertainty regarding, *inter alia*, future revenues, project design requirements, project approvals/licensing and long-tail risks associated with liability for project sponsors, developers, lenders and potential network users.
2. **Technical and operating risks**. Risks relating to the performance of the technology and equipment across the value chain, the integration of the network components, and ensuring non-disruption to plant performance and managing the balance between CO_2 volume supply and demand.
3. **Economic and market risks.** Risks arising from key factors that may impact the fundamental economic performance of the network as a whole, as well as the separate investments made within it across the project cycle i.e. costs and revenues.

Because of these risk factors, commercial lending rates may be too high for early-stage CCS projects to be viable. Depending upon the specific details of the project, such risks therefore need to be managed and overcome with suitable financing arrangements and public support (e.g. through concessional finance; grants; co-finance; carbon pricing).

3.2.4 Technical barriers

Although the individual components of the chain of capture, transport, injection and storage have been proven, there is relatively little experience of a fully integrated technology chain at significant and replicable scale. Meanwhile, notwithstanding the large potential, the availability of sufficient, accessible, and secure geological storage formations for storage has yet to be fully proven. Site appraisal and monitoring techniques also need further application and demonstration.

Some other technical and operational issues arising from experiences to date with CCS deployment include the following:

- **Project and process integration.** An overriding challenge associated with demonstrating an integrated CCS project at scale arises from achieving project and process integration across all components of the project chain. Members of the GCCSI and the Carbon Sequestration Leadership Forum (CSLF) Technical Group (GCCSI/CSLF, 2011) have identified this topic as a key area. Specific challenges identified include project element (storage, capture, transport) development schedule staging, heat integration, plant operability, environmental control, CO_2 specifications, scale-up challenges, the size of equipment and the physical space required.

- **CO_2 stream composition.** Fossil-fired flue gas contains a mixture of O_2, CO_2, NO_X, SO_X, particles and other impurities as well as other trace elements that are potentially hazardous to human health and the environment. Hydrates and free water may also potentially be present in CO_2 capture streams, causing operational challenges to transport of CO_2. Impurities can pose various challenges for an integrated CCS project chain, both within the capture plant(s) itself, as well as for the transport and storage components (EU CCS Network, 2012a; IEAGHG, 2011b).

- **CO_2 flow assurance.** CO_2 flow assurance has been identified as a priority topic for CCS project design and operation. For example, the *European CCS Demonstration Project Network* notes that for some of the Network's projects, the supply of CO_2 into the pipelines is expected to vary considerably - following the output of the production process as well as shut downs and maintenance outages. The availability of the storage site may also vary. The dynamic flow over irregular periods will require both design and operating consideration, primarily to avoid or minimise excessive phase changes to the CO_2 stream or two-phase flow, which may over time impact the integrity of the system (EU CCS Network, 2012a).

- **Supply chain and capacity constraints.** A recent study undertaken by the IEA Greenhouse Gas R&D Programme (IEAGHG, 2012) assessed whether there are supply and capacity constraints associated with equipment for CCS plants that might cause issues with CCS implementation worldwide. The components that represent a high risk of causing a supply constraint mainly relate to storage and transport. These include: large scale pipelines (limited number of manufacturers with full order books) and availability of drilling rigs, competition from the oil and gas sector for petroleum engineers and geo-scientists and the availability of large CO_2 compressors (limited number of manufacturers with proven technology). For capture, supply chain issues include the availability of hydrogen rich gas turbines, catalysts, absorption towers, air separation units, and advanced flue gas treatment (*ibid*).

- **CO_2 injection and storage.** Project experiences shared through such networks and initiatives often highlight the scale and breadth of the challenges associated with storage aspects relative to the capture and transport stages (Statoil, 2010; EU CCS Network, 2012b; RCI, 2011, 2012). For example, the Rotterdam Climate Initiative (RCI) project has cited storage as the key operational challenge to date and reports that knowledge and experience in storage is sparsely available, as is the number of CO_2 storage experts. They observe that this is already a cause for delay and that this shortage of expertise could present a major barrier to widespread application of CCS (*ibid*).

3.2.5 Institutional and public acceptance barriers

Inadequate in-country capacity can act as a major barrier to CCS project development. This may include, for example, a lack of suitable institutions and regulatory capacities to provide oversight on project design, development, operation, closure and longer-term aspects of site stewardship. There may be a lack of awareness about CCS technologies, including their costs, potential applications, legal aspects and technical factors. The required skills and expertise, particularly regarding the sub-surface aspects of CO_2 storage may also not be available. Furthermore, responsibilities relevant to CCS regulation may be split between agencies, in a way that limits the ability of authorities to implement decisions, resulting in poor policy integration and coordination, inefficient and counterproductive roles and procedures, public, political and media resistance to policies.

Public perception and acceptance can have a major influence on the success or failure of major planned projects involving new technologies and practices such as CO_2 storage. If the public is not supportive of, or is even actively opposed to, a new technology, it can become politically and/or socially unacceptable. Frequently cited issues for public opposition to CCS projects include *inter alia* concerns around the permanence of geological CO_2 storage, acceptance of additional costs associated with products from CCS-installed facilities (see 3.2.3), and the location of CO_2 pipeline corridors and CO_2 storage sites. As with any new technology, the successful large-scale deployment of CCS will need to gain public acceptance in order to avoid potential future opposition. Social opposition to CCS has already led to costly delays and in some cases project abandonment, for example as seen with Shell's Barendrecht project in the Netherlands.

3.3 Key indicators of CCS support and deployment

Overcoming the large range of barriers outlined above will require significant efforts from policy-makers. As described in Chapter 2, localised national circumstances greatly affect the potential and likelihood of CCS deployment. Given the importance of national circumstances and the fact that CCS is a policy-driven technology, commitment is needed from governments to establish an optimal set of policies, actions and practices that fit the needs of a country or region (UNFCCC, 2014). To deploy CCS on the scale and timeline required by the 2DS, major efforts will be required at the international, regional and national level. This section presents a step-wise framework of actions which can be undertaken by governments at the national and regional level to overcome the types of barriers outlined above, and help support and deploy CCS. Section 4 assesses what actions can be taken at the international level.

A Technical Expert Meeting (TEM) of the ADP held in October 2014 considered the need for a policy response to unlock the global mitigation potential of CCS.[34] Various options and actions were identified that could assist countries in addressing the challenges and removing the barriers faced by CCS. These were structured into three broad groups (after *ibid*):

- **Scoping and agenda-setting.** An important basis for developing and deploying CCS projects is to establish the technical potential of the technology in a certain region. Building expertise is also key to any policy that aims to advance CCS. Examples of expertise-building are the creation of national R&D to stimulate the creation and sharing of knowledge among stakeholders. Access to international research and knowledge-sharing initiatives is imperative to accelerate capacity-building in countries where CCS

[34] The purpose of the TEMs is to examine clean energy technology options and help governments understand how various technologies can enhance domestic mitigation efforts in the pre-2020 period. A series of TEMs were held throughout 2014, including on renewable energy, energy efficiency and CCS.

development is currently in an early phase. This policy option includes stakeholder engagement, which is crucial in the acceptance of CCS (IPCC, 2014).

- **Strengthening institutional arrangements and legal and regulatory frameworks.** There is a strong need for comprehensive and transparent regulatory frameworks for CO_2 storage. Experience with the development of these frameworks is growing, but in many cases they need to be developed in parallel with the operation of the first major projects, incorporating lessons learned from these projects and ensuring that the concerns of local populations have been recognised and addressed. Institutional capacity-building for this purpose is needed and may be based on the experience gained with the development and deployment of existing CCS projects.
- **Design and implementation of effective and multifaceted policy portfolios.** Policies are required to improve the cost-competitiveness of CCS compared to other technologies and to ensure investor confidence. The provision of investment grants and tax credits, credit guarantees and/or insurance are considered suitable means to support CCS technologies, as long as they are in the early stages of development (IPCC, 2014). Policies stimulating CCS should take into account the need to maintain a stable, long-term policy environment and reach a level playing field. Depending on the phase of CCS development and the country circumstances, several policy options are already available and have been practiced globally that stimulate or regulate the deployment of CCS. These include economic, financial and regulating instruments.

Outside of the UNFCCC process, governments have made various other attempts to describe the policy responses and options required for accelerating CCS support and deployment (IEA, 2009, 2010, 2012a, 2013a; 2014f; CSLF, 2013; GCCSI, 2014a; UNECE, 2014).[35] Drawing upon these sources, and also the various barriers and challenges identified in the section above, Table 3.1 presents some key elements of government-level progress towards implementing the policies and actions needed for effective CCS support and deployment. The policies and actions concern a sequential series of measures needed to overcome the barriers to CCS and establish a pathway for the technology, resulting in large-scale project deployment and emissions mitigation. The way in which this framework can overcomes the barriers identified for CCS, along with specific actions/responses under each thematic area, is summarised in Figure 3.4.

Each of these key elements, or indicators, is described further below with reference to specific policy options, case studies and examples of best practise worldwide.

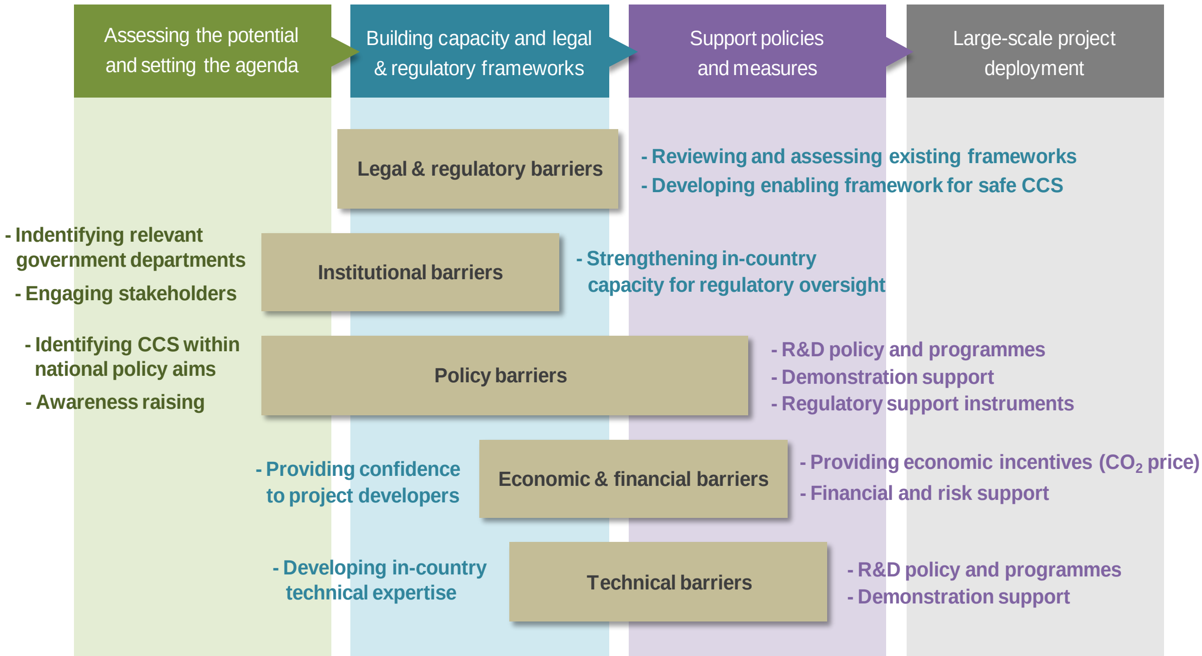
[35] The GCCSI has also developed a 'CCS Development Lifecycle' that can be used to locate a country's position with respect to CCS development. Five broad stages are described: Scope Opportunity; Put CCS on Policy Agenda; Create Enabling Environment for CCS; Project Delivery; Multiple large-scale CCS projects.

Table 3.1 Key indicators of national progress towards CCS support and deployment

1. Assessing the potential and setting the agenda	
Identify technical potential	Develop CO_2 storage atlases and technical assessments of capture potential across sources and sectors; undertake source-sink mapping and identify suitable candidate areas and/or potential pilot projects
Assess and recognise the role of CCS within national circumstances	Assess how CCS technology can play a role as a GHG mitigation option within the context of specific national circumstances and priorities; identify CCS within national climate change plans and strategies
Identify stakeholders and raise awareness	Identification of key stakeholders and raising awareness of CCS across government, industry and civil society; public engagement and education
Develop action plan/roadmap	Develop action plans, strategies or roadmaps for CCS support and deployment assessing the role and potential of CCS within national circumstances, including clear objectives/targets and specific actions to be taken
2. Building capacity and developing legal and regulatory frameworks	
Review and assess existing frameworks for CCS development	Undertake detailed assessment of the legal and regulatory needs for CCS development and how these map across the existing frameworks at national, regional and state/province level; identify and assess gaps and options
Review and assess existing institutional capacity	Gain understanding of existing institutional arrangements and expertise across government; identify and assess capacity-building needs and options
Strengthen institutional arrangements	Introduce and strengthen in-country capacity for regulation and oversight of projects, ensuing effective coordination between relevant bodies
Develop enabling framework for safe and effective CCS deployment	Design and implement the required legal and regulatory frameworks addressing all phases and aspects of CCS project development
3. Designing and implementing support policies and measures	
R&D policy and programmes	Public R&D funding and programmes to support research for early-stage projects and experimental development (e.g. pilot-scale projects)
Demonstration support	Support at- or near-commercial scale applications of CCS technology and commercial-scale projects that aim to show viability of integrated CCS
Economic and financial instruments	Includes e.g. government investment grants and tax credits, credit guarantees carbon taxes, emissions trading schemes, and contract for differences
Regulatory support instruments	Includes e.g. emissions performance standards, mandatory capture-readiness
4. Large-scale project deployment	
Project execution	Develop of large-scale integrated CCS projects from design stages through to Final Investment Decision stage and project execution
Projects operation	Successfully deliver large-scale integrated operational CCS projects
Communicate project outcomes	Communicate and disseminate project successes, technical barriers and lessons learned to key stakeholders and wider CCS community
Develop common CCS infrastructure	e.g. common carrier pipelines; CO_2 transport networks; storage hubs

Source: based on UNFCCC, 2014; IEA, 2009, 2010, 2012a, 2013a; CSLF, 2013; GGCSI, 2014a; UNECE, 2014

Figure 3.4 Overcoming barriers to CCS through a supporting framework



3.3.1 Assessing the potential and setting the agenda

An important first step towards CCS support and deployment is to **identify the technical potential** of the technology in a certain region. First-stage assessments of CCS potential may range from high-level scoping of suitable emissions sources and potential storage regions, including the use of source-sink matching to determine project viability. The IEA notes that identifying suitable storage capacity that can safely accept CO_2 at desired injection rates and retain this injected CO_2 is perhaps the largest challenge associated with CCS (IEA, 2013a).

Over 13 Gt of CO_2 storage capacity is required by 2030 under the 2DS, and approximately 120 Gt by 2050 (IEA 2012a). Although worldwide, the currently estimated storage resources are more than sufficient to meet these targets, the geographic distribution of usable CO_2 storage capacity in many parts of the world is unknown (ibid). As described in Section 2.5, a growing number of countries and regions worldwide have developed CO_2 storage capacity assessments. These range from high-level estimates (e.g. at the formation or basin level) to more detailed analyses of suitable storage sites and their proximity to candidate emissions sources. These include the following activities:

- The *North American Carbon Storage Atlas* identifies the potential CO_2 geological storage capacity in North America covering the **United States**, **Canada** and **Mexico.** Several other assessment programmes are ongoing within the United States and Canada.
- **Europe**'s GeoCapacity project maps CO_2 point sources, infrastructure and geological storage within 25 countries in order to assess European capacity for geological storage of CO_2 in deep saline aquifers, oil and gas structures and coal beds.

- Storage assessments have also been undertaken by several European countries including **Norway**, the **UK**, **Germany** and the **Netherlands.**
- **Australia** has undertaken a range of storage assessment activities at both the federal and state level, including an assessment of national storage capacity by the *Australian Carbon Storage Taskforce.*
- Several studies have been carried out in **Japan**, including a national assessment of saline aquifer storage capacity.
- A preliminary assessment of CO_2 storage capacity in **China** was undertaken under a five-year joint Chinese-American study. The Ministry of Science and Technology (MOST) have since begun a national level capacity assessment and a number of recent programmes and studies have assessed storage potential at the regional, province and basin-level.
- A programme supported by the Asian Development Bank (ADB), the GCCSI and the UK Government is assessing prospects for CCS development in Southeast Asia including estimating theoretical storage potential for **Vietnam**, **Indonesia**, **Thailand** and the **Philippines**.
- The CCOP CO_2 Storage Mapping Program (or CCS-M) is a 4-year program involving several CCOP member countries including **China**, **Vietnam**, **Malaysia** and **Indonesia**.
- A regional assessment of the potential for CO_2 storage in the Indian subcontinent was undertaken by the IEAGHG covering **India**, **Pakistan**, **Bangladesh** and **Sri Lanka**.
- The CARBMAP project aims to assess stationary emission sources in **Brazil** and estimate CO_2 storage capacity on a country- to basin scale.
- The Council for Geosciences has published a CO_2 Storage Atlas of **South Africa**.
- The World Bank CCS Trust Fund programme has commissioned nine country-level programmes involving CO_2 storage assessments: **South Africa**, **Botswana**, **Egypt**, **Jordan**, **Kosovo**, **Indonesia**, **China**, **Mexico** and the **Maghreb** region.

A number of these initiatives, and other separate studies, also involve the identification of CO_2 capture potential and the development of source-sink matching analysis. Several other high-level assessments have been, or are currently being, undertaken in countries worldwide, as a first step to scoping national potential for CCS deployment.

As well as establishing the *technical* potential for CCS, there is a need at a *strategic* level for countries and regions to **assess and recognise the role of CCS within national circumstances**. As described in Section 2, the technology offers the potential for realising deep emissions reductions from carbon-intensive power generation and industrial sectors, whilst allowing countries to continue to develop valuable hydrocarbon resources. When combined with utilisation technologies such as CO_2-EOR, CCS can also help to maximise the use of domestic energy resources. Governments must therefore assess the role of CCS in their energy future, explicitly recognise the role CCS is to play and send clear, consistent policy signals. Without an understanding of the role CCS could play in their energy futures, countries (or other jurisdictions) cannot develop clear policies to enable and encourage deployment of CCS technology (IEA 2012a). Several countries/regions worldwide have explicitly identified CCS within the context of broader strategic objectives and policy aims, including for example regional energy security (Box 3.2) and GHG mitigation within the national oil and gas sector (Box 3.3).

Box 3.2 CCS within the European Energy Security Strategy [36]

The EU imports more than half of all the energy it consumes. Its import dependency is particularly high for crude oil (more than 90%) and natural gas (66%). Many of the Member States are also heavily reliant on a single supplier, including some that rely entirely on Russia for their natural gas. In response to these concerns, and re-stating the path towards a low-carbon, competitive and energy-secure Europe, the European Commission released its *Energy Security Strategy* in May 2014.

The Strategy aims to ensure a stable and abundant supply of energy for Europe, setting out those areas where concrete actions should be implemented to respond to energy security concerns. Of the eight key pillars identified in the strategy, one is focused specifically on maximising the use of indigenous sources of energy, including the exploitation of conventional oil and gas resources in Europe. The Strategy indicates that coal and lignite fuel sources have a long-term future in the EU where CCS is used, representing 27% of Europe's electricity generation, and that 'CCS also offers the potential to further improve gas and oil recovery that would otherwise remain untapped'.

Noting the lack of progress with CCS uptake, the document notes that 'further efforts in research, development and deployment should be made in order to fully benefit from this technology'. It further indicates that Member States should 'support demonstration projects for carbon capture and storage, particularly those co-financed by the NER 300 Programme and the European Energy Programme for Recovery, such as the ROAD project'.

Source: EC, 2014

[36] COM(2014) 0330 final. http://ec.europa.eu/energy/doc/20140528_energy_security_communication.pdf

Box 3.3 The role of CCS within Indonesia's national climate policy

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

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

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

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

Source: GCCSI, 2014

Putting CCS on the national policy agenda involves **identifying key stakeholders** across government and industry and **raising awareness** of the technology. In many countries worldwide, CCS is poorly understood and may be perceived as being a high-risk technology by the public as well as key stakeholders within government and industry. Concerted effort by all relevant players is needed to address these concerns and win support for CCS. Governments need to take responsibility for explaining the role of CCS in national energy and climate strategies, also discussing its risks and the ways of addressing them (IEA, 2013a). National, regional and local government, where political, social and cultural traditions allow, should also work with important stakeholders at both national and CCS project levels to facilitate information exchange. Industry must take responsibility for explaining the benefits and risks of particular CCS projects to the local population (*ibid*).

Working actively to gain public acceptance is an integral part of any single CCS project and subsequently of wider deployment. Recent examples in Germany and the Netherlands illustrate that under-appreciation of public concerns over CO_2 storage can easily be fatal for CCS (IEA, 2012a). The Netherlands has since elected to allow only off shore storage of CO_2, while in Germany CO_2 storage legislation has been side-tracked. Engagement should occur at strategic, policy level, with government highlighting the role of CCS within a country's energy and climate mitigation mix; and at the project level, by ensuring transparency, flexibility and a two-way flow of information from early stages (*ibid*).

For many OECD countries at an advanced stage of developing legal and regulatory frameworks for CCS, robust stakeholder engagement and public consultation have helped to shape these frameworks. These include CCS regulations and policies developed in the **United States**, **Canada**, **Australia** and the **European Union** (and in addition, many of the EU Member States). Besides, stakeholder engagement and awareness raising activities have been undertaken in countries as part of initial efforts to scope the potential for CCS technology, including for example in **China**, **South Africa**, **Botswana**, **Mexico**, **Brazil**, **Egypt**, **Jordan**, **Indonesia** and **Malaysia**. Such activities may be undertaken as international efforts aimed at building capacity for CCS deployment in developing countries: for example as part of the work of the World Bank CCS Trust Fund's country-level programmes described above.

A growing number of countries worldwide have developed **CCS action plans and technology roadmaps** outlining a framework of steps and actions needed to move towards successful project deployment. These provide an opportunity to define a vision for national CCS deployment, typically based around a timetable moving from the pilot and demonstration phase to commercial-scale deployment.

National CCS Roadmaps and action plans have now been developed by organizations in the **United States**, **Canada**, **Australia**, the **UK**, the **Netherlands**, **Portugal**, **China**, **South Africa**, **Japan**, **Malaysia, Mexico, Indonesia**, **Hungary** and **Poland**. In addition, CCS is integral to the climate mitigation roadmaps and strategies of several other countries. For example, in **Saudi Arabia**, Saudi Aramco's Carbon Management Technology Roadmap includes CO_2 capture from fixed sources, CO_2 reduction from mobile sources, industrial applications, CO_2 storage and CO_2-EOR. In the **UAE**, Abu Dhabi has started evaluating a policy framework for a domestic CCUS industry, and is identifying a roadmap for technology deployment and rollout of commercial scale projects (GCCSI, 2014).

A review of current roadmaps developed worldwide shows that a variety of approaches have been taken, both in terms of content and overall focus. Those of the United States and Canada for example provide a high level of engineering information for each component of CCS technology linked to associated economic and regulatory issues. For example, in the United States roadmap (*Carbon Dioxide Capture and Storage RD&D Roadmap;* NETL, 2010g) very specific R&D timetables are given for each separate capture, storage and CO_2 utilization technology and the precise role of government programs related to the CCS development are specified, including the funding sources and amounts. Others, such as Mexico's *CCUS Technology Roadmap* (SENER, 2014) provide a broader step-wise approach (Box 3.4.).

Box 3.4 Mexico's CCUS Technology Roadmap

Since 2008, Mexico has taken a number of measures to implement CCS and CCUS technologies. In 2012, the Mexican Congress approved the *General Climate Change Law* to reduce greenhouse gas emissions. A key strategy identified to reach this objective is the application of CCS on fossil fuel power plants and in the oil industry for CO_2-EOR.

In March 2014, the Ministry of Energy of Mexico (SENER) published its *CCUS Technology Roadmap*. The Roadmap identifies five key stages:

1. *Incubation*. Includes a Technology Deployment Framework Agreement (SENER, SEMARNAT, PEMEX and CFE) and an analysis of carbon markets and the existing regulatory framework to support CCS.
2. *Public policy*. Actions covering capacity building and public engagement; developing a regulatory framework; a national plan for CO_2 transport; national and international incentive mechanisms; the use of international finance mechanisms and the creation of a National Innovation Centre for CCUS
3. *Planning*. An implementation plan for integrated power plants with CCS; an assessment of storage capacity in deep saline aquifers; selection and prioritization of hydrocarbon fields for storage; and the development of a CO_2-EOR strategy
4. *Pilot and demonstration scale projects*, including a pilot project in the oil industry, a pilot project in the power generation sector, and a demonstration-scale project
5. *Commercial-scale project*. Integrated CCS system(s) with other activities including e.g. construction of CO_2 pipeline network and MRV of stored CO_2

Source: SENER, 2014

3.3.2 Building capacity and developing legal and regulatory frameworks

The **development of a robust legal and regulatory framework** is an essential requirement for safe and effective deployment of CCS. Developing appropriate laws and regulations is also key to ensuring public confidence (CSLF, 2013). Governments need to ensure that the terms of regulatory frameworks (or their absence) do not impede demonstration and deployment of CCS. In this context, a regulatory framework is the collection of laws (and rules or regulations, where applicable) that removes unnecessary barriers to CCS and facilitates its implementation, while ensuring it is undertaken in a way that is safe and effective (IEA, 2012a).

As noted in Section 3.2, the capture and transport components of CCS can typically be accommodated through existing regulations in most jurisdictions. Sub-surface injection and long-term storage of CO_2 however poses additional issues which are unlikely to be met through existing legal and regulatory arrangements. Issues to be addressed include the scope of CO_2 storage projects; property rights associated with the CO_2 and the sub-surface; project permitting; project development through exploration to operation and closure; and long-term liability for the stored CO_2.

Many countries which are leading in CCS project support and development have developed their legal and regulatory frameworks partially through amending existing legislation e.g. environmental and petroleum and mining laws. A first step for many governments in developing the required frameworks for CCS is therefore to assess the extent to which CCS (and in particular

CO_2 storage) may be accommodated within existing frameworks. A thorough review of existing regulatory frameworks and policy should therefore be undertaken before developing dedicated CCS regulatory frameworks (IEA, 2010). In so doing, governments should engage with industry, academia, and civil society to develop suitable laws and regulations, including permitting procedures, to enable safe and effective storage (IEA, 2013a).

In their *Model Regulatory Framework* for CCS, the IEA highlights the need to consider four key issues when carrying out such a review (IEA, 2010):

1. How issues raised by CCS operations can potentially be regulated by modifying existing regulatory frameworks to cover certain aspects of the CCS chain (for example, existing industrial pollution control legislation or underground fluid injection laws);
2. Whether existing regulatory frameworks pose potential barriers to various aspects of CCS (for example, groundwater protection legislation may prevent CO_2 injection into saline formations);
3. Whether a CCS regulatory regime could have any unintended consequences or interaction with existing laws (for example, regarding the exclusion of CCS activities from waste regulations); and
4. Once the context is understood, any gaps in which aspects of the CCS chain are not addressed by existing laws can also be identified. It is only once all gaps and barriers have been identified that it becomes clear whether existing frameworks should be amended or new frameworks developed to regulate CCS.

Legal and regulatory reviews have now been undertaken within many countries worldwide. While these have typically been in-depth and multi-phased for those countries leading in CCS development worldwide, a growing number of 'scoping' level activities have been undertaken within developing countries. Several of these have been supported through organisations such as the World Bank CCS Trust Fund, the GCCSI and the Asian Development Bank (Box 3.5).

Box 3.5 Southeast Asia CCS Scoping Study

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

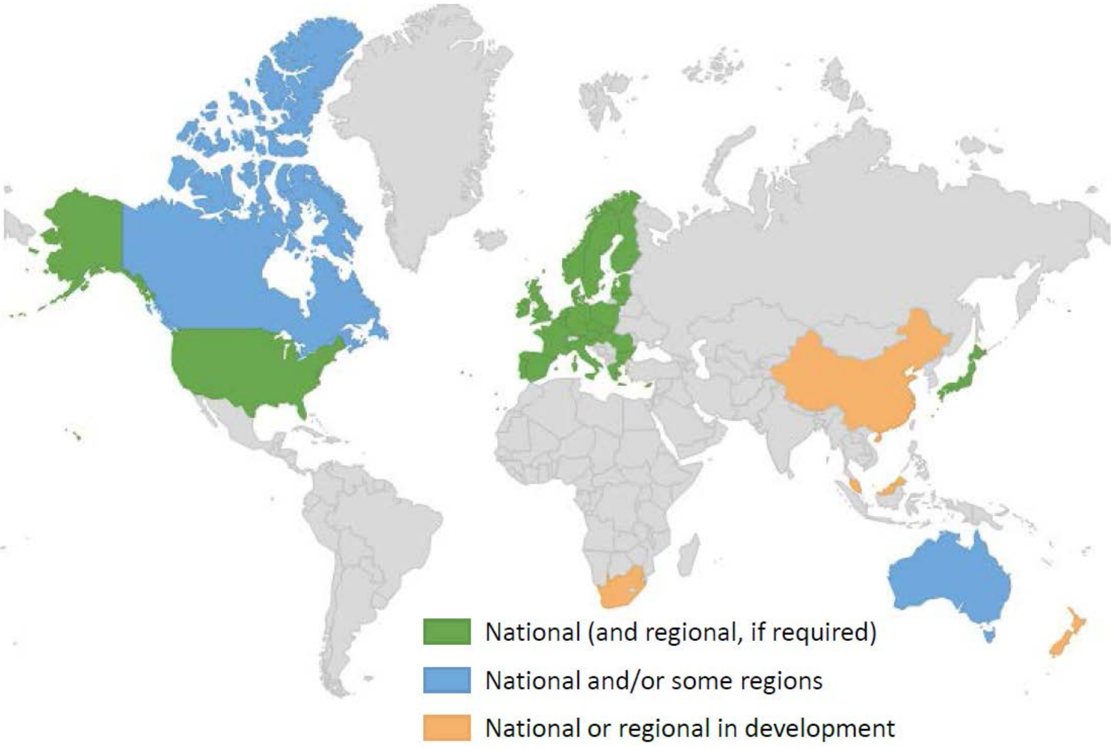
While the four countries considered have all adopted domestic climate change policies, the report highlights that none have developed or enacted CCS-specific legislation. Closer examination of their domestic energy and resource legislation did, however, reveal that all four countries have aspects of their regulatory regimes that may be adapted to accommodate CCS activities. For example, all of the countries have existing regulatory frameworks covering surface and subsurface rights and environmental concerns, including land, air, water, and impact assessments. The study concludes that several other key regulations will need to be developed covering health and safety, liability, investment, ownership, and CO_2 transport, but that most of these can also be adapted from existing regulations.

Developing a comprehensive regulatory framework for CCS will involve several ministries, agencies, and nongovernment stakeholders. The study recommends that such a framework be developed at the same time as implementing pilot and demonstration projects so that the framework can be in place by the time commercial-scale CCS projects are ready to be deployed. As the broader framework is being prepared, the pilot and demonstration projects can proceed with select changes to a few relevant regulations, which are just enough for these projects to commence operations.

Source: ADB, 2013; GCCSI, 2014

As CCS is increasingly recognised by policy-makers as a key carbon abatement technology, legal and regulatory frameworks for CCS are being developed in a number of jurisdictions worldwide. The IEA produces an annual *CCS Legal and Regulatory Review* which surveys the recent developments of legal and regulatory frameworks in jurisdictions worldwide. The IEA also maintains a CCS regulation database which is a comprehensive collection of enacted legislation and regulation governing CO_2 storage. These sources indicate that worldwide, over 50 legal instruments relating to storage have been adopted since 2005 (Figure 3.5). Legal and regulatory measures have been enacted at the regional, national, province and state level across the **United States**, **Canada**, **Europe**, **Japan** and **Australia** to address a wide range of storage related issues and provide the permitting framework for undertaking CCS projects. Meanwhile, several emerging economies are at different stages of developing the required national frameworks - including for example **South Africa**, **China** and **Malaysia**.

Figure 3.5 Status of legal instruments relating to CO_2 storage globally



Source: http://www.iea.org/topics/ccs/subtopics/permittingframeworksforccs/

Different jurisdictions worldwide have sought to address issues relating to CCS through a variety of legal and regulatory frameworks, reflecting national circumstances, such as e.g. the existence of well developed hydrocarbon and/or mining laws.

For example, **Norway** has a mature and highly regulated offshore oil and gas industry; Statoil's Sleipner project is regulated under the Norwegian *Act relating to petroleum activities* (under the Ministry of Petroleum and Energy) and the Pollution Control Act (under the Ministry of Environment). The building and operation of pipelines, exploration of offshore reservoirs for permanent storage, the need for an environmental impact assessment, monitoring, or third party access to pipelines or storage will fall under new regulations in the *Continental Shelf Act*. All data and reports are disseminated to the Norwegian environmental monitoring database overseen by the Norwegian environmental agency (KLIF) (EU CCS Network, 2013). Federal CCS legislation in **Australia** has similarly been accommodated within existing hydrocarbon law, with the development of the *Offshore Petroleum and Greenhouse Gas Storage Act* (Commonwealth) of 2006; and in **Poland** the transposition of the EU CCS Directive has been achieved largely through amendment of that country's *Geological and Mining Law Act*.

The IEA *Model Regulatory Framework* for CCS presents a large number of case studies illustrating how different aspects of CCS have been addressed within jurisdictions' legal and regulatory frameworks worldwide.

Effective regulation and permitting of CCS projects also involves efforts to **strengthen institutional arrangements** across relevant government departments and bodies - as part of a broader requirement to build up in-country capacity, through the creation of the information, tools, skills, expertise and institutions needed to successfully implement CCS projects.

A number of capacity building activities have accordingly been initiated worldwide, including in **Brazil**, **China**, **Indonesia**, **Malaysia**, **Poland**, **South Africa**, **Egypt**, **Botswana**, **Mexico** and **Vietnam**; broader efforts are also underway in the Asia Pacific region, Southern Africa, and developing economies elsewhere (CSLF, 2014). Several organisations worldwide have developed initiatives aimed at helping to build in-country institutional capacity, working closely with national governments, state-owned enterprises and other major companies, research and educational bodies. Key funding mechanisms for capacity building are provided primarily by the Asia Pacific Economic Cooperation (APEC), the ADB, EuropeAid, the World Bank Group, the GCCSI and CSLF (*ibid*). Many of these activities have focused on raising CCS awareness and understanding, and identifying country-specific concerns, barriers and potential solutions regarding challenges to deployment. IEAGHG and CO2CRC run CCS schools focussing on students from CCS related disciplines, such as geology, engineering, economic and early stage professionals. Participants are from developed and developing countries and teaching sessions include such topics as capture, transport, storage, economics, health and safety, risk assessment, legal and regulatory requirements, monitoring and verification, community consultation and in-depth storage technology (*ibid*). As part of their Capacity Development Program, the GCCSI has also recently initiated and facilitated capacity-building initiatives in **Brazil**, **China**, **India**, **Indonesia**, **Malaysia**, **Mexico**, **South Africa**, **Trinidad and Tobago**, and **Venezuela** (GCCSI, 2014c).

3.3.3 Designing and implementing support policies and measures

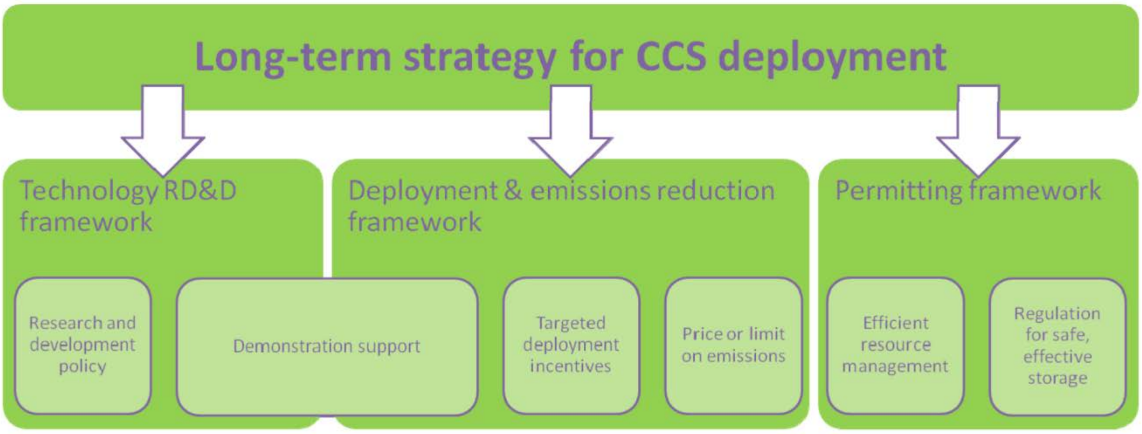
With the exception of using CO_2 for EOR or other commercial purposes which give rise to revenues, CCS will primarily be undertaken at an additional cost to businesses and consumers. Consequently, policy-makers worldwide need to provide incentives or mandate operators to engage in CCS promote deployment and reduce GHG emissions.

Compared to other emissions reduction measures such as renewables and energy efficiency, implementation of national commitments and policies worldwide in respect of CCS is currently low. For example, the UNEP *Emissions Gap Report 2014* (UNEP, 2014) provides an assessment of the emission reduction potential offered by different GHG mitigation options and indicate the extent to which they are at present covered by national actions and international cooperative initiatives. Their analysis, which builds upon that of Braun *et al*, 2014, suggests that worldwide only 10% of national policies and pledges address those energy supply measures which include CCS (among other energy supply technologies). The Braun *et al* study indicates that worldwide, less than 3% of policy instruments applicable to industry address CCS (Braun *et al*, 2014).

Several attempts have been made to describe the required elements of an effective CCS policy framework which can provide support during demonstration and pre-commercial phases as well as the long-term signals needed for widespread project investment. The IEA recently proposed the following key indicators for assessing government progress towards implementing the necessary drivers for CCS demonstration and deployment (IEA, 2014f):

- **Research and development (R&D) policy:** funding for CCS-relevant basic and applied research and experimental development (e.g. bench- and pilot-scale projects).
- **Demonstration support:** support for at- or near-commercial-scale applications of novel or innovative CCS-related technologies and first-wave commercial-scale CCS projects that aim to show the viability of integrated CCS.
- **Targeted deployment incentives:** targeted measures such as feed-in-tariffs or portfolio standards aimed at significantly accelerating full-scale CCS project deployment (i.e. beyond first-wave demonstration projects), while driving down costs, improving technical performance and overcoming other market and non-market barriers.
- **Price or limit on emissions:** a price on GHG emissions arising from an emissions trading system or carbon tax that could, in the future, provide an incentive for CCS deployment by making CCS competitive amongst other climate change mitigation technologies. At present, carbon prices worldwide are at an insufficient level to incentivise widespread deployment of the technology (unless combined with other forms of support). In the absence of a carbon price covering all installations in a given sector, non-price based regulatory mechanisms could be used (e.g. performance standards).

Figure 3.6 Key elements of a comprehensive CCS policy framework



Source: IEA, 2014f

R&D policy and **demonstration support** is critical to proving CCS technology and gaining the experience needed for wider deployment. An estimated USD 100 billion is required to deliver CCS to levels envisaged in a least-cost climate mitigation portfolio through 2020 (IEA, 2012a). Between 2007 and 2012, cumulative spending on large-scale demonstration projects under construction or operating reached almost USD 10.2 billion (IEA, 2013b), of which government grants represent USD 2.4 billion of the total. **Australia**, **Canada**, the **European Union**, **France**, **Japan**, **South Korea**, **Norway**, the **UAE**, the **United Kingdom** and the **United States** are among those countries to have implemented significant demonstration support for CCS to date (IEA, 2014f). Examples of specific activities include (based on IEA, 2013a):

- **United Kingdom**: The UK CCS Commercialisation Competition makes available GBP 1 billion capital funding, together with additional support through the UK Electricity Market Reforms, to support practical experience in the design, construction and operation of commercial-scale CCS.
- **European Union**: Recognising the insufficient incentive for CCS by the EU ETS, the European Commission introduced a specific mechanism to provide further incentives to CCS. This instrument, referred to as the “NER 300” programme, allocates 300 million EU emission allowances (EUAs) from a New Entrants Reserve to be used to support development of CCS and innovative renewable energy technologies. In addition, the EC supports CCS demonstration in Europe through the European Energy Programme for Recovery. Six demonstration projects had a fast start aided by a total of EUR 1 billion.
- **Japan**: Building on a number of R&D projects, Japan is developing an integrated CCS demonstration project at Tomakomai refinery site with a public fund of JPY 50 billion. CO_2 injection is scheduled to start at a rate of over 0.1 $MtCO_2$ per year in 2016.
- **United States**: Extensive R&D programme, focused on large-scale demonstration projects (both industrial sources and power plants) as well as development of second-generation and transformational technologies.
- **China**: There is significant activity in both government and industry R&D programmes to explore options for CCS. China’s current RD&D efforts emphasise various carbon capture technologies, with an increasing focus on utilisation opportunities. Since 2005, the Ministry of Science and Technology (MOST) has launched several R&D programmes focusing on CCS and CO_2 utilization.

Several regions worldwide are also actively deploying CCUS with a current focus upon demonstrating commercial-scale CO_2 capture (Box 3.6).

Box 3.6 Current progress with CCUS demonstration in Gulf Cooperation Council countries

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

- *Saudi Arabia* is constructing the world's largest CO_2 purification and liquefaction plant in Jubail to bring 1,500 tonnes per day of raw CO_2 coming from two ethylene glycol plants to three Saudi Basic Industries Corporation (SABIC)-affiliated companies for enhanced methanol and urea production. The country is in the process of developing several similar CCS projects, including some pilot projects for CO_2-EOR.
- The *Qatar* Fuel Additives Company plans to install a CO_2 capture plant in its methanol production plant by autumn 2014. Meanwhile, Qatar Petroleum has a joint venture with Shell and some academic institutions to establish the Qatar Carbonates and Carbon Storage Research Centre (QCCSRC). Bahrain has a project that captures flue gases from an existing petrochemical plant for urea and methanol production.
- *Abu Dhabi*, as the major oil producing emirate of the United Arab Emirates (UAE), is making major progress on CCUS beyond carbon capture with Masdar's development of a domestic CCUS network. In addition to the completion of a two-year CO_2-EOR pilot project in November 2011 at an onshore field, Masdar is implementing a CO_2-EOR project that brings 800,000 tonnes of carbon annually from the Emirates Steel Industries (ESI) factory to an oil field of the Abu Dhabi National Oil Company (ADNOC).
- *Kuwait* launched a project in 2010 to capture more than 150,000 tonnes of CO_2 annually from Equate, a large petrochemicals company, for food and beverage production.
- *Oman* is primarily focused on the R&D of feasible CCUS technology.

So far, no CCUS specific regulation has been developed in the GCC. Only Abu Dhabi has started evaluating a policy framework for a domestic CCUS industry, and is identifying a roadmap for technology deployment and rollout of commercial scale projects. For the remaining GCC countries, it is believed that the environmental regulations related to carbon capture and transportation can be governed by existing environmental laws. Property rights of CO_2 transport facilities and pore spaces will continue to be regulated by national oil companies. New regulation for permanent storage has to be developed.

In the absence of strong economic incentives, government commitment for CCUS as a climate change mitigation measure is critical to drive CCUS development and deployment. So far, Saudi Arabia and the UAE are the only two countries in the GCC that acknowledge CCS as one of the key greenhouse gas mitigation strategies in their national communications to the UNFCCC.

Source: Summarised from GCCSI, 2014a

Incentive policies adopted by governments may be technology-neutral such as those which place a **price or limit on emissions** (e.g. emissions trading schemes, carbon taxes) which allow deployment of CCS when it is most cost effective among other abatement options. A growing number of countries have enacted carbon pricing policies such as emissions trading schemes and carbon taxes, of which several accommodate CCS activities. These include various instruments proposed and enacted over the past two decades:

- **Norway**: The carbon price of USD 51 per tonne introduced in 1991 and imposed on hydrocarbon fuels produced offshore, prompted Statoil to begin its Sleipner CCS project in the North Sea in 1996, thereby avoiding payment on around 1 million tCO_2 per year.
- **European Union**: Although CCS was not included in the original 2003 EU Emissions Trading Scheme (EU ETS) Directive, it was later included in the revised 2009 version: EU Emissions Trading Directive (Directive 2009/29/EC). This version explicitly includes CCS in Annex I (activities which are covered by the EU ETS), and emissions captured, transported and stored according to the CCS Directive are considered as not emitted, thereby providing a carbon price signal for CCS deployment.
- **Alberta, Canada**: The Specified Gas Emitter Regulation (SGER), passed in 2007, was North America's first GHG compliance and carbon pricing measure and requires large-emitting Alberta facilities including thermal power stations to reduce emissions or purchase eligible emission reduction offsets.
- **United States**: On 20 September 2013, the EPA issued a revised proposal for a *Carbon Pollution Standard for New Power Plants*. The proposal sets separate standards for natural gas-fired turbines (1,000 lbs CO_2 per MWh output[37]) and coal-fired units based on partial implementation of CCS (1,100 lbs CO_2 per MWh output).
- **Canada**: The Government of Canada's *Reduction of Carbon Dioxide Emissions from Coal-Fired Generation of Electricity Regulations* come into effect 1 July 2015. Under these regulations, all new coal-fired units and units reaching the end of their economic life that incorporate CCS will receive a temporary exemption until 2025 from a performance standard based on the emissions performance of natural gas combined cycle generation (IEA, 2013a).

During early-stage deployment when project risks and costs are relatively high, technology-neutral policies are unlikely to provide the required incentives to address the commercial risks associated with CCS technology and to guarantee the levels of investment required. Governments therefore need to consider a comprehensive framework which may include the combination of several policies and measures. **Targeted deployment incentives** can be specifically designed to address the economic and financial barriers facing CCS deployment (see Section 3.2.3). The **United Kingdom** is currently implementing such support through a range of policies specifically aimed at supporting CCS demonstration (Box 3.7).

This section has reviewed existing efforts undertaken by governments worldwide to support CCS development. However, additional action will be needed at the international level. In particular widespread deployment of CCS will require the creation of appropriate mechanisms and channels through which climate finance can be leveraged to least developed countries. This aspect will be explored in Section 4.

[37] Applies to larger gas-fired units only; smaller units may emit up to 1,100 lbs CO_2 per MWh output

Box 3.7 CCS support provisions within the UK Energy Act 2013

The UK Government's proposals for Electricity Market Reform (EMR) were published in a White Paper in July 2011. The EMR aims to secure the significant investment needed to upgrade the UK's electricity sector whilst ensuring a reliable, diverse, and low carbon supply. The proposals included several policy instruments which could help drive commercial CCS deployment:

- Feed-in tariffs with Contracts for Difference (CfD): generators receive support in the form of a "top-up" payment that pays the difference between the *strike price* (the long-term price needed to bring forward investment in a given technology) and the *market price*. The aim is to help offset the additional costs associated with low-carbon investment, providing long-term revenue stability and helping to lower investment risk. As the total amount available to fund CfDs for power generation from renewable, nuclear and CCS-equipped sources is capped, the ability of CCS projects to secure contracts will be influenced by the allocation of CfDs to other low carbon technologies.
- *Emissions performance standard (EPS)*: initially set at 450g CO_2/kWh as a base-load limit on carbon emissions, the emissions performance standard is determined so to ensure that no new coal-fired power plants above 50 MW capacity can be built without CCS. Demonstration projects, which may only operate with partial CO_2 capture, would however be exempted from the EPS.
- *Carbon Price Floor (CPF)*: this is intended to provide a clear economic signal to invest in low carbon technologies, including CCS, by increasing the price paid for emitting CO_2, through imposition the use of a tax underpinning the market carbon price in the EU ETS.

The UK government introduced legislation to implement these reforms into the UK parliament in November 2012, which was subsequently passed as The Energy Act 2013 in December 2013. Under current arrangements, the CPF will be capped at GBP £18 per tCO_2 from 2016-17 to 2019-20.

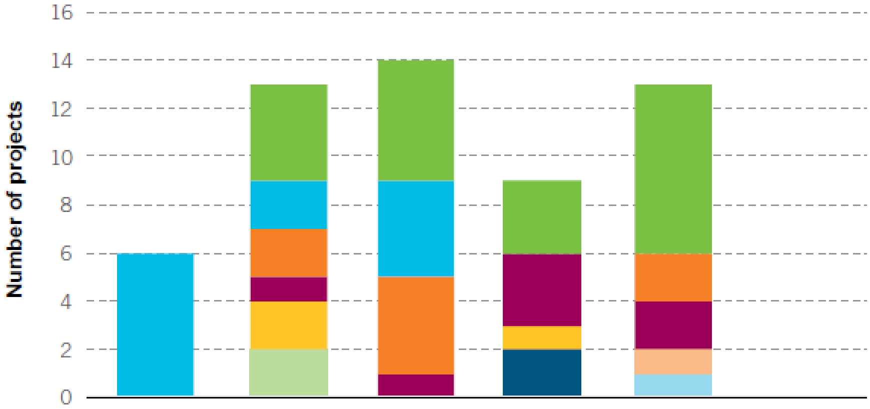
Source: DECC, 2012; 2013, HMRC, 2014.[38]

3.3.4 Large-scale project deployment

The objective of establishing a regulatory and policy framework for CCS is to achieve large-scale project deployment. The latest version of the GCCSI's *Global Status of CCS 2014* publication indicates that there are currently 55 large-scale CCS projects in different stages of development worldwide. These include 22 'active' CCS projects, of which 13 are operational and nine are under construction (GCCSI, 2014a). As shown in Figure 3.7, the United States has the largest number of projects worldwide, including ten projects in either operation or construction. China has a total of 12 projects, four of which are in an advanced stage of development planning (*ibid*). Of the 13 projects currently in operation, nine are located in North America (seven in the **United States**; two in **Canada**); two are located in **Norway**; with one in **Brazil** and one in **Algeria** (Figure 3.8).

[38] See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48371/5349-electricity-market-reform-policy-overview.pdf; https://www.gov.uk/government/collections/energy-act; https://www.gov.uk/government/publications/carbon-price-floor-reform

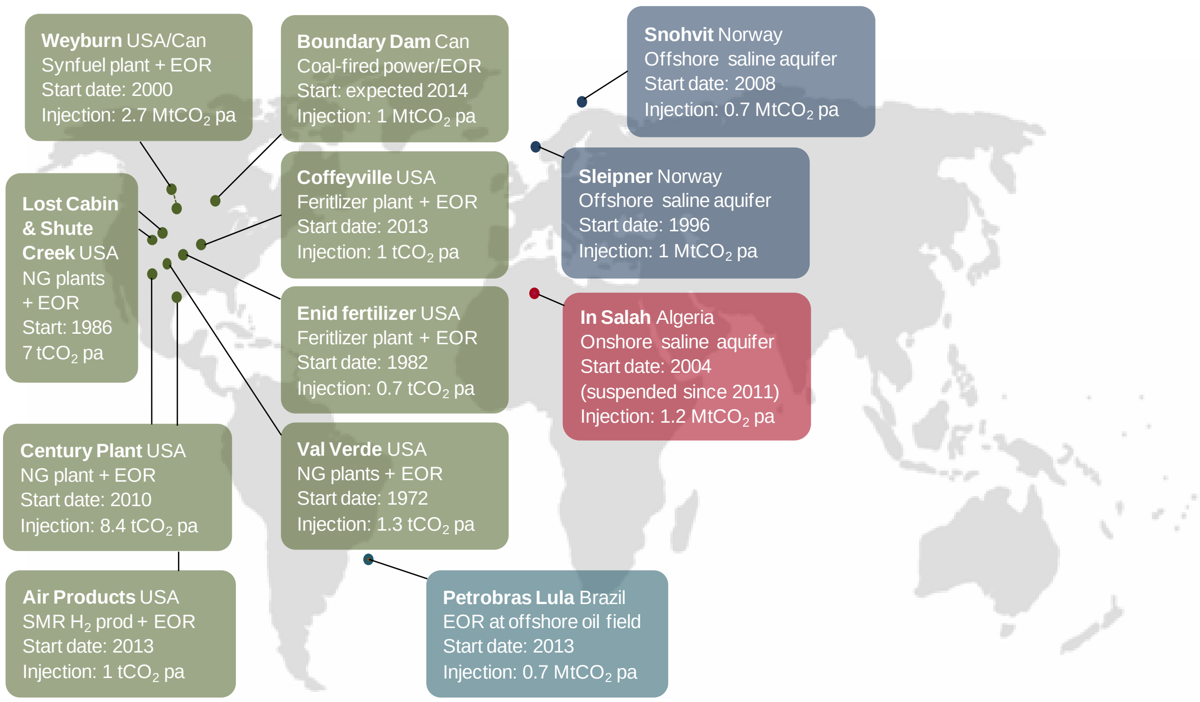
Figure 3.7 Large-scale CCS projects by life-cycle stage and region/country



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

Source: GGCSI, 2014a

Figure 3.8 Commercial-scale CCS projects in operation



Source: Carbon Counts CCS project database

The **communication and dissemination of results** from the operation of large-scale CCS projects is also key action for ongoing international knowledge-sharing and successful technology demonstration. These may include sharing technical information and lessons learned (e.g. relating to capture plant operation, CO_2 injection or the efficacy of MRV techniques) as well as organisational challenges and how these were overcome. Results from several operational projects have been widely shared through various knowledge-sharing fora (e.g. CSLF, GCCSI, regional CCS workshops and international R&D initiatives). For example, Statoil has broadly communicated experience gained through almost 20 years' of CO_2 injection associated with the Sleipner project (Box 3.8).

At present, there are only a small number of large-scale CCS projects in operation worldwide, most of which are located in North America involving CO_2-EOR. As recognised by the *IEA Technology Roadmap* and other sources, the ambitious deployment levels required under 2DS will require many regions and countries to develop large numbers of integrated CCS projects capturing from multiple sources. Achieving economically viable deployment across many different sources will require investment in **transport and storage infrastructure** such as common carrier pipelines, transport networks and offshore CO_2 storage hubs. Significant public intervention will be needed to overcome the various commercial risks in developing such infrastructure. For example, studies indicate that significant economies of scale can be achieved by over-sizing pipelines for initial 'anchor' CCS projects, thereby allowing additional capture points to connect to the pipeline at much lower cost than where each source to build its own pipeline - which in any case may be unfeasible (Element Energy and Carbon Counts, 2010). Analysis however shows that such up-front investments are associated with large financial risks, and that the public sector can play a key role in helping to overcome such challenges (*ibid*).

Box 3.8 Statoil's Sleipner and Snøhvit CO_2 injection projects

The Sleipner Project in Norway, operated by Statoil, is associated with natural gas production in the North Sea. Since 1996, it has been injecting CO_2 offshore into sandstones of the Utsira Formation (saline aquifer) 1 km below the sea floor. The gas in the Sleipner oil and gas field has a very high CO_2 content (up to 9 per cent); the CO_2 is removed from the unprocessed gas using conventional amine capture technology installed on the offshore platform and the CO_2 is injected back underground into the aquifer. Sleipner is the world's first commercial–scale dedicated storage project. CO_2 is currently injected at a rate of about 0.9 Mtpa and, to date, more than 14 Mt of CO_2 has been injected and stored. Statoil also operates the Snøhvit storage project, which in April 2008 began injecting CO_2 into the Tubåen sandstone formation 2.6 km below the sea floor in the Barents Sea, and by 2011 had stored 1.1 Mt of CO_2. Statoil experienced operational issues with injectivity in the Tubåen formation and later in 2011 began injecting into the Stø formation, where about 0.82 Mt of CO_2 had been stored by May 2013. In total, more than 1.9 Mt of CO_2 has so far been stored as part of the Snøhvit project.

Statoil have communicated progress with the Sleipner and Snøhvit projects, including sharing of technical information, through various fora, including the *European CCS Demonstration Projects Network*. With Sleipner, they conclude that injection has been unproblematic with wellhead pressures stable at around 64 – 65 bar (with 38% porosity and 1-8 Darcy permeability). They suggest that the most valuable information has come from the repeat series of time-lapse seismic data, giving important information on CO_2 behaviour in the subsurface. Statoil state that while capture typically takes around 80% of the initial capital investment, Storage risks are often underestimated. Important Storage risks are cited as geological uncertainties; well technology developments and interventions; and public perception on safety of storage sites.

Some key learnings from Statoil's CO_2 storage operations have been identified as:

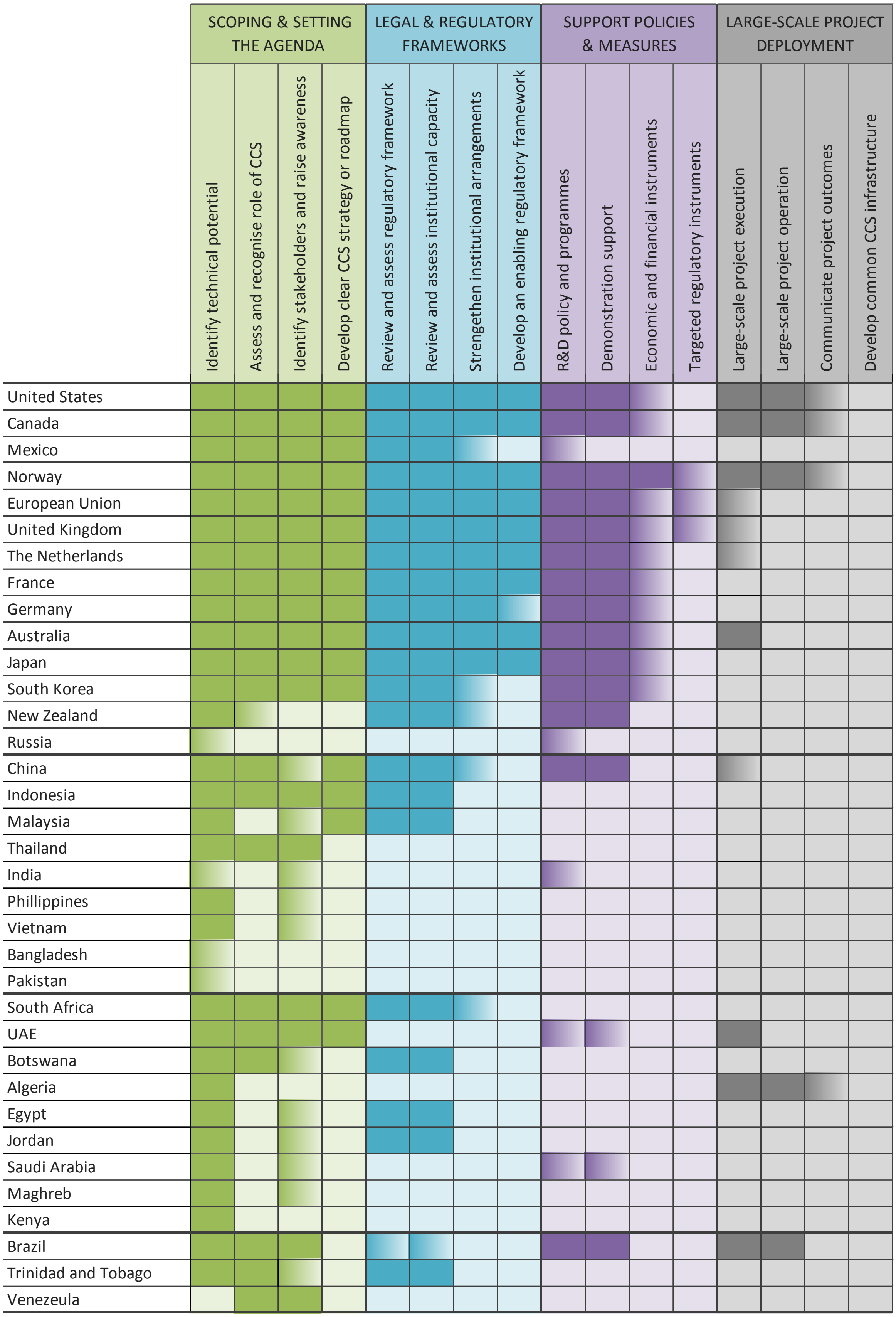
- Importance of developing early experience on CO_2 injection at multiple storage sites
- Importance of phased capture-to-storage integrated systems allowing gradual experience building
- Importance of flexibility at storage sites – flexible well designs, etc.

Source: Statoil, 2010; GCCSI, 2013a

3.3.5 Summary

Figure 3.9 presents a summary of current progress worldwide against key indicators within a national-level framework of CCS support and deployment. The figure shows how countries are at various stages of development in implementing the required policies and actions - and also that various components of the framework shown may be developed at different rates (e.g. large-scale projects may be delivered whilst the framework needed for wider deployment is developed). Most OECD countries have now assessed their potential for CCS, have recognised the role of the technology within national climate policy responses and have reached an advanced stage of developing the required legal and regulatory framework. Although most of these countries have introduced wide-ranging R&D programmes and project demonstrations, economic and financial measures have however proved insufficient to incentivise widespread deployment: the use of targeted regulatory instruments is currently very limited. The figure also shows progress in many non-OECD regions. These are largely focusing on scoping and capacity-building exercises at present, although several countries (Algeria, the UAE and Brazil) have successfully delivered large-scale projects and significant progress is being made elsewhere.

Figure 3.9 Progress against key indicators of CCS support and development

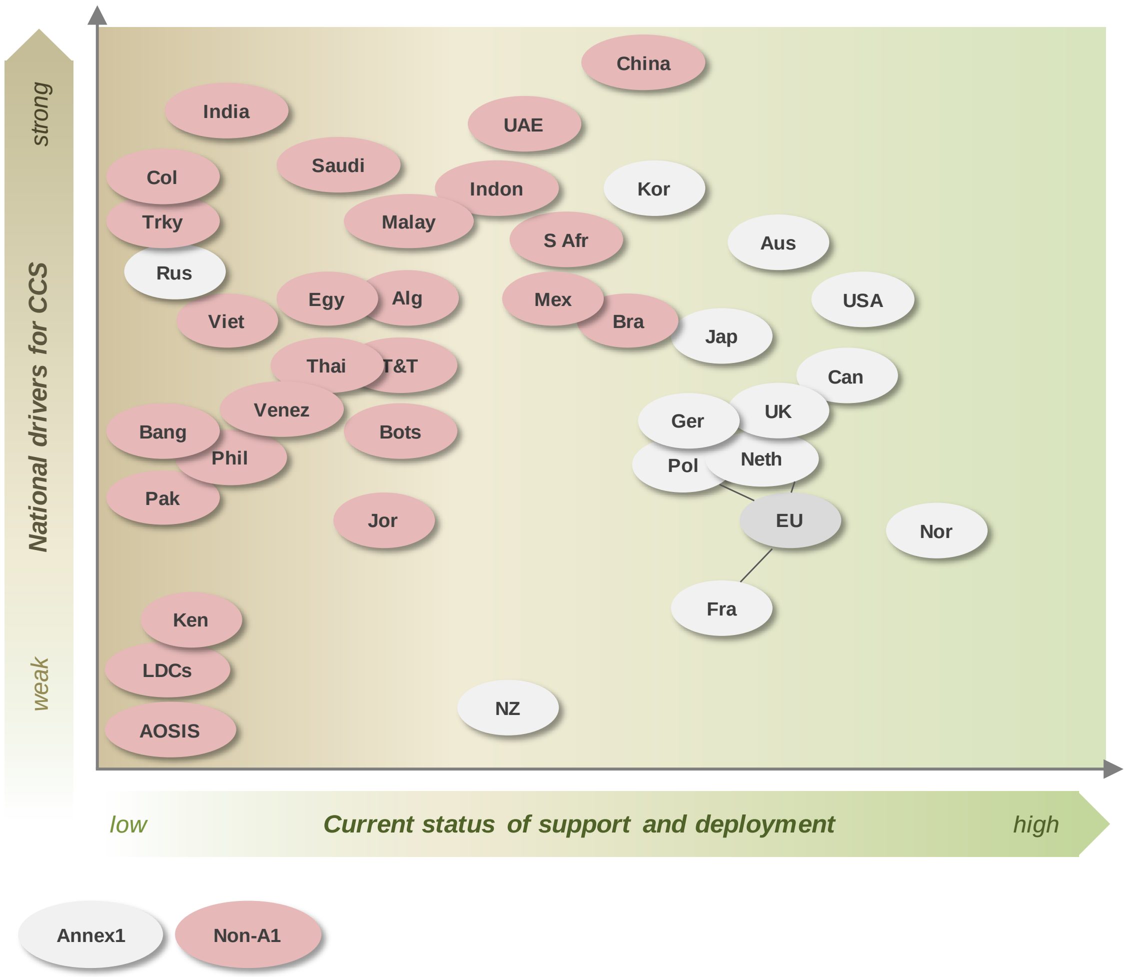


Note: Partially coloured areas indicate only limited activities and/or activities currently in progress. Assessment in made based on authors' expert judgement, drawing from the report's evidence base.

3.4 Conclusions

The above summary is combined with the assessment of national drivers for CCS presented in Chapter 2, and the resulting matrix shown in Figure 3.10. Countries are plotted according to (a) the key drivers for undertaking CCS and (b) indicators of CCS support and development. No attempt is made to rank or weight the different factors, although it should be noted that certain requirements will be essential for wide-spread deployment, for example establishing the presence of suitable CO_2 storage sites. The figure provides a snap-shot of both the rationale for undertaking CCS as an abatement option globally, and also the remaining progress to be made across world regions in supporting and deploying the technology - from undertaking initial scoping studies through to establishing the regulatory and policy frameworks needed.

Figure 3.10 Assessment of national drivers versus current stage of support and deployment



4 HOW CAN THE UNFCCC SUPPORT UPTAKE OF CCS?

4.1 Introduction

The previous section showed that different countries and regions are at various stages of progress with CCS support and deployment. Some have begun to put in place the required laws, regulations and policy incentives needed for deployment whereas for others, CCS remains at the scoping level. Despite increasing activity, in both developed and developing countries, progress is slow and there remains little long-term incentive for developers to invest in CCS. Furthermore, the various drivers for undertaking CCS are not always fully realised within national circumstances, or aligned with other areas of national policy.

As shown in Section 2, CCS faces a number of challenges at the current time, limiting its uptake compared to some others emissions reduction technologies. While some countries are designing the policies and programmes at the *national* level to help overcome these, measures taken at the *international* level within the UNFCCC framework can also work to address some of the challenges. Deploying CCS on the scale needed will also require significant investment – across many sectors and regions worldwide. The Convention's mechanisms can facilitate technology development and transfer as well as the sharing of knowledge and best practice. Crucially, the UNCCC framework can help Parties – both developing and developed countries – to move one or more step further along the pathway described in Section 3. The UNFCC therefore has an important role to play in driving CCS forward.

The architecture of the UNFCCC is evolving. The focus is currently upon reaching an international agreement at COP21 in December 2015. The mechanisms through which CCS technology can be supported under the UNFCCC must therefore be considered in the context of these ongoing discussions. Many of the details of the agreement remain unresolved, including the overall level of ambition to reduce emissions. There are significant uncertainties too concerning the building blocks of the new agreement and how they can facilitate mitigation under the Convention (Figure 4.1).

Despite these uncertainties, the UNFCCC framework can help support CCS deployment through the following routes:

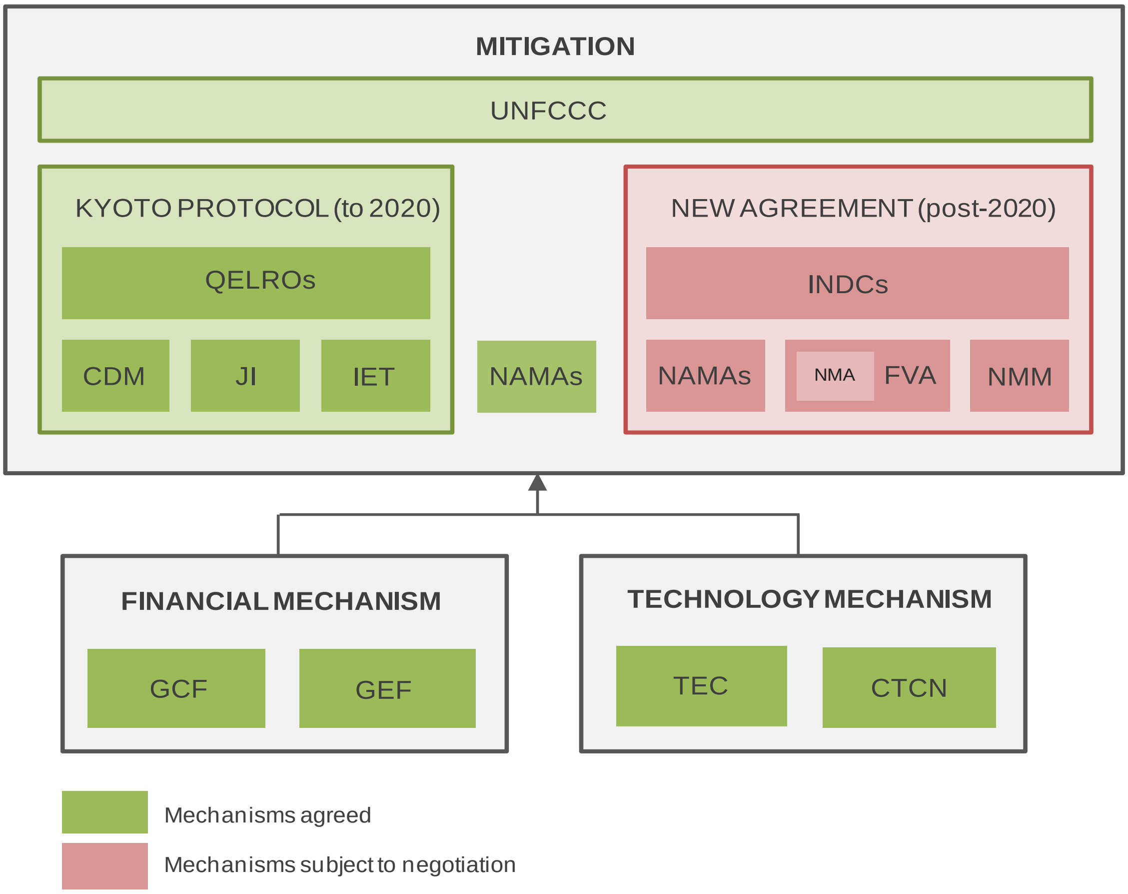
- Providing the overall **mitigation** policy framework for CCS development and deployment
- Mobilising **finance** into CCS projects and programmes
- Addressing **technology** needs and helping to build capacity

The new agreement, if adopted in Paris, will come into force in 2020. INDCs submitted by the Parties will collectively determine global efforts to reduce emissions under the agreement. The ambition of the commitments made will in turn provide the demand for deploying step-change mitigation technologies including CCS to help meeting those commitments. Parties will need to implement – in support of their INDCs – the domestic policies and measures needed to enable and incentivise investment in mitigation projects. While developed countries will need to develop and deploy CCS using their own finance and technology, developing countries may need financial and technological assistance from developed countries. The mitigation framework of the new agreement should provide for the transfer of technology and finance from developed to developing countries. Under the Kyoto Protocol, this is achieved through the Clean Development

Mechanism (CDM), within which CCS projects are eligible. Other potential mechanisms subject to the ongoing negotiations, and which could play a role in the new agreement, include Nationally Appropriate Mitigation Actions (NAMAs) of developing countries, New Market Mechanism (NMM) and actions taken under the Framework for Various Approaches (FVA).

Depending upon their design and implementation, these mechanisms should provide channels for supporting and mobilising climate finance and technology into CCS. The Convention's Finance Mechanism, comprising the Global Environment Facility (GEF) and the new Green Climate Fund (GCF) also provide important channels through which developed countries can help finance CCS projects and programmes. Finally, the Convention's Technology Mechanism, comprising the Technology Executive Committee (TEC) and Climate Technology Centre and Network (CTCN) has an important role to play in putting CCS on the international agenda, sharing technical expertise and knowledge worldwide, and building in-country capacity for CCS support and deployment.

Figure 4.1 Overview of UNFCCC framework for mitigation



In the context of the post-2020 agreement, this section assesses how CCS can be supported within this evolving framework. The assessment is structured around the four key areas of support and deployment identified in Section 3, namely:

1. Assessing the potential and setting the agenda
2. Building capacity and developing legal and regulatory frameworks

3. Designing and implementing support policies and measures
4. Large-scale project deployment

4.2 Assessing the potential and setting the agenda

4.2.1 Setting the agenda for CCS through INDCs

In order to drive CCS forward as part of global efforts to meet the UNFCCC 2°C goal, Parties must first assess how the technology can play a role as a GHG mitigation option within the context of their national circumstances and priorities (see Section 2). For those countries where drivers exist, this involves putting CCS firmly on the policy agenda – including identifying it within national climate change plans and strategies. In the context of the post-2020 agreement, this also means Parties recognising CCS as a key part of their INDCs. As of 16 June 2015, twelve INDCs have been received by the UNFCCC.[39] Of these, just four had specifically referred to the role CCS will play in meeting their contributions (Norway, the EU, Mexico and Canada).

INDCs need to be devised using a step-by-step process based on assessing mitigation potential. They involve identifying promising mitigation actions and describing national coordination and implementation. *The Lima Call for Climate Action* also asks Parties to outline in the INDCs how they will cut emissions for the post-2020 period beyond *existing* efforts, i.e. demonstrating that efforts go beyond business-as-usual or reference emissions. For those countries where CCS represents a potentially important mitigation option, this essentially involves articulating a national roadmap for CCS and clearly demonstrating its role within national GHG efforts. The inclusion of CCS should therefore consider the following types of questions:

- What is the technical potential for deploying CCS?
- What can it contribute towards national GHG emission reductions? Across what types of sectors and activities?
- How does CCS align with national circumstances and priorities?
- What steps and measures are required to provide an enabling framework?
- What are the specific actions and/or targets for emissions mitigation through CCS deployment?
- What additional assistance is required to undertake specific actions and/or targets?

Each country faces different **national circumstances**, with a different emissions profile and emissions reduction opportunities. As described in Section 2 of this report, for many countries and regions worldwide, CCS will represent an important option for achieving deep cuts within key emitting sectors. For some countries it may offer specific project opportunities within high-purity low-cost sectors (e.g. natural gas processing), whereas for others it will be required as part of a longer-term vision for aligning continued fossil fuel use (e.g. coal-fired power generation) with the move towards a low carbon pathway.

INDCs can be framed as either **action-based commitments** or **outcome-based targets**. Parties can therefore commit to implementing specific emissions-reduction actions, including policies or mitigation actions for low carbon technologies including CCS. Alternatively, Parties can commit

[39] Andorra, Canada, Ethiopia, European Union (EU), Gabon, Lichtenstein, Morocco, Mexico, Norway, Russia, Switzerland, United States of America.

to a certain outcome or result, such as reducing emissions to a specific level (a GHG outcome) or generating a certain share of low-carbon energy (a non-GHG outcome). The variety of national circumstances each Party faces will drive a wide diversity of INDCs, ranging from emissions targets to actions taken in particular sectors.

Tackling climate change through an INDC-driven process will be iterative: initial submissions will only be the start of a longer process towards continuous and increasingly ambitious commitments. As described in Section 3, regions and countries worldwide are at different stages with respect to a pathway of CCS support and deployment. The focus of CCS within INDCs should therefore **identify suitably ambitious and practical steps** to move beyond the current step of the pathway.

In this context, the inclusion of CCS within Parties' INDCs could include the following:

- **Estimated potential contribution from CCS within national GHG reduction plans** - based on techno-economic CCS assessments across sources and sectors, including CO_2 storage mapping source-sink matching
- **R&D activities and programmes** - including specific pilot and demonstration projects
- **Policies and measures to incentivise CCS** - including targeted deployment incentives e.g. feed-in-tariffs, emissions performance standards, and emissions pricing/limiting instruments e.g. carbon taxes, carbon trading)
- **Sectoral targets and goals** - e.g. application of CCS to a given industrial sector (% share of production capacity by year x); CCS capacity installed within the power sector over a specified timeframe (GW or GWh by year x)
- **National targets and goals** - e.g. CCS deployment over a specified timeframe (tCO_2 avoided by year x)

For some countries further along the CCS pathway – for example, developed countries who have introduced CCS regulatory and policy frameworks – the last two approaches may be appropriate. For other countries such as developing countries at earlier stages of the pathway, the first three approaches may be more relevant. Developing countries can also choose to highlight needs and priorities to assist in the implementation of the INDC, including with regard to finance, technology, and capacity building. In so doing, they can express the *additional level of emissions reduction* that could be achieved with access to **international support and climate finance**. Further below, this section describes the extent to which UNFCCC mechanisms - some existing and others emerging - can help support developing countries undertake the types of measures outlined above, and increase the ambition of their INDCs.

4.2.2 Support in assessing the potential

Section 3 described several initiatives undertaken by multilateral banks outside of the UNFCCC framework (including e.g. the World Bank and ADB's CCS Trust Funds), helping developing countries to establish their CCS potential. Within the UNFCCC, an important resource in this context is the **Technology Needs Assessment (TNA)** programme.[40] Supported by the **Global Environment Facility (GEF)**, TNAs are a set of country-driven activities that identify and

[40] The TNA programme is managed by the United Nations Environment Programme (UNEP)

determine the mitigation and adaptation technology priorities of countries. Based on the TNAs, national **Technology Action Plans (TAPs)** can then be developed which prioritise nationally appropriate mitigation technologies, recommend enabling frameworks and facilitate the identification of projects and links to relevant funding sources.[41] To date, 36 developing countries have undertaken TNAs and prepared TAPs and project ideas, and 25 more will do so through 2015-16. Several countries have assessed national CCS potential within these assessments and plans, including identifying specific project opportunities (Box 4.2).

However, given the large range of national drivers for CCS outlined in Section 2 of this report, there is greater potential for CCS to be fully identified as a prioritised mitigation technology within TNAs. In the UNFCCC review of Phase 1 (ending 2013) of the global TNA project, CCS was not listed in the ten most prioritised technologies identified by Parties for the energy industries sub-sector of the 'energy' sector. Prioritised technologies were reported as: solar voltaic, biomass/biogas, efficient lighting, waste to energy, wind turbines, hydropower, energy efficiency, CHP, efficient cook stoves, and natural gas combined cycle plants. [42]

The TNAs represent an important activity, because as well as helping to identify the role of CCS within the preparation of INDCs (see above), they can help support, and link to, the development of NAMAs (see 4.4.1) which could help support CCS through specific funded mitigation actions. Parties should therefore ensure CCS is adequately assessed within TNAs and, where found to be nationally relevant, clearly identified as a key mitigation option within TAPs - and INDCs.

[41] TAPs also aim to outline practical steps needed to reduce or remove policy, finance and technology related barriers to the uptake and scaling up of investment in mitigation technologies.

[42]See http://unfccc.int/ttclear/templates/ttclear/misc_/StaticFiles/gnwoerk_static/HOME_carousel/ff36315120154f119f19b295f348e700/329ae298f41f40708df6344b0618d39c.pdf

Box 4.1 Assessing the role of CCS within Technology Needs Assessments

Technology Needs Assessments (TNAs) can assist developing countries in identifying and analyse their priority technology needs, which can be the basis for a portfolio of mitigation technology projects and programmes. Concluded in 2013, Phase I of the global TNA project provided targeted financial and technical support to 36 developing countries in Africa and the Middle East, Asia and CIS, and Latin America and the Caribbean to undertake TNAs and prepare TAPs and project ideas. This project was supported by the Global Environment Facility (GEF) under the *Poznan Strategic Programme on Technology Transfer* and implemented by UNEP and UNEP DTU. Starting in late 2014, the UNEP and UNEP DTU Partnership is providing similar support to a second phase of 25 new countries through 2015/16, also funded by the GEF.

To date, several countries have assessed CCS within their TNAs and TAPs:

- **Bangladesh** identified clean coal as a national priority and assesses CCS applied to gas- and coal-fired power generation. IGCC with CCS is identified as a project idea within the TAP
- **Kazakhstan** assessed CCS as a potential mitigation option within the cement sector, with greater potential in the west of the country in proximity to potential injection sites
- **Moldova** assessed CCS as a mitigation option when combined with IGCC for coal-fired electricity generation
- **Morocco** considered CCS to offer significant emissions reduction potential and proposed potential pilot projects in combination with solar energy
- **Mongolia** identified CCS as a potential mitigation option within fossil fuel electricity supply, but only over the longer term
- **Rwanda** assessed CCS applied to peat-fired IGCC, ECBM and methane CCGT within the TNA; methane CCGT with CCS is taken forward in the TAP and identified as one of six a project ideas within the energy sector
- **Thailand** identified CCS as one of five national mitigation technology priorities but concluded that it has yet to develop the appropriate CCS policy framework needed

Source: TNA reports submitted by UNFCCC Parties (as of 11 May 2015)

4.3 Building capacity and developing legal and regulatory frameworks

4.3.1 Support in building capacity, technical expertise and awareness raising

The Technology Mechanism was established to facilitate enhanced action on technology development and transfer to support action on mitigation and adaptation. It consists of two components:

- The **Technology Executive Committee (TEC)**, which provides strategic guidance relating to technological needs and analysis of policy and technical issues related to the development and transfer of technologies; and
- The **Climate Technology Centre and Network (CTCN)**, which supports implementation

For CCS, the Technology Mechanism could be an important catalyst in a number of areas. The TEC plays an important role in advising the COP on technology development, deployment, and transfer and how the UNFCCC architecture can better assist countries to adopt low emissions technologies including CCS. It also has significant interactions with the multilateral banks (e.g.

The World Bank and The ADB) and the private sector in relation to finance for mitigation technologies. Within the agreed modalities of the TEC, it can play a strategic role in:

- Assessing and reporting to the COP on barriers and challenges facing CCS;
- Providing information on nationally determined mitigation technology options including CCS;
- Examining and advising on the opportunities within the UNFCCC architecture for advancing international CCS deployment;
- Producing regular reviews of CCS progress within technology development and transfer activities, and identifying key achievements and gaps, good practices and lessons learned.

The TEC therefore has an important 'top-down' role within the UNFCCC with the potential to further help build capacity, facilitate knowledge transfer and assess how CCS can be driven forward within the UNFCCC process. CCS should therefore be included within the TEC's work-plan.

As the implementing body of the Technology Mechanism, the CTCN can also assist CCS support and development in a number of specific ways. The CTNC was established to facilitate an international network of technology networks and to engage participants in those networks in providing advice, support, information and training. It can therefore help promote CCS internationally through e.g.:

- Providing access to technical information and knowledge on CCS technology and implementation experiences;
- Providing technical assistance to help accelerate the uptake of CCS;
- Assessing CCS readiness within countries and gaps/barriers;
- Identifying specific CCS projects internationally and linking these to funding partnerships including through the GCF;
- Assisting the development of international and regional R&D and demonstration partnerships and programmes relating to CCS;
- Creating international information and awareness-raising campaigns relating to CCS.

The Technology Mechanism has an important role to play. However, the TEC and the CTCN need a mandate from Parties to work on CCS. In raising CCS within the UNFCCC agenda and exploring new initiatives to drive deployment of the technology forward, progress with CCS in both developed and developing countries might be enhanced. Specific actions aimed at achieving greater progress might include holding regular technical workshops on CCS, publish technical guidance, develop codes and practices (e.g. in relation to MRV and best practice for CO_2 storage) and regulatory information (see below). Those developed countries which have been at the forefront of international efforts to support CCS and develop the relevant technical standards and regulations, might be best placed to spear-head such efforts within the UNFCCC process.

Finally, the development of a specific international partnership for CCS (as has been developed for other clean technologies and areas of climate policy e.g. NAMAs; LEDS) might help to foster greater collaboration and alignment between the current activities of different organisations internationally to accelerate support for CCS. Such a partnership could aim to identify best practices and share knowledge to facilitate wider CCS uptake within both developed and developing countries. Such a partnership could operate with the close participation of, or even under the aegis of, the UNFCCC, whilst drawing from a wide range of organisations with a role in supporting the technology worldwide.

4.3.2 Developing legal and regulatory frameworks

Countries worldwide will need to put in place their own laws and regulations needed to support CCS deployment. As described in Section 3, many developed countries have developed the required frameworks in accordance with their own domestic arrangements, whilst some developing countries are currently assessing options for their own frameworks. These must address, among other issues, the need to ensure robust MRV of CCS activities and the safety and effectiveness of storage activities. Within the context of the UNFCCC, both aspects are essential for emissions reductions to be recognised and accounted for within Parties' national inventories (and by extension, their INDCs), and also within the accounting frameworks of emerging mechanisms within which CCS could attract climate finance such as the GCF and via the NMM and NAMAs (see below).

Two important provisions exist under the UNFCCC which can help Parties in this context:

- The **Modalities and Procedures for CCS under the CDM**[43]. These form a set of rules agreed by Parties under which CCS projects can generate emissions reduction credits under the CDM. Their relevance extends beyond the current narrow window of the CDM however. They address a range of specific issues through fairly detailed guidance on aspects that must be taken into consideration, including specific requirements upon countries hosting CCS projects (Box 4.1). The M&Ps provide guidance for Parties to develop the domestic regulations and provisions needed to provide assurances concerning safe and effective CO_2 storage.
- The **2006 IPCC Guidelines for National Greenhouse Gas Inventories**[44]. These provide the emissions accounting framework for CO_2 storage activities for compilation in Parties' national GHG inventories submitted to the UNFCC (other components are included across the 2006 IPCC Guidelines to accommodate the capture and transport of CO_2, including broad guidelines relating to CO_2-EOR). As well as providing the basis by which countries may report emissions as not emitted to the atmosphere for the purpose of their national GHG inventory (and the generation of emissions reductions under UNFCCC mechanisms), the monitoring of CCS projects according to the Guidelines also ensures that any releases from storage sites are fully accounted for. They also provide the basis for Parties to develop country-specific and more detailed MRV guidelines.

The rules and procedures contained in the M&Ps text thus provide an important foundation for how CCS projects might be supported under other new forms of international climate finance,

[43] UNFCCC (2011) *Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities*. Decision 10/CMP.7

[44] Volume 2, Chapter 5: Carbon Dioxide Transport, Injection and Geological Storage. As the IPCC Guidelines set down an internationally agreed set of MRV rules for all UNFCCC Parties, they form a basis to develop national level guidelines. More detailed and specific articulation of Monitoring and Reporting guidelines (MRGs) has subsequently taken place within several jurisdictions including within the EU, USA and Canada.

such as the GCF and via the NMM and NAMAs (see below); whilst the IPCC Guidelines provide the basis for their MRV by Parties under the UNFCCC.

Box 4.2 Modalities and Procedures for CCS as CDM project activities

The Modalities and Procedures (M&Ps) for CCS as CDM project activities modify existing elements of the CDM M&Ps to address CCS-specific issues raised by Parties and Observers to the UNFCCC over several years of negotiation. These include additional participation requirements for non-Annex I Parties wishing to host CCS projects. In addition to communicating to the UNFCCC Secretariat its intention to host CCS projects, a host Party must ensure laws and regulations are in place regarding the following:

a) site selection, characterisation and development;
b) the right to store CO_2 and obtain access to the site;
c) redress for any significant damage caused by the project;
d) remedial actions to stop and control any seepage and restore the integrity of the storage site and long-term environmental quality;
e) liability arrangements for environmental and other damage; and
f) measures to comply with the obligations to address seepage ('net reversal of storage'), if the host Party has previously indicated its acceptance of such obligations.

The M&Ps also include new technical elements to address CCS-specific concerns raised by Parties and Observers to the UNFCCC over several years of negotiations, covering:

- site selection and characterisation
- risk and safety assessment
- monitoring
- financial provision
- environmental and socio-economic impacts
- permanence and liability

Any CCS requirements set at the national level should be developed consistent with the requirements set out in the CCS M&Ps, thereby ensuring that the results of work undertaken for national requirements can also be used for the purposes of CDM applications (and other emerging/future mechanisms). The CCS M&Ps provide the rulebook, agreed at an international level, upon which CCS projects can be developed by countries globally under UNFCCC activities and mechanisms.

Source: UNFCCC (2011) *Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities*. Decision 10/CMP.7

The development of a legal and regulatory framework for CCS could also in theory be recognised as a NAMA undertaken by a developing country Party, and as such could be eligible for funding through the GCF or other sources (see below).

4.4 Support policies and measures

4.4.1 Nationally Appropriate Mitigation Actions

The Lima Call for Climate Action requests Parties to describe how their INDCs will be implemented: Parties must design and implement the policies and measures needed to fulfil the ambition contained in their submissions. For low carbon technologies including CCS, this involves putting in place the specific programmes to support demonstration and the longer-term incentives needed to drive wider deployment. As described in Section 3.3.3, these are emerging in several regions worldwide within the context of national and regional climate policy. For developing countries, domestic efforts to enact policies and measures could be further supported through the UNFCCC process, potentially through the use of NAMAs.

NAMAs are voluntary bottom-up instruments with a clear focus on mitigation actions, including the use of support policies to drive low carbon technology. Importantly, the term recognises that different countries may take different *nationally appropriate* actions in line with their circumstances and priorities. These might be focused on one particular sector or actions taken across sectors for a broader national focus. NAMAs can have several functions within a post-2020 climate regime, including the following (Röser and van Tilburg, 2014):

- NAMAs can be logical building blocks for domestic action plans, low emission development strategies, and targets;
- NAMAs can be convenient vehicles for concrete action on the ground and associated international finance and technical assistance;
- NAMAs can be a basis for international reporting and/or articulation of commitments.

NAMAs can be seen as useful tools to fulfil the mitigation ambitions contained in Parties' INDCs. However, their exact role within a post-2020 agreement remains undefined, including key issues around how they could receive funding via the GCF (see 4.5.2), UNFCCC reporting requirements, their link to INDCs and also the link between NAMAs and other mechanisms under the Convention.

NAMAs potentially provide an important mechanism for CCS. They must include only those actions that go beyond business-as-usual emissions, which is easily demonstrated in the case for CCS (excepting certain activities involving commercial CO_2 utilization). NAMAs can also easily co-exist with other instruments such as market mechanisms (*ibid*) – for many CCS project types, combining support through a mixture of market- and non-market based funding will likely be essential (see 4.5.1). They will also need to be subject to robust MRV, the basis for which is contained in the IPCC 2006 Reporting Guidelines and M&Ps for CCS as CDM (see above).

Although the NAMA concept is still open to broad interpretation, most discussions have interpreted them to have a focus on sector-based mitigation actions. NAMAs could include developing the policy frameworks needed to drive CCS - using measures tailored to national priorities and across those sectors and sources reflecting national circumstances. NAMAs specific to CCS could also extend to actions other than policy development, and might include the following types of actions:

- **Indirect support** (e.g. capacity and enabling frameworks):
    - CO_2 storage mapping and site identification
    - Development of CCS legal and regulatory framework
    - In-country capacity building, including MRV and technical expertise
- **Direct support** (e.g. policies and projects):
    - Funding for specific pilot and demonstration CCS projects

- Development of specific regulations and policies (e.g. emissions performance standards, feed-in-tariffs)
- Financial incentives for CCS (e.g. domestic tax measures, emissions trading, subsidies, grants and concessional loans)

4.4.2 Support under the Global Environment Facility

The Financial Mechanism's **Global Environment Facility (GEF) Trust Fund** provides grants and concessional funding to developing countries for climate-related programmes and projects. The goal of the current cycle's Climate Change Mitigation Program is to support developing countries and economies in transition to make transformational shifts towards a low emission development path[45]. A total of USD 1.26 billion is allocated to climate change mitigation, spread across three core objectives and five programs.[46]

Although CCS projects and activities are not excluded from the GEF, the Climate Change Mitigation Strategy makes no reference to the technology. The focus of Program 1, for example, is on energy efficiency, renewable energy and sustainable transport systems, whilst Programs 3 and 4 focus explicitly upon mitigation within the urban environment (e.g. buildings, transport) and forestry, land use and agricultural sectors. CCS can however potentially be supported through two key program areas:

- **Program 2** aims to "support countries that articulate, particularly in the national communications, and other assessments, a need for policy packages for emission mitigation while maximizing economic benefits and/or minimizing the socio-economic consequences of ambitious mitigation measures". These could include the design and assessment of CCS-related policies and measures, and support in their subsequent implementation, including through pilot and demonstration projects.
- **Program 5** aims to "facilitate the integration of reporting and assessment results into the national planning process and to help countries mainstream mitigation action in support of the proposed 2015 agreement". This includes providing resources to developing countries seeking to assess national mitigation potential and undertake Technology Needs Assessments (TNA) and capacity-building activities, within which CCS can play an important role (see 4.2.2).

In addition to the GEF Trust Fund, the GEF administers the **Special Climate Change Fund (SCCF)** - focussed on several areas including technology transfer and assistance to countries whose economies are highly dependent on fossil fuel exports. The SCCF has particular relevance to the demonstration of CCS technology and can allow developing countries to access funds to support pilot-scale projects in key sectors according to their national circumstances. For example, the GEF has approved USD 2.7 million of support from the SCCF for a USD 10.4 million CCS pilot project at an ethanol plant in Brazil. Despite its relatively modest size, the GEF can play a useful role in supporting pilot- and demonstration-scale project deployment. Given the applicability of the technology to the national circumstances of many developing countries worldwide, CCS should be explicitly identified as an important mitigation option within future funding cycles.

[45] The current funding cycle, GEF-6, covers the period of 1 July, 2014 to 30 June, 2018

[46] The GEF also provides support in the preparation of INDCs and may provide support for the development of MRV systems within NAMAs and/or other emerging financial mechanisms.

4.4.3 The development of a CCS-specific Mechanism

Most discussions concerning the role of the UNFCCC in supporting CCS technology focus upon the use of existing or emerging mechanisms. However, it is also possible within the UNFCCC framework to establish by COP decision a specific mechanism for the promotion and deployment of CCS. The rationale for developing a mechanism specific to CCS would presumably be that alternative mechanisms were failing to achieve progress with CCS deployment and/or that CCS required specific considerations which might be best served through a new approach - tailored to overcome specific barriers and issues.

The closest analogy to such a mechanism would likely be Reducing emissions from deforestation and forest degradation (REDD), and subsequently REDD+, which has been under negotiation within the UNFCCC since 2005.[47] Experiences with establishing the mechanism and the first generation of REDD initiatives point to a number of challenges (Angelson *et al*, 2012; IIED, 2015). For example Angelson *et al* (2012) describe a series of specific issues with respect to the MRV of REDD activities, including *inter alia*:

- **Determining suitable emission factors** (e.g. the need to use country, region and forest-specific data; the extrapolation of existing datasets and emission factors to ecosystems over large scales)
- **Establishing reference emissions levels** (e.g. uncertainties in predicting business as usual emissions scenarios; availability and quality of baseline data)
- **Availability and use of monitoring techniques** (e.g. use of remote sensing technologies to detect deforestation, reforestation and forest degradation)
- **Uncertainties regarding scientific knowledge of carbon stocks and GHG fluxes** associated with land use and land use change (e.g. understanding the relationship between changes in forest conditions and changes in emissions)

The inherent uncertainties associated with MRV of REDD activities mean that such specific challenges can only be partially addressed through the IPCC 2006 Reporting Guidelines and the use of the IPCC 'Good Practice Guidance for Land Use, Land Use Change and Forestry' (GPG-LULUCF) published in 2003. Despite the use of several MRV capacity building efforts undertaken as part of REDD+ readiness activities, progress on building institutional capacity has been slow (Angelson *et al*, 2012). Despite some challenges associated with MRV of CCS activities – largely in respect of the CO_2 storage stage – many of the issues outlined above in respect of REDD do not pose similar challenges for CCS. For example, CO_2 storage (in the absence of CO_2 utilization) is inherently additional to what would occur in the absence of emissions mitigation policy. Furthermore, a large number of established techniques exist for accurate monitoring of CO_2 in the sub-surface. REDD has also faced specific challenges in respect of the multiple actors involved in forestry, including issues around land use ownership, forest tenure and complex interactions with biodiversity programs. In contrast, ownership of the sub-surface (into which CO_2 is stored as part of CCS projects) is typically subject to state control and a simpler set of

[47] The agenda item on "Reducing emissions from deforestation in developing countries and approaches to stimulate action" was first introduced into the COP11 agenda (December 2005). The COP has since adopted a number of decisions on REDD+, most recently at COP19 (the Warsaw Framework for REDD+). The scope of REDD+ extends beyond deforestation and forest degradation to include also the role of conservation, sustainable management of forests and enhancement of forest carbon stocks.

jurisdictional and ownership considerations. Crucially, a number of the challenges encountered by REDD are addressed (for CCS) through the CCS M&Ps arising from extensive discussions within the UNFCCC, particularly in respect of MRV and host country requirements. This suggests that the establishment and implementation of a CCS mechanism might be subject to less difficulties than those experienced by REDD.

The potential ring-fencing of the Green Climate Fund for CCS activities or the establishment of a dedicated CCS fund (see below) represents one such approach to providing targeted UNFCCC-level support for CCS. A CCS-specific mechanism could in addition be designed to address or overcome issues specific to the technology, and might also potentially seek actions to accelerate support and deployment in both developed and developing countries. Notwithstanding the above comparison with REDD, the development of a mechanism specific to a given technology raises many complicated issues, and to gain widespread support would further need to demonstrate the case that the technology was not being (or was unable to be) sufficiently supported under alternative mechanisms within the new post-2020 agreement framework.

4.5 Large-scale project deployment

4.5.1 Climate finance under the UNFCCC

Climate finance can be broadly categorised into:

- **Non market-based mechanisms**, which provide up-front support through grants, concessional finance for programmes and projects as well as through ongoing activities around technology transfer and capacity building; and
- **Market-based mechanisms**, which provide support based on emissions reduced through UNFCCC instruments. These may include project-based or sector-based approaches, and include trading and/or crediting mechanisms.

Achieving wide-spread CCS deployment will require a mix of different types of support, reflecting different Parties' needs and current stage of 'CCS readiness' – and also the specific type of programmes and projects which might be implemented. Market-based mechanisms have an important role in supporting near-term demonstration and deployment of CCS, helping to mobilise private sector finance into low-cost projects. Such projects could bring about significant in-country experience including sub-surface CO_2 storage, which will be critical for the technology development phase (Zakkour *et al*, 2011). Project-based mechanisms such as the CDM may be well-suited to such low-cost 'early opportunity' projects, whereas other project types may benefit from the scaled-up support potentially offered through sector-based approaches such as the NMM.

For higher cost projects, additional (non-market) support will be required to make them financially viable. Many CCS projects are typically capital intensive and, as with other large-scale clean energy options, require substantial upfront capital. In supporting technology deployment, non-market based finance can help in assisting the planning stages and upfront capital requirements, while the operating costs can be best supported through market-based finance over a project's lifecycle. Clearly, much depends on the carbon prices that may be provided under emerging mechanisms such as the NMM, which in turn will be driven by the depth of

Parties' commitments under a new agreement. Where carbon prices are low, the incentive provided through market revenues will only be sufficient to incentivise a modest number of low-cost projects – and significant additional support will therefore be needed to achieve wider deployment. The most effective additional support is likely to take the form of up-front access to capital, whether from grants or concessional loans, which can overcome the considerable investment risks faced by CCS project developers and commercial lenders. The UNFCCC can help provide both *non-market-* and *market-based* climate finance to support CCS.

4.5.2 Non-market based finance

The **Green Climate Fund (GCF)** is expected to raise, manage and disburse significant sums into mitigation projects within developing countries.[48] Developed countries are currently converting pledges made to the GCF in 2014 into actual contributions that will enable the Fund's Board to allocate resources for projects and programmes before COP 21 in December 2015.[49] What share of the USD 100 billion funding target sum will be channelled through the GCF remains uncertain – as well as the extent to which this sum will be based on public sources, or whether leveraged private finance will be counted towards the total. Another key issue concerns how the GCF will link to other emerging mechanisms such as the NMM (see below). Many of the rules according to which the GCF will operate and link to other UNFCCC mechanisms remain to be resolved.

CCS projects and programmes fall within the Fund's remit and are eligible for funding. The GCF will finance projects through a mix of grants and concessional loans. It therefore has an important role to play in helping make mitigation projects with high upfront costs such as CCS commercially viable, and helping to leverage climate finance from more risk-averse private sector investors.

The GCF Board has stated that investment priorities should include *inter alia* enabling a reduction in the *emission intensity* of industrial production and support for the development, transfer and deployment at scale of *low-carbon power generation*. CCS clearly has a role within both of these priority areas. GCF funding is to be allocated on the ability of a proposed mitigation activity to demonstrate its potential to limit and reduce emissions in the context of promoting a "paradigm shift towards low-emission and climate-resilient development pathways". Indicators recently developed by the GCF Board for assessing mitigation projects and programme include the following (GCF, 2013):

- reduced emission intensity of industrial production (tCO_2-eq/year)
- deployment of low-carbon power generation technologies (tCO_2/kWh)
- carbon intensity of nationally determined sectors (tCO_2/gross domestic product)
- support to development of negative emission technologies (number of carbon capture and storage projects, tCO_2 sequestered)

---

[48] The Cancun Agreements included the commitment by developed countries to jointly mobilise up to USD 100 billion per year by 2020 in climate finance to developing countries and to establish the Green Climate Fund (GCF) to help channel these resources.
[49] The GCF's authority to commit funds will only become effective when 50% of the contributions pledged are received. The total pledges made to the Fund amount to around USD 10.2 billion and as of 17 April 2015, USD 179 million had been contributed to the Fund - around 2% of the pledges made.

CCS technology therefore has a key role to play within the GCF and is identified as an eligible activity. However, there is a need to better define the types of projects eligible for funding to ensure a 'paradigm shift' towards low-emissions pathways. Within the currently broadly defined rules on eligibility criteria, the resources made available by the GCF could be at risk of being channelled towards unabated coal-fired power plants and other projects (to which CCS could be applied, resulting in large emissions reductions). For example, the recent provision of loans for commercial-scale unabated coal plants in Indonesia, India and Bangladesh not only potentially undermines the environmental integrity of the GCF but could also act to disincentivise the uptake of CCS within the coal-fired power sector (the retrofitting of CCS to these projects, which will be required to meet the 2°C goal under the Convention would be more costly than integrating CCS within new-build projects, and may in some cases not be possible due to space constraints and project location). Unabated coal-fired power generation is not identified as a clean technology option within existing studies of mitigation technologies required to meet scenarios of global emissions reductions.

In this context, there is a need to ensure that a sufficient share of GCF finance is made available for CCS deployment in relevant sectors such as thermal power generation, and according to national circumstances. Such provision, which would need to be considered and agreed by the GCF Board, could potentially be met through one or more ways, including for example:

- a dedicated **funding window for CCS** projects and programmes
- a defined **portfolio of mitigation measures**, within which a contribution from CCS technology could be specified

Both approaches has been identified elsewhere as an option for CCS support within the UNFCCC (Levina, 2014; GCCSI, 2013b). Either approach could potentially be implemented on a temporary basis and reviewed according to the ongoing monitoring of GCF funded projects and programmes according to the Fund's agreed criteria.

4.5.3 Development of a CCS fund

Commentators have assessed the option of establishing a new dedicated CCS trust fund from which projects would count towards a Party's climate funding commitments (Almendra et al, 2011; GCCSI, 2013b). Such a fund could provide public financial support to CCS in developing countries through the use of capital grants, loans, partial risk guarantees or insurance contracts (Almendra et al, 2011). The leveraging of private finance through the provision of up-front finance and risk reduction would be critical given the scale of investments required. The World Resources Institute (WRI) has estimated that a CCS fund would need to be USD 5-8 billion in order to meet the IEA deployment goals through 2020 (*ibid*) – although other sources suggest the total investment needed to be as high as USD 25 billion over the period 2010-2020 (Zakkour et al, 2011).

As described in Section 3, the World Bank and ADB already operate dedicated CCS trust funds through which developed country donor finance has been channelled into demonstration projects and programmes in developing countries. Preliminary phases of these work programs have focused on country-level assessments of geological storage and the applicability of capture technologies, as well as training and workshops on various aspects of CCS. Follow-on phases are currently focused on capacity building through implementation of pilot CO_2 storage and capture projects. Some commentators have noted the possibility of scaled-up finance for CCS being channelled through these existing funds (GCCSI, 2013b). Whether additional funding is provided through these existing channels or view a new fund with its own governance arrangements, these provide a useful basis for a potentially much larger fund operating within the UNFCCC framework.

Regarding the modalities of a new dedicated CCS fund, the WRI notes the benefit of allowing funding applications for a period at least ten years, in light of the long investment and planning timelines typically required for CCS projects (Almendra et al, 2011). The use of such a guaranteed funding period could help overcome the challenge of uncertain revenue streams associated with carbon market-based finance to date, which has acted as a specific barrier to CCS deployment (see Section 3.2.3). Similarly, there is a need to encourage project developers to stick to schedules: in this context, the WRI note the potential use of modified sunset provisions within funding agreements to ensure that funds not committed after ten years are returned to funders or shifted to other climate mitigation funds (*ibid*).

Within the context of the UNFCCC process, the option of a dedicated CCS fund has the advantage of not being dependent on potentially lengthy negotiations and establishment of governance arrangements required for the GCF. Interested donor countries could more quickly and easily establish a dedicated CCS fund, identifying governance arrangements and selection criteria tailored specifically to CCS (GCCSI, 2013b). Donor countries could also choose how the dedicated funding will be administered (*ibid*). The establishment of such a fund would however clearly take time and effort within the UNFCCC agenda, whilst in contrast the GCF already exists as an existing alternative funding option.

4.5.4 Market-based mechanisms

The Clean Development Mechanism

In 2005, two new methodologies for prospective CCS projects were submitted to the CDM Executive Board (EB)[50] setting in train a long series of negotiations resulting in the agreement of Modalities and Procedures (M&Ps) for CCS undertaken as CDM activities. These, along with the MRV requirements set out in IPCC Reporting Guidelines, now provide the basis for CCS projects undertaken in developing countries to be able to generate credits within the UNFCCC framework.

A number of weaknesses identified by Parties - in combination with low prices in the international carbon markets - have restricted the success of the CDM over recent years. A High Level Panel on the CDM Policy Dialogue was convened in 2012 to make recommendations on a reformed CDM. A key recommendation was to "develop … sectoral approaches within the CDM, while maintaining the availability of the current project-based approach" (CDM Policy Dialogue, 2012). Discussions around a new market-based mechanism within the UNFCCC have similarly focused on scaling up mitigation actions beyond the project-level which have potential implications for how CCS projects and programmes might generate credits (see below).

Reform of the CDM has since been part of discussions within the UNFCCC. Brazil has for example submitted a proposal to the ADP for an Enhanced Clean Development Mechanism (or CDM+),

[50] The White Tiger project (Vietnam) and Bintulu project (Malaysia).

based on existing CDM rules, but entailing *inter alia* a new Economic Mechanism and an option to account the voluntary cancellation of CDM carbon offsets towards Parties' financial commitments.[51] The proposal essentially proposes the CDM as an appropriate basis for developing a NMM under the new agreement, within which CCS could be incentivised (see below).

The New Market Mechanism

Discussions around a **New Market Mechanism (NMM**) refer to several potential new market-based schemes designed to scale-up activities beyond the project and programme level to promote mitigation across 'broad segments of the economy'. As currently envisaged, the UNFCCC will provide common rules for the NMM whilst Parties will design and implement the details. This includes the requirement for Parties participating in the NMM to define the scope of relevant 'segments'. Different views remain as to what 'broad segments of the economy' might mean, although it is typically understood to refer to activities at a sector and sub-sector level, or cross-sectoral mitigation measures through policies or NAMAs (4.4.1). Some Parties have also called for project-level activities to be included.

Most Parties understand NMM to include a combination of sector-based trading and/or crediting mechanisms, whereby mitigation actions can earn credits for emissions reductions achieved below a pre-defined level.[52] Many details remain to be decided regarding the functioning of these 'sectoral mechanisms' within the NMM, including *inter alia* how baselines and allowances/thresholds will be determined; how to ensure suitably robust common standards and rules, including MRV; and how to ensure comparability (and fungibility) of the credits generated. Ensuring the environmental integrity of the NMM is an overriding issue, and Parties have submitted various principles and procedures, including in relation to an international scrutiny process.[53]

The NMM could help drive CCS deployment within international mitigation efforts. According to current options being discussed, one or more approaches can be envisaged:

1. **Sector- (or sub-sector) based CCS activities** - these might include actions within a Party's power, iron and steel, chemicals or cement sectors to implement CCS
2. **Sector- (or sub-sector) based emissions reductions** - within which CCS is deployed as one of a portfolio of GHG reduction technologies
3. **Cross- or multi-sectoral emissions reductions** - within which CCS is deployed as one of a portfolio of GHG reduction technologies
4. **Project-based CCS activities**

In principal, CCS is highly suited to crediting under the NMM, both at a project and sector-level. This is because unlike with many other low carbon options, undertaking CCS is always additional

---

[51] See http://www4.unfccc.int/submissions/Lists/OSPSubmissionUpload/73_99_130602104651393682-BRAZIL%20ADP%20Elements.pdf

[52] In the case of trading, where emissions exceed the pre-defined allowance (cap), the implementing Party must purchase units from the carbon market; in the case of crediting, there is no such requirement or penalty in the event of the Implementing Party exceeding the pre-defined emissions level.

[53] Several options have been summarised in a technical paper prepared by the UNFCCC Secretariat in relation to key NMM issues. See: FCCC/TP/2014/11; unfccc.int/resource/docs/2014/tp/11.pdf

to what would have occurred in its absence: the storage of CO_2 is undertaken for the purposes of climate mitigation only (unless combined with CO_2 utilisation e.g. EOR). Furthermore, in the case of (2) above, CCS may represent the only major technology option for some sectors to achieve deep emission cuts (e.g. the cement sector). In each case, the IPCC 2006 Reporting Guidelines and the CCS M&Ps provide the basis, within the framework of the UNFCCC, for the NMM being subject to stringent MRV and robust host country participation requirements, satisfying issues around liability, site characterisation etc.

A major consideration however is the type of baseline that might be employed under different types of NMM, and how these could apply to CCS. Avoided CO_2 emissions can be calculated at a high level by comparing an equivalent plant or facility with the same output but not using CCS. However, in practice, alternative approaches may be employed within different market-based mechanisms to calculate the baseline, both at a project- and sector-level, which could result in the generation of significantly less carbon assets (Zakkour *et al*, 2011). For example (after *ibid*):

- **Project-based mechanisms** - this is primarily a consideration for CCS power sector projects. Emissions baselines under existing CDM approved methodologies for new-build power generation projects may be calculated according to approaches other than an equivalent non-CCS plant, in order to demonstrate *conservativeness* given the uncertainty around the counterfactual Depending upon the baseline calculation, which may vary considerably by region, only 40-60% of the deployment potential ('avoided emissions') might therefore be realised as carbon assets. In addition, in the case of CCS retrofitted to existing power generation or industrial facilities, it is not clear which baseline might apply (i.e. whether historical emissions or an alternative approach e.g. based on benchmarks would be used). In theory, this factor could penalise against new build CCS projects (an unintended outcome).
- **Sector-based mechanisms** - under such approaches, carbon assets generated from CCS projects would likely be determined according to the trading or crediting baseline(s) for a sector or sub-sector below which credits could be generating. Scaling-up mechanisms to account for sector-wide actions rather than just on a project basis also creates other issues that could potentially restrict carbon asset creation. For example, it is conceivable that a CCS project undertaken within a given sub-sector might not be able to generate any carbon assets unless other operators within the sector also act to abate emissions at a level that brings down the sectors overall emissions below the crediting baseline. In more general terms, this type of approach can act as a major disincentive for investments into any expensive step-change emission reduction technology, including CCS.

Baseline approaches will therefore be a key factor in determining which sectors may be more or less suitable for creating CCS-derived carbon credits under the NMM, based on either project-based or sector-based approaches, as summarised below (Table 4.1).

Table 4.1 Issues for CCS activities under new market-based mechanisms

Sector	Project-based mechanisms	Sector-based mechanisms
Power	Baselines for new-build CCS projects likely to be determined using similar approach to existing CDM methodologies e.g. calculation of baseline grid emissions using combined margin (CM). Will likely result in significantly reduction in carbon asset creation for fossil-fuel projects compared to estimates used in this analysis. Possible use of historical emissions as baseline methodology to retrofit projects could penalise against new builds (unintended outcome).	CCS could play an important role in generating credits within power sector mitigation agreements. Likely to be most applicable to countries with power grids with high carbon intensity, dominated by coal-fired power (e.g. China, India, South Africa, Botswana). Development of appropriate crediting baseline(s) likely to be subject to similar methodological considerations to CDM (e.g. combined margin approach). Use of sector-wide crediting baseline(s) may erode potential for carbon asset generation (under e.g. 'no lose' type sectoral crediting NMM).
Industry	Potentially suitable, depending upon sector/product factors. Baseline determination for new builds may make use of benchmarks (e.g. tCO_2 per t output). The possible use of benchmark-based baseline methodology (as opposed to historical emissions) to retrofit projects would be unlikely to penalise against new builds (unintended outcome).	Standardised baselines (e.g. tCO_2 per t output) may be applicable to relatively homogenous (e.g. in terms of products and emissions) industrial process sectors such as cement and some chemicals processes. Use of sector-wide crediting baseline(s) may erode potential for carbon asset generation (under e.g. 'no lose' type sectoral crediting NMM).
Upstream	Typically single-operator projects e.g. isolated natural gas field developments – well suited to project-based approaches. Clusters of high-CO_2 gas fields with single storage could potentially be developed under CDM, or similar type of mechanism.	For natural gas processing CCS projects, the heterogeneity of CO_2 content within natural gas reservoirs means that it is not possible to develop credible sectoral baselines. Unlike relatively homogenous industrial processes (e.g. cement and certain chemicals process), the counterfactual is highly case-specific (i.e. the natural gas reservoir).

Source: based on Zakkour *et al*, 2011

Framework for Various Approaches

Different countries worldwide are considering various market- and non-market based approaches to reduce GHG emissions. A Framework for Various Approaches (FVA) has therefore been proposed aimed at ensuring different mitigation schemes worldwide can operate effectively within a common set of internationally (UNFCCC-level) agreed rules and standards.[54] Any emissions reduction units arising from different mitigation approaches that are transferred internationally, e.g. through linkage of domestic emissions trading schemes, can therefore be used by Parties for international compliance with UNFCCC obligations. One recent proposal has been put forward by Japan to include bilateral credit mechanisms as eligible activities under the FVA.[55] This envisages the use of joint crediting with a de-centralised structure (compared to the centralised arrangements of the CDM and other mechanisms to date) involving the donor and

[54] The FVA envisages a set of components and rules to ensure that all approaches used for mitigation meet certain standards (criteria and procedures to ensure environmental integrity e.g. through providing robust MRV, delivering net emission reductions, and avoiding double counting). The FVA will only cover mitigation actions, which produce units that are used for compliance with international obligations by a jurisdiction other than the one where they were created, or issued. Although most Parties see the FVA as a framework to govern internationally traded units, views remain divided as to what extent the FVA should include mechanisms designed by Parties, as well as whether non-market-based approaches (NMA) should be included.

[55] Joint Crediting Mechanism (JCM) / Bilateral Offset Credit Mechanism (BOCM); see http://www.mmechanisms.org/e/initiatives/jcm_history.html

host country government and a Joint Committee. CCS technology could clearly play an important role within such schemes, with important cooperation and capacity-building arising between the two countries – in addition to credit generation.

4.6 Conclusions

Table 4.2 summarises the main areas where CCS can be supported and deployed within the evolving UNFCC framework. The table also identifies key issues likely to determine successful support for the technology.

This section finds that the UNFCCC process can help support CCS within a new climate agreement. There is more to be done, particularly around providing the funds needed to support the technology in developing countries, and the design of effective mechanisms which can provide climate finance for ambitious projects and programs. However, these provide an enabling framework only. Progress with CCS on the required scale will require a significant shift by Parties in recognising its role as a key mitigation option within their INDCs. The 'top-down' framework provided by the UNFCCC can only help CCS if complimented by real 'bottom-up' efforts made by Parties reflecting the ambitions for a new agreement.

Table 4.2 How can CCS be supported at the UNFCCC level?

Area of support	UNFCCC role	Relevant mechanism	Key issues
Assessing the potential and setting the agenda	Providing the overall framework for ambitious mitigation efforts agreed by Parties in support of the UNFCCC goals.	**INDCs** should set the agenda for deploying CCS as a mitigation option within national circumstances. Developed and developing Parties should outline specific actions for CCS, including needs e.g. finance, capacity and technology.	CCS has a key role to play within many Parties' GHG reduction efforts. Inclusion of CCS should be ambitious but also reflect current stage of "CCS readiness" and needs.
	Assisting Parties in assessing their potential for CCS.	**TNAs** and **TAPs** can help assess CCS potential in developing countries and feed into INDCs.	Parties should request TNAs and clearly identify CCS within them where relevant.
Building capacity and developing legal and regulatory frameworks	Addressing CCS technology needs and helping to build capacity in developing countries.	The **TEC** provides technical guidance on needs for CCS, including how to drive it forward within the UNFCCC.	The TM could seek to assess and review progress on CCS within the UNFCCC framework. It can provide technical guidance to the COP on overcoming specific issues, also strengthening partnerships and initiatives.
		The **CTCN** can implement a wide range of actions around capacity building, information, knowledge transfer and awareness raising for CCS.	
	Providing rules and standards in respect of MRV for use in emissions accounting under the UNFCC.	The **2006 IPCC Reporting Guidelines** provide for robust MRV of CCS.	Provide the basis for MRV and national standards in respect of safe and effective CCS. Parties should ensure alignment in developing domestic regulations.
		The **M&Ps for CCS** as CDM activities provide a rule book for CCS under the CDM and future market instruments such as the NMM (see below).	
Designing and implementing support policies and measures	Supporting the development of national frameworks needed to deploy CCS in developing countries.	**NAMAs** could include domestic actions by developing countries to develop CCS support policies and measures.	CCS have yet to figure within Parties' NAMAs, although are potentially well suited.
		The **GEF** could support additional efforts to support CCS technology demonstration	CCS can be identified within future funding cycles.
		Potential development of **CCS-specific mechanism** or fund at UNFCCC level	Would entail significant time, effort and complexity
Large-scale project deployment	Providing the mechanisms to help mobilise climate finance for CCS deployment.	The **GCF** provides the key UNFCCC mechanism for funding CCS activities and scaled-up deployment in developing countries; CCS is an eligible technology.	Potential use of funding window for CCS to drive deployment; funding for unabated coal poses barrier.
		NAMAs could provide climate finance for scaled-up CCS deployment in developing countries via the GEF and other sources.	CCS have yet to figure within Parties' NAMAs, although are potentially well suited.
		The **NMM** could provide market-based finance for sector- and cross-sectoral CCS actions (and also, potentially, projects).	Various methodological issues (e.g. around baselines for sector-based schemes) need to be addressed.
		The **FVA** can allow different international approaches to generate credits from bilateral CCS activities for UNFCCC use within a common MRV and standards.	CCS opportunities could be identified between participating Parties.
		The **CDM** provides an existing incentive for generating offsets via CCS under Kyoto through to 2020.	Window closing on CDM; however, benefits from continued technical work.

5 CONCLUSIONS

Meeting the long-term goal to limit global temperature rises to 2°C compared to pre-industrial levels requires large-scale deployment of low carbon technologies including CCS. This report finds that CCS presents an opportunity for many countries worldwide to reduce GHG emissions. The drivers for undertaking CCS as part of emissions mitigation efforts are diverse and vary according to the different *national circumstances* of countries and regions. They include:

- Large economic dependence on fossil fuels
- Energy security issues
- High national CO_2 emissions, CO_2 intensity of economy, projected CO_2 increases
- Sufficient capture and storage potential
- Availability of in-country capacity and technology capabilities

CCS projects are technically feasible at scale and have costs that are comparable with other mitigation technologies. A portfolio of technologies is available depending on the relevant emission sources and availability of suitable geological storage sites. Furthermore, assessments made to date indicate a large potential for CCS, including sufficient storage for several decades of emissions, in many countries worldwide. However, progress with deployment of the technology is currently falling far behind the levels envisaged by low carbon scenarios. This report finds a broad spectrum of barriers to the deployment of CCS: some are technical, some are economic, some are institutional and regulatory, and some concern the cost effectiveness of CCS compared to alternative mitigation options.

Large-scale CCS deployment involves the development of a pathway establishing the necessary framework to overcome these barriers and incentivise projects and programmes. This report finds that countries and regions worldwide are at different stages of undertaking the required actions and policies. Some countries have put in place the legal and regulatory frameworks needed and are leading the way in large-scale project deployment (e.g. Norway, Canada, United States). Overall, however, despite progress made in both developed and developing countries, the steps and level of ambition needed to incentivise wide-spread CCS deployment is lacking.

Strenuous efforts will clearly be needed at the national level to put the enabling frameworks in place to accelerate deployment of CCS. However, the technology can also benefit from support at the international level. This report finds that the new climate agreement being negotiated under the UNFCCC could help facilitate CCS as a mitigation option. A number of mechanisms within the emerging framework could support technology development in both developing and developed countries and help mobilise climate finance into projects and programs. Into this 'top-down' framework, INDCs provide a 'bottom-up' opportunity for establishing CCS firmly within national GHG efforts and a new international climate agreement.

INDCs submitted by Parties will collectively determine global efforts to reduce emissions under a new post-2020 agreement. The ambition of the commitments will in turn provide the demand for deploying step-change mitigation technologies including CCS to help meet them. Regions and countries worldwide are at different stages with respect to a pathway of CCS support and deployment: the focus of CCS within INDCs should therefore identify suitably ambitious and practical steps to move beyond the current step of this pathway. For some countries at early stages along the CCS pathway, this may involve *action-based commitments* to develop an enabling regulatory and policy environment; whereas for others at a more advanced stage, specific *outcome-based targets* may be more appropriate. For both developed and developing countries, such national efforts can be assisted at the international level. The UNFCCC framework can help support CCS through the following routes:

- Providing the overall **mitigation** policy framework for CCS development and deployment
- Mobilising **finance** into CCS projects and programmes
- Addressing **technology** needs and helping to build capacity

Mechanisms are available within the evolving UNFCCC framework to help CCS support and deployment. Modalities and procedures exist for undertaking CCS projects, which provide the basis for the legal regulatory actions and steps needed to host projects under UNFCCC mechanisms. In addition, the IPCC GHG Reporting Guidelines provide the basis for robust MRV of CCS. The UNFCCC also provides channels for mobilising climate finance into CCS support, including via the GCF and the potential for scaled-up project development under the NMM, a reformed CDM and potentially via the use of NAMAs. The potential use of bilateral crediting and other approaches accommodated under the FVA offers the potential for developed and developing countries to work closely together and share the benefits from CCS deployment. Furthermore, the Technology Mechanism offers the potential to provide technical and capacity support for CCS projects and activities, and to highlight its importance as a low carbon technology within the UNFCCC. Although there are ongoing uncertainties and challenges, not least regarding the future form and scale of market-based support for projects, CCS can be supported within the UNFCCC process. It is also potentially well-suited to the types of mechanisms currently envisaged under a new agreement.

This report finds there is more to be done to help support CCS at the international level, both in terms of providing the required levels of funding to achieve scaled-up deployment and also in the details of how the technology can be accommodated within the UNFCCC's specific funds and mechanisms. An international partnership for CCS could be instrumental in driving this process forward and raising awareness of the technology. However, these provide an enabling 'top-down' framework only. Progress with CCS on the scale required to meet the 2°C goal will also require a concerted 'bottom-up' effort by Parties in recognising its role as a key mitigation option within their INDCs. When compared to other mitigation options and technologies, and despite its appropriateness to many countries, national climate plans do not always adequately recognise the potential of CCS, as reflected for example in the submission of NAMAs to date. As of the end of 16 June 2015, only four Parties (Norway, the EU, Mexico and Canada) had made specific reference to CCS within their submissions. Parties should therefore seek to make CCS central to their INDCs. Parties can propose a wide range of actions and measures to help promote CCS according to their national circumstances and current stage of "CCS readiness". In doing so, INDCs could become more ambitious and help move the international effort further along the low carbon pathway needed to meet the long-term goals of the UNFCCC.

6 REFERENCES

ADB (Asian Development Bank), 2013. Prospects for Carbon Capture and Storage in Southeast Asia. Mandaluyong City, Philippines, 2013.

Almendra, F., West, L., Zheng, L., and Forbes, S., 2011. CCS Demonstration in Developing Countries: Priorities for a Financing Mechanism for Carbon Dioxide Capture and Storage. WRI Working Paper. World Resources Institute, Washington DC

Angelsen, A., Brockhaus, M., Sunderlin, W.D. and Verchot, L.V. (eds) 2012 Analysing REDD+: Challenges and choices. Center for International Forestry Research, Bogor, Indonesia.

Bakker, S., de Coninck, H., Groenenberg, H., 2010. Progress on including CCS projects in the CDM: Insights on increased awareness, market potential and baseline methodologies. Intl. J. GHG Control. Vol 4 pp. 321-326.

Bentham, M., Mallows, T., Lowndes, J., & Green, A., 2014. CO_2 Storage Evaluation Database (CO_2 Stored). The UK's online storage atlas. Energy Procedia 63 (2014) 5103-5113.

Blondes, M.S., et al., 2013. "National Assessment of Geologic Carbon Dioxide Storage Resources–Methodology Implementation", U.S. Geological Survey Report Series, Report 2013–1055,United States Geological Survey, Reston, VA, http://pubs.usgs.gov/of/2013/1055/; accessed 30 June 2013

Borlee, J., 2007. Low CO_2 Steels - ULCOS Project, ETP 2008 Workshop on Deploying Demand Side Energy Technologies. OECD/IEA, Paris (October 8-9)

Bradshaw, J. 2006, Geological Assessment and Storage Capacity: An International Perspective: Storage Retention Time of CO_2 in Sedimentary Basins: Examples from Petroleum Systems, UNFCC, SBSTA 20th, May 2006.

Bradshaw, B.E., et al. 2009, Queensland Carbon Dioxide Geological Storage Atlas, compiled by Greenhouse Gas Storage Solutions on behalf of Queensland Department of Employment, Economic Development and Innovation, Brisbane, Australia, http://mines.industry.qld.gov.au/geoscience/carbon-dioxide-storage-atlas.htm

Brennan, S.T., et al., 2010, "A Probabilistic Assessment Methodology for the Evaluation of Geologic Carbon Dioxide Storage", U.S. Geological Survey Report Series, Report 2010–1127,United States Geological Survey, Reston, VA

Braun, N., Höhne, N., Hagemann, M., Day, T., Healy, S., Schumacher, K., Duscha, V., 2014. Instruments to increase climate policy ambition before 2020 – economic and political implications in selected industry and emerging countries. Ökoinstitut. Freiburg.

BP, 2014. *BP Statistical Review of World energy 2014*. British Petroleum, 2014.

Carbon Counts, ERM and Environics, 2014. Assessment of Carbon Capture and Storage (CCS) potential in Egypt. Report for the World Bank, unpublished.

Carbon Counts, ERM and Wellfield Geosciences, 2015. Assessment of Carbon Capture and Storage (CCS) potential in Botswana. Report for the World Bank, forthcoming.

Carbon Storage Taskforce, 2009, National Carbon Mapping and Infrastructure Plan – Australia: Full Report, Department of Resources, Energy and Tourism, Canberra.

CDM Policy Dialogue, 2012. Report of the High-Level Panel on the CDM Policy Dialogue, Luxembourg.

Chen, C. and E.S.Rubin, 2009. CO_2 control technology effects on IGCC plant performance and cost. Energy Policy Vol 37 pp. 915-924.

Cook, G., 2009. Climate Change and the Cement Industry: Assessing emissions and policy responses to carbon prices. Climate Strategies, Cambridge, UK.

Coulson, M., S. Fergusson, T. Bullen, 2010. Carbon Capture Options for LNG Liquefaction. Foster-Wheeler, Reading. Paper prepared for the Sixteenth Intl. Conf. Nat. Gas. Oran, Algeria, 18-21 April 2010.

CSLF (Carbon Sequestration Leadership Forum), 2011. Underground CO_2 Storage: A Reality? September 2011.

CSLF, 2013. Re-energizing Global Momentum for CCS and Identifying Key Actions Needed for CCS Deployment. Ministerial Communiqué. 7 November 2013.

CSLF, 2014. Carbon Capture and Storage in Focus: *What is Capacity Building?*

Dahowski, R.T., Li, X., Davidson, C.L., Wei, N., Dooley, J.J., Gentile, R.H., 2009. A preliminary cost curve assessment of carbon dioxide capture and storage potential in China, Energy Procedia, 1(1): 2849-2856, February 2009.

Darman, N.H. and Harun, A., 2006,Technical Challenges and Solutions on Natural Gas Development in Malaysia, the Petroleum Policy and Management Project, 4th Workshop on the China-Sichuan Basin Case Study, Beijing, May 30-June 3.

Davidson, J., 2007. Performance and Costs of Power Plants with Capture and Storage of CO_2. Energy, Volume 32 pp. 1163-1176.

DNV (Det Norske Veritas), 2010. Global Technology Roadmap for CCS in Industry. Sectoral Assessment: Refineries. Research Report for UNIDO. London.

Dooley, J., Dahowski, R., & Davidson, C., 2007. CCS: A Key to Addressing Climate Change, Chapter 4 in: Fundamentals of the Global Oil and Gas Industry, 2007. vol. 2007, 67-69.

Element Energy and Carbon Counts, 2010. Developing a CCS network in the Tees Valley Region. A Report for One North East, UK.

EPRI (Electric Power Research Institute), 2009. Updated cost and performance estimates for clean coal technologies including CO_2 capture. Palo Alto, California, 2009. 1017945

Eskom, 2011.Kusile and Medupi coal-fired power stations under construction. COP17 factsheet.

EU CCS Network, 2012a. Situation Report 2012 - a public report outlining the progress, lessons learnt and details of the European CCS Demonstration Project Network.

EU CCS Network, 2012b. Lessons learned from the Jänschwalde project - Summary report. A European CCS Demonstration Project Network Report, Cottbus, May 2012.

EU CCS Network, 2013. Project Regulatory Updates in 2013. Website information accessed 26 March, 2015. http://ccsnetwork.eu/more-about-ccs/how-ccs-works/regulations

EU GeoCapacity, 2009. Assessing European Capacity for Geological Storage of Carbon Dioxide. Project no. SES6-518318. WP2 Report: Storage Capacity.

Fang, Z. & Li, X., 2011. Preliminary assessment of CO_2 geological storage potential in Chongqing, China. Procedia Environmental Sciences. Volume 11, Part C, 2011, pp 1064–1071.

Gary, J. and Handwerk, G., 2001. Petroleum Refining Technology. New York.

GCCSI (Global Carbon Capture and Storage Institute), 2009. Strategic Analysis of the Global Status of Carbon Capture and Storage Report 2: Economic Assessment of Carbon Capture and Storage Technologies. Canberra.

GCCSI, 2011. Economic Assessment of Carbon Capture and Storage Technologies: 2011 Update. A report prepared by J. Simpson, McConnel, C., and Matsuda, Y. (Worley Parsons Services Pty.) with input from Schlumberger for the GCCSI. Canberra.

GCCSI, 2013a. The Global Status of CCS 2014. Melbourne, Australia.

GCCSI, 2013b. Making the case for funding Carbon Capture and Storage in Developing Countries. March 2013.

GCCSI, 2014a. The Global Status of CCS 2014. Melbourne, Australia.

GCCSI, 2014b. Website information; project data up-to-date as of 15 July 2014; accessed February 2015. Melbourne, Australia.

GCCSI, 2014c. Annual Review 2014. Melbourne, Australia.

GCCSI/CSLF, 2011. Summary Report from the GCCSI/CSLF Workshop on CCS Process Integration, London, 3 November 2011.

GHG IA (Greenhouse Gas Implementing Agreement), 2009. Biomass CCS Study, 2009. Report number 2009-09.

Government of India Ministry of Power, 2015. Website information on UMPP programme; accessed 25 February, 2015; http://powermin.nic.in/upload/pdf/ultra_mega_project.pdf

Hamilton, M.R., Herzog, H.J., and Parsons, J.E., 2009. Cost and U.S. Public Policy for New Coal Power Plants with Carbon Capture and Sequestration. Energy Procedia Vol. 1 (1). pp. 4497-4494.

Hendriks, C., W. Graus and F. van Bergen (2004), Global Carbon Dioxide Storage Potential and Costs, ECOFYS report EEP-02001, 2004.

Hektor, E. and Berntsson, T. 2007, Reduction of Greenhouse Gases in Integrated Pulp and Paper Mills – Possibilities for CO_2 Capture and Storage CO_2.

Holler, S., & Viebahn, P., 2011. Assessment of CO_2 Storage Capacity in Geological Formations of Germany and northern Europe. In: Energy Procedia 4 (2011) 4897–4904.

IEA (International Energy Agency), 2008. CO_2 Capture and Storage: A Key Carbon Abatement Option. OECD/IEA, 2008. Paris.

IEA, 2009. Technology Roadmap: Carbon capture and storage. OECD/IEA, Paris.

IEA, 2010. Carbon capture and storage: Model Regulatory Framework. Information paper, November 2010. OECD/IEA, Paris.

IEA, 2011a. Combining Bioenergy with CCS – Reporting and Accounting for Negative Emissions under the UNFCCC and the Kyoto Protocol. A report by Riitta Pipatti, Statistics Finland, for the IEA, Paris.

IEA, 2011b. Costs and Performance of Carbon Dioxide Capture from Power Generation. IEA Working Paper by M. Finkenrath, IEA. OECD/IEA, Paris.

IEA, 2012a. Energy Technology Perspectives 2012. OECD/IEA. Paris.

IEA, 2012b. World Energy Outlook 2012. OECD/IEA. Paris.

IEA, 2013a. Technology Roadmap: Carbon capture and storage. 2013 Edition. OECD/IEA, Paris.

IEA, 2013b. CO_2 Emissions from Fuel Combustion, 2013 Edition. OECD/IEA. Paris.

IEA, 2014a. Energy Technology Perspectives 2014. OECD/IEA. Paris.

IEA, 2014b. CO_2 Emissions from Fuel Combustion, 2014 Edition. OECD/IEA. Paris.

IEA, 2014c. World Energy Outlook 2014. OECD/IEA. Paris.

IEA, 2014d. World Energy Balances. Data accessed online February, 2015. OECD/IEA. Paris.

IEA, 2014e. Key World Energy Statistics 2014. OECD/IEA. Paris.

IEA, 2014f. Carbon Capture and Storage: Legal and Regulatory Review. Edition 4. OECD/IEA. Paris.

IEA/UNIDO (International Energy Agency and United Nations Industrial Development Organization), 2011. Technology Roadmap: Carbon Capture and Storage in Industrial Applications. OECD/IEA. Paris.

IEA ETSAP (Energy Technology Systems Analysis Programme), 2010. CO_2 Capture and Storage. Technology Brief E14, October, 2010.

IEAGHG (IEA Greenhouse Gas R&D Programme), 2008a. CO_2 Emissions Database version 2008. Cheltenham, UK.

IEAGHG, 2008b. Carbon Dioxide Capture and Storage in the Clean Development Mechanism: Assessing market effects of inclusion. 2008/13, November 2008. Cheltenham, UK.

IEAGHG, 2008c. A Regional Assessment of the Potential for CO_2 storage in the Indian Subcontinent. 2008/2, May 2008. Cheltenham, UK.

IEAGHG, 2011a. Potential for Biomass and Carbon Dioxide Capture and Storage. 2011/06, July 2011. Report for the IEA Greenhouse Gas Programme by Ecofys Netherlands BV. Cheltenham, UK.

IEAGHG, 2011b. Effects of Impurities on Geological Storage of CO2. 2011/04, June 2011. Cheltenham, UK.

IEAGHG, 2012. Barriers to implementation of CCS: capacity constraints. 2012/9 July 2012. Cheltenham, UK.

IEAGHG, 2014. Biomass and CCS - guidance for accounting for negative emissions. (IEA/CON/12/206). IEA Greenhouse Gas R&D Programme, Cheltenham, UK.

IEAGHG, Geogreen and GCCSI, 2011. Global Storage Resources Gap Analysis for Policymakers. Report 2011/10. September 2011. Cheltenham, UK.

IFA (International Fertilizer Association), 2010. Greenhouse Gas Emissions and Fertiliser Production. IFA website: http://www.fertilizer.org/ifa/Home-Page/SUSTAINABILITY/Climate-change/Emissions-from-production.html; accessed 22 July 2010.

IFA, 2015. Fertiliser statistics, 2015. IFA website: http://www.fertilizer.org//En/Statistics; accessed February, 2015.

IIASA (International Institute for Applied Systems Analysis), 2012. Global Energy Assessment: Toward a Sustainable Future. Austria.

IIED (International Institute for Environment and Development), 2015. REDD+ for profit or for good? Review of private sector and NGO experience in REDD projects.

IPCC (Intergovernmental Panel on Climate Change) 2014. Edenhofer, O., et al., ed., Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III (WG3) to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change. Cambridge University Press. Archived 29 June 2014

Jayaraman, K. S., 2007. India's carbon dioxide trap: Nature, v.445, p350

Ketzer, J. M., J. A. Villwock, G. Caporale, L. H. da Rocha, G. Rockett, H. Braum, and L. Giraffa, 2007, Opportunities for CO_2 Capture and Geological Storage in Brazil: The CARBMAP Project, Sixth Annual Conference on Carbon Capture & Sequestration, Pittsburgh, Pennsylvania.

Levina, E. 2014. 'Carbon Capture and Storage: What support is needed and how the UNFCCC can help?' presentation given by Ellina Levina (IEA) at the ADP Technical Expert Meetings: Carbon capture, use and storage: 21 October, Bonn.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B, Frieler, F., Knutti, R., Frame, D.J., & Allen, M.R., 2009. Greenhouse-gas emission targets for limiting global warming to 2 °C. In: Nature 458, 1158-1162, 30 April 2009.

Melien, T. and S. Brown-Roijen, 2009. "Economics" Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project Volume 3. Eide (Ed.). CPL Press, Berkshire, United Kingdom.

Metz, B, Davidson, O., de Coninck, H. C., Loos, M., and Meyer, L. A. (eds.), 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change Cambridge and New York: Cambridge University Press.

MIT (Massachusetts Institute of Technology), 2007. The Future of Coal. The Massachusetts Institute of Technology, Massachusetts, United States.

Möllersten, K., Gao, L., Yan, J., 2006. CO_2 capture in pulp and paper mills: CO_2 balances and preliminary cost assessment. Mitigation and Adaptation Strategies for Global Change 11 (5-6), 1129-1150.

NETL (National Energy Technology Laboratory), 2008. Pulversied Coal Oxycombustion Power Plants, Final Report, August 2008. DOE/NETL- 2007/1291.

NETL, 2010a. Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 2, November 2010. DOE/NETL-403/1397.

NETL, 2010b. Life Cycle Analysis: Integrated Gasification Combined Cycle (IGCC) Power Plant, September 30, 2010. DOE/NETL-403/110209.

NETL, 2010c. Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant, September 30, 2010. DOE/NETL-403/110509.

NETL, 2010d. Life Cycle Analysis: Supercritical Pulversied Coal (SCPC) Power Plant, September 30, 2010. DOE/NETL-403/110609.

NETL, 2010e. Cost and Performance for Low Rank Pulversied Coal Oxycombustion Energy Plants, Final Report, September 2010. DOE/NETL-401/093010.

NETL, 2010f. Coal-Fired Power Plants in the United States: Examination of the Costs of Retrofitting with CO_2 Capture Technology, Revision 3, January 4, 2011. DOE/NETL-402/102309.

NETL, 2010g. Carbon Dioxide Capture and Storage RD&D Roadmap. DOE/NETL.

North American Carbon Storage Atlas, 2012. First Edition. United States Department of Energy.

NPD (Norwegian Petroleum Directorate), 2011. CO_2 Storage Atlas: Norwegian North Sea. Stavanger, 2011.

Ogawa, T., et al. (2011), Saline-Aquifer CO_2 Sequestration in Japan – Methodology of Storage Capacity Assessment, International Journal of Greenhouse Gas Control, Vol. 5, No. 1, Elsevier, pp. 318-326

Olivier, J.G.J., Janssens-Maenhout, G., and Peters, J.A. H. W. Trends in Global CO_2 Emissions; 2012 Report. PBL Netherlands Environmental Assessment Agency, The Hague/Bilthoven.

Philibert, C., Ellis, J., and Pokanski, J., 2007. Carbon Capture and Storage in the CDM. OECD/IEA. Paris.

Purvin and Gertz Inc., 2008. Study on Oil Refining and Oil Markets. Prepared for European Commission

RCI (Rotterdam Climate Initiative), 2011. Rotterdam CCS Network project – Case Study on 'Lessons learnt' – interim slide report, August 2011.

RCI, 2012. Rotterdam CCS Cluster Project Case Study on lessons learnt - Final Report. February, 2012.

Rootzen, J., Kjarstad, J. & Johnsson, F., 2009. Assessment of the potential for CO_2 capture in European heavy industries. In: Sustainable Development of Energy, Water and Environment Systems. Dubrovnik, Croatia.

Röser, F. and van Tilburg, X., 2014. *The Future of NAMAs*. Briefing paper based on side-event organised by Ecofys and ECN during UNFCCC SBSTA sessions, Bonn, June 2014.

Rubin, E.S., C.Chen, and A.B.Rao, 2007. Cost and performance of fossil fuel power plants with CO_2 capture and storage. Energy Policy Vol. 35 (9) pp. 4444-4454.

SBC Energy Institute, 2013. Carbon Capture and Storage: Bringing Carbon Capture and Storage to Market. SBC (Schlumberger Business Consulting) Energy Institute. January 2013, Gravenhage, Netherlands.

SENER (*Secretaria de Energia*; Mexican Ministry of Energy) 2014. CCUS Technology Roadmap in Mexico. March, 2014.

Sonde, R. R., 2007. Carbon Capture and Storage: Indian Perspective, CSLF meeting, Paris.

South African Department of Energy, 2013. Integrated Resource Plan (IRP) for Electricity. 2010-2030. Update Report 2013. 21 November, 2013.

SRI Consulting (2009) Ethylene Oxide WP Report

SRI Consulting (2010) Ethylene Oxide WP Report

Statoil, 2010. Expectations of non-member CCS projects: Statoil CCS operations experience. Presented by Dr. Philip Ringrose, Statoil ASA. EC Directorate-General for Energy CCS Project Network Advisory Forum, 17 September 2010, Brussels.

Stevens, S.H., et al. (2001), CO_2 Injection and Sequestration in Depleted Oil and Gas Fields and Deep Coal Seams: Worldwide Potential and Costs, Environmental Geosciences, 8, 200-209.

Straelen, J. van, F. Geuzebroek, N. Goodchild, G. Protopapas, L. Mahony (2009). CO_2 capture for refineries, a practical approach. In: Energy Procedia 1 (2009) 179-185

Suekane, T., T. Nobuso, S. Hirai, and M. Kiyota, 2008, Geological storage of carbon dioxide by residual gas and solubility trapping: International Journal of Greenhouse Gas Control, v. 2, p. 58-64.

Sun, Q., 2008. CTL Development in China presentation given April 24, 2008, Washington, D.C. See: http://files.asme.org/asmeorg/NewsPublicPolicy/GovRelations/21387.pdf

UK SAP, 2011. The Energy Technology Institute's UK Storage Appraisal project (UKSAP). http://www.eti.co.uk/project/uk-storage-appraisal-project/

UNECE (United Nations Economic Commission for Europe), 2014. Revised recommendations of the United Nations Economic Commission for Europe to the United Nations Framework Convention on Climate Change on how carbon capture and storage in cleaner electricity production and through enhances oil recovery could be used in reducing greenhouse gas emissions. Prepared by the Group of Experts on Cleaner Electricity Production from Fossil Fuels. ECE/Energy/2014/Rev.1. 28 November 2014.

UNEP (United Nations Environment Programme), 2014. The Emissions Gap Report 2014. A UNEP Synthesis Report, Nairobi, November 2014.

UNFCCC (United Nations Framework Convention on Climate Change), 2014. Technical examination process to unlock mitigation potential for raising pre-2020 ambition through carbon dioxide capture, use and storage. Technical paper. FCCC/TP/2014/13/Add.3. 26 November, 2014.

UNIDO (United National Industrial Development Organization), 2010. Global Technology Roadmap for CCS in Industry. Background Paper prepared for the Sectoral Workshops. Vienna.

US EIA (United States Energy Information Administration), 2014. China analysis. Website information posted 4 February, 2014; accessed 20 February, 2015; http://www.eia.gov/countries/cab.cfm?fips=ch

VLEEM (Very Long-Term Energy and Environment Model), 2003. Final Contract Report, http://www.enerdata.fr/VLEEM/PDF/30-05-05/fi nal%20report.pdf

Wang, S. Vincent, C. J., Stephenson, M.H. & Zeng, R, 2014.. Assessment of storage capacity for CO_2 in saline aquifers near hydrocarbon fields, northern Songliao Basin, China. Greenhouse Gases: Science and Technology Volume 4, Issue 3, pages 366–383, June 2014.

WBCSD/IEA (World Business Council for Sustainable Development), 2009. Cement Technology Roadmap 2009: Cement Emission Reductions up to 2050. World Business Council for Sustainable Development (Geneva), International Energy Agency/Organization for Economic Cooperation and Development (Paris), 2009.

WEC (World Energy Council), 2013. World Energy Resources: Survey. London.

Wikipedia, 2015. Ultra Mega Power Projects (UMPP); accessed 25 February, 2015; http://en.wikipedia.org/wiki/Ultra_Mega_Power_Projects

World Bank, 2011. Carbon Capture and Storage in Developing Countries: a Perspective on Barriers to Deployment. June, 2011. The World Bank, Washington, DC.

World Bank, 2012. Hashemite Kingdom of Jordan: Carbon Capture and Storage (CCS) Capacity Building Technical Assistance. March, 2012. The World Bank, New York.

World Steel Association, 2013. World Steel in Figures 2013. Belgium.

Xinhuanet, 2014. "China unveils energy strategy, targets for 2020", 19 November, 2014. Article accessed 28 February 2015; http://news.xinhuanet.com/english/china/2014-11/19/c_133801014.htm

Zakkour, P.D., and Cook, G., 2010. CCS Roadmap for Industry: High purity CO_2 sources. Sectoral Assessment for the United Nations Industrial Development Organization (UNIDO).

Zakkour, P.D., 2011. Accessing carbon finance for CCS projects in emerging and developing economies. In: Havercroft, I, Macrory, R. And Stewart, R. (eds) Carbon Capture and Storage: Emerging Legal and Regulatory Issues. Wildy & Sons.

Zakkour, P.D., Cook, G., Carter, A., Streck, C., and Chagas, T., 2011. Assessment of climate finance sources to accelerate carbon capture and storage deployment in developing countries. Report for the World Bank.

Zhou, D., Li, P., Zhao, Z., Liao, J., Zhang, C., Zhang, Y., Xie, H., Li, F. & Peng, J., 2013. Feasibility Study of CCS-Readiness in Guangdong Province, China (GDCCSR) Final Report: Part 2. Assessment of CO2 Storage Potential for Guangdong Province, China, March 2013.

Carbon Counts Company (UK) Ltd.

web: www.carbon-counts.com

email: enquiries@carbon-counts.com