UKERC

UKERC ENERGY RESEARCH ROADMAP SYNTHESIS: CARBON CAPTURE & STORAGE (CCS)

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1. Overview

This document reviews and highlights the most important information presented in five carbon capture and storage (CCS) roadmaps. These include:

- Technology Roadmap for Carbon Capture and Storage- International Energy Agency
- CCS Roadmap-Supporting Deployment of Carbon Capture and Storage in the UK- Department of Energy and Climate Change
- DOE/NETL Carbon Dioxide Capture and Storage RD&D Roadmap-US Department of Energy and National Energy Technology Laboratory
- CCSTRM: Canada's CO_2 Capture & Storage Technology Roadmap-CANMET Energy Technology Centre
- A Roadmap for US-China Collaboration on Carbon Capture and Sequestration-Asia Society, Center for American Progress and MONITOR Group
- Cleaner Fossil Power Generation in the 21st Century-Moving Forward- UK Advanced Power Generation Technology Forum

This document provides the key themes and actions required to build a successful CCS industry. The roadmaps summarised within this document provide various perspectives considering actions to be taken in order to build a CCS industry, and whilst concerns may be different between countries, the roadmaps reviewed in this document agree on the need to implement CCS in order to reach global emission reduction targets.

The roadmaps within this document examine the variety of capture technologies along with plans to incorporate CCS into national electricity portfolios, which can be seen within the US, UK and Canadian roadmaps. Further, the IEA roadmap provides a global view of CCS, whilst the US-China roadmap examines the potential of collaboration efforts between the two largest producers of greenhouse gas emissions.

Despite the focus on national or global efforts, several common themes are shown throughout all of the roadmaps. These include the need for increased large-scale deployment in order to gain a better understanding of CCS capabilities, pipeline transportation options, establishment of safe and sound monitoring capabilities. There is also a focus on the need for collaborative research, learning by doing and the need to create a skilled supply chain. Finally, there is a large focus on the need to establish regulation and policy frameworks to ensure best practices.

The roadmaps reviewed within this document provide a high-level understanding of the current status of the CCS industry, its current challenges and the actions necessary to establish a successful industry. Whilst each country may have their own initiatives, the examination of these roadmaps identifies the key areas that can lead to collaboration and acceleration within the industry.

2. TECHNOLOGY ROADMAP FOR CARBON CAPTURE AND STORAGE

International Energy Agency

http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf

The IEA Technology Roadmap for Carbon Capture and Storage (CCS) commences by presenting an introduction to CCS. The purpose of the roadmap is intended to describe and analyse actions necessary to accelerated CCS deployment to levels that could allow it to fulfil its CO_2 emissions reduction potential. The roadmap identifies the target to limit the global average temperature rise to 2°C between 2013 and 2050. Additionally, the roadmap presents CCS as a solution to protect the climate whilst preserving the value of fossil fuel reserves and existing infrastructure.

The document also notes that there has been $10.2 billion of spending for CCS demonstration between 2007 and 2012, of which $7.7 billion came from private financing.

The roadmap continues, identifying the several existing technologies that are technically ready for deployment including:

- Post-process capture
- Syngas/hydrogen capture
- Oxy-fuel combustion
- Inherent separation

The document then highlights that transporting CO_2 is the most technically mature step in CCS and that CO_2 storage, although successfully demonstrated, further experience is needed at a larger scale.

The remainder of the roadmap outlines actions and milestones until 2050. The actions and milestones are broken into three distinct timeframes, looking at near-, medium- and long-term actions for the CCS sector. The first set of actions and milestones outlines the next 7 years, highlighting how critical this period is for both technology development and deployment, and other stakeholders. The vision from 2013-2020 is to have over 30 projects in operation, providing experience and enabling cost reduction, putting incentive polices in place and examining the policy framework critical to the success of CCS deployment.

From 2020-2030, the focus is to grow the industry with more large-scale deployments, continuing R&D and economies of scale to significantly reduce costs. By this time, the aim is to have more private investment.

From 2030-2050, the aim is for CCS to be routinely used to reduce CO_2 emissions from fossil fuel power plants and all suitable industrial applications.

The roadmap concludes by once again highlighting the near-term actions for stakeholders, recommending that governments and key stakeholders implement 7 key actions necessary for the success of CCS for 2020. These actions are:

- Introduce financial support mechanisms for demonstration and early deployment of CCS to drive private financing of projects.
- Implement policies that encourage storage exploration, characterisation, and development for CCS projects.
- Develop national laws and regulations as well as provisions for multilateral finance that effectively require new-build, base-load, fossil-fuel power generation capacity to be CCS-ready.
- Prove capture systems at pilot scale in industrial pilot applications where CO_2 capture has not yet been demonstrated.
- Significantly increase efforts to improve understanding among the public and stakeholders of CCS technology and the importance of its deployment.

- Reduce the cost of electricity from power plants equipped with capture through continued technology development and use of highest possible efficiency power generation cycles.
- Encourage efficient development of CO_2 transport infrastructure by anticipating locations of future demand centres and future volumes of CO_2.

3. CCS ROADMAP- SUPPORTING DEPLOYMENT OF CARBON CAPTURE AND STORAGE IN THE UK

Department of Energy & Climate Change

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48317/4899-the-ccs-roadmap.pdf

The UK has identified itself as a leader in the Carbon Capture and Storage (CCS) technology sector. An extensive seabed, power clusters, offshore expertise and academic excellence in research, the UK possesses several key advantages for the deployment of CCS. This roadmap provides a framework for the Government's interventions to support the development and deployment of CCS technologies.

First, the roadmap highlights the UK Government's commitment to making CCS a viable option as a part of the low-carbon generation mix. They have a concerted effort on reducing costs and risk associated with CCS so it can be cost competitive with other low-carbon technologies by the 2020s. The Government identified 3 main challenges which are presented in this roadmap:

- Reducing costs and risks associate with CCS.
- Putting in place the market frameworks that will enable CCS to be deployed by the private sector, cost effectively.
- Removing key barriers to the deployment of CCS for the power and industrial sectors.

The roadmap then continues to note the advantages of deploying CCS in the UK which include the geographical location, the well-understood basins, storage capacity and the idea that with CCS, fossil fuels can be maintained within the UK generation mix whilst meeting 2050 decarbonisation targets. The CCS Association has set a target of 20-30GW of CCS deployed by 2030.

The roadmap then identifies the green growth opportunity that comes with implementation of CCS on a UK and global scale. World-wide, up to $40 billion has been committed by Governments in support of CCS. It is estimated that export opportunities for the UK could be between £3-6.5 billion a year by the later parts of the 2020s. These opportunities would be found by exporting supply chain to the EU and global markets.

Furthermore, the roadmap states that CCS has the potential to address up to 38Mt of CO_2 emission per annum in 2030. In order to make this a reality, the UK is taking the following actions:

- Reforming the electricity market.
- Developing long-term contracts.
- Exempting power stations with CCS from the Carbon Price Floor.
- Exempting CCS project from the Emissions Performance Standard.

The roadmap identifies that the UK Government plans to address CCS first in the power sector, followed by other industrial sectors. This is due to the fact that the power sector is the largest source of emissions, therefore can contribute most to the reduction.

Moving forward, the roadmap discusses the Government's 'learning by doing, learning by research' tactics, which include the following to promote learning:

- Launching a CCS Commercialisation Programme with £1billion capital support focused on learning by doing and knowledge sharing, focusing on the cost reduction of CCS.
- Delivering £125 million, 4-year coordinating R&D and innovation programme.

The CCS Commercialisation Programme is one of the most comprehensive programmes offered by any country in the world.

Finally, the Roadmap provides a discussion on the key requirements for overcoming many of the sector's key barriers. These include:

- Implementation of a regulatory framework.
- Developing a storage strategy.
- Working with BIS and the sector skills councils to ensure people with the right skills and supply chains are available to provide the required goods and services.
- Engaging with the industry on a transport and storage infrastructure to gain an understanding of how, where and when to develop.

The Roadmap concludes by providing an Action Plan timeline Gantt chart, and a summary of actions that fall under the categories of Understanding the Challenge, Enabling commercial CCS, Learning by doing, learning by research and Tackling barriers to deployment.

4. DOE/NETL CARBON DIOXIDE CAPTURE AND STORAGE RD&D ROADMAP

U.S. Department of Energy and National Energy Technology Laboratory

http://www.netl.doe.gov/File%20Library/Research/Carbon%20Seq/Reference%20Shelf/CCSRoadmap.pdf

The first chapter of this roadmap provides an overview of the CO_2 emissions level and the need for CCS, highlighting that fossil fuels accounted for 71% of total US electricity generation in 2008. It then provides an overview of CCS technologies and identifies the CCS RD&D goals including cost reduction and deployment.

Looking forward, the document presents a timeline of the focused effort to deploy CCS technologies. DOE funding to support CCS amounts to a total contribution of approximately $2 billion between 2011 and 2015. The document also acknowledges the fact that DOE is collaborating with other US Government agencies, and other countries, in an effort to create an international effort of quality research. The document provides a list of ongoing international projects.

The next chapter focuses on CO_2 capture and compression, noting the likelihood that coal-based plants in the US will eventually be required to implement CCS technologies to control their CO_2 emissions. The chapter continues on to discuss the main barriers of CCS technologies, which are currently delaying widespread deployment, these include:

- Not been demonstrated at a large-enough scale necessary for power plant application;
- Parasitic loads (steam and power) required to support CO2 capture would significantly decrease power generating capacity; and
- If successfully scaled-up, they would not be cost effective at their current level of process development.

Furthermore, the document examines the 3 main general technology approaches for CO_2 capture- pre-, post- and oxy-combustion, and examines the cost-effectiveness of CCS. Current technologies are expensive and very energy intensive due to the large quantity of energy required to capture, compress, transport and store CO_2. Currently, the LCOE of CCS ranges from $116/MWh to $151/MWh, depending on the type of facility and whether the technology will be applied to a new plant, or to be retrofit on an existing plant. Additionally, the cost of CO_2 avoided at a range of $60-$114 per tonne.

Continuing, the document suggests that one or more advanced technologies will be available for full-scale demonstration by 2020. It also presents the goal of NETL's CO_2 capture technology RD&D effort as a focus to develop fossil fuel conversion systems that achieve 90% CO_2 capture at a less than 10% increase in COE for pre-combustion capture at IGCC power plants and a less than 35% increase for post- and oxy-combustion coal-fired power plants.

Chapter 3 primarily focuses on CO_2 transportation storage highlighting the idea that due to the large volume of CO_2, transportation will most likely take place via the use of a pipeline. The chapter also examines the potential impacts to a variety of stakeholders and the challenges associated with building a national CO_2 pipeline, including:

- Public perception
- Regulatory uncertainty
- Uncertain CO_2 demand and price-economic feasibility
- Liability risks
- Large-scale integration of pipeline network
- Corrosion resistant alloys and coatings

Next, the document examines the monitoring, verification and accounting capabilities and challenges. It is stated that the capabilities will be critical to ensuring long-term viability of CCS. The amount of CO_2 stored at a site must be tracked, monitoring for leaks or other deterioration of storage integrity over time, and verifying that the CO_2 is sustaining expected levels of permanence. The challenges that come with this are:

- Quantification and verification of stored CO_2;
- Development of robust, flexible accounting protocols; and
- Reducing the cost of monitoring.

The document continues, examining the several types of monitoring that can occur, which include:

- Atmospheric and remote sensing
- Near surface monitoring
- Wellbore monitoring
- Deep subsurface monitoring
- Accounting protocols

The document also addresses the need for accurate simulation and the importance of the development of risk assessment protocols and models that can be tailored to individual sequestration sites.

The document concludes with a discussion of the Regional Carbon Sequestration Partnerships (RCSP), which are a public/private partnership that involves over more than 400 organisations within 43 states and 4 Canadian provinces. This allows for contributions from local citizens, institutions and organisations, for the development of the technologies best suited for the region. The RCSP effort will take place in three phases: Characterisation, Validation and Development.

5. CCSTRM: CANADA'S CO_2 CAPTURE & STORAGE TECHNOLOGY ROADMAP

CANMET Energy Technology Centre

http://www.publications.gc.ca/site/eng/337371/publication.html

The vision which emerges in this technology roadmap is 'technology for today's energy economy providing the basis for transformative change tomorrow,' and resonates throughout, presenting the importance of CCS on a local and global scale. First, the roadmap notes that CCS is important on a global scale because of the potential to disconnect the relationship between economic growth and global greenhouse gas emission rates.

The roadmap commences by providing an overview of the opportunity for Canada to include CCS into their energy portfolio, including an overview of the CCS technologies. Canada, with its abundant fossil fuel and natural gas deposits, and coal reserves, has the potential to implement CCS for economic benefits of existing resources whilst maintaining the environmental objectives. This first section also presents the vision/goals of the roadmapping exercise, which include:

- Accelerate the development of cost-effective CO_2 capture, transportation and storage technologies.
- Building on the intellectual foundation that already exists in Canada to enable the development of a home-grown, world-class CCS industry.
- Force alliances and partnerships to advance research, development and demonstration programmes and projects.
- To engage Canadian experts, researchers, practitioners and policymakers in CCS.

Next, the current challenges and issues presenting a need for CCS are identified, including:

- Oil imports may account for 57% of North America's consumption by 2030.
- 77% of primary energy demand in 2000 in Canada was from oil, natural gas and coal.

The next section identifies the lack of clear, concise policy for CCS, and the incentives and regulations that would result from a policy agenda pressing the idea that policy makers must make CCS a priority, and develop a framework for which a 'robust and vibrant' industry can emerge. It is necessary for Canada to address questions such as- what amount of reductions are expected from CCS; what is the timeframe; who will pay; and what CCS activities are most socially acceptable. This section also highlights that a variety of stakeholders are recognised and their needs must be met.

Further, addressing the establishment of a regulatory framework to tackle the issue of 'avoided' versus 'captured' emissions needs to be created so the two can be distinguished, and accurate tracking can occur. Other issues such as geological permanence, monitoring and measurement and verification of the stored emissions must also be considered.

Moving forward, the roadmap notes the high cost of developing CCS and the need to develop and approach of cost-sharing, pooling expertise, collaborating and disseminating knowledge in an effort to build global capacities in CCS. Also highlighted is the need for pilot projects and testing as well as investment in human capital through education and training, and effective outreach and education with the public.

Next, the roadmap identifies the specific opportunities which lie in Canada, first noting that Canadian territories include 68 individual sedimentary basins which could be used for CCS development. There is a focus on the Western Canadian Storage Basin, which is considered to be a world-class site for geological storage (estimated potential capacity of 3762 $MtCO_2$), and therefore much effort and research is being

undertaken for characterisation and assessment for the region. An issue for Canada is that whilst storage capacity is not limiting, storage opportunities in some area are limited. Many of the provinces have few storage options for the large industrial emitters. Regardless, CCS development in Canada could enable the development of low-emissions fossil fuel industries in Canada, making Canada a world leader in CCS technology.

The roadmap continues by examining the technology pathways, giving an in-depth overview of the main four capture system technologies, the transfer methods and storage needs. For each component of CCS, the technology options, cost and needs are presented. These are summarised:

Capture Technology	Post Combustion	Pre-Combustion	Oxy-Fuel
Costs	$50-70/tCO$_2$	$20-50/tCO$_2$	$13-80/tCO$_2$
Needs	Improved contactors and mass transfer systems for large-scale facilities.	Modular test facilities for assessing advanced gasification, reformation, carbonation and hydrogen separation processes.	System integration and cycle development

Also noted is that the IPCC indicates a price signal of $25-$30/tCO$_2$ may be enough to induce the development and deployment of CCS technology.

Transportation of the compressed CO_2 will be undertaken via pipeline or tanker, with costs estimated at $6/tCO$_2$ for 650km transported in a common carrier network with a capacity of 14.5 MtCO$_2$/year.

Transportation needs include a comprehensive database of CO_2 emission streams in Canada, and a better understanding of optimal pipeline parameters for CO_2 transportation. Finally, storage is discussed, noting that there is an allowable rate of seepage of up to .1%/year which still results in an effective outcome when dealing with greenhouse emission reductions. Needs for the storage component include the confirmation that CCS is a safe, reliable and environmentally beneficial option.

Finally, the roadmap concludes by looking forward. Canada has positioned itself as a country with:

- Vast fossil fuel resources
- Internationally competitive industry producers and exporter of fossil fuels
- Enormous potential for geological storage of CO_2 in various regions across the country
- Existing, leading-edge knowledge and expertise in CCS application

Additionally, six objectives for moving forward with CCS were identified:

- Need for policy and regulatory frameworks
- Public outreach and education
- Technology watch and international collaboration
- Science and technology R&D
- Demonstration of systems and applications
- National coordination

Canada recognises that investment in CCS needs to happen now, and development should occur over the next 25 years, or Canada will be further from reaching emission reduction goals.

6. A ROADMAP FOR US-CHINA COLLABORATION ON CARBON CAPTURE AND SEQUESTRATION

A partnership among: Asia Society, Center for American Progress, and the Monitor Group

http://asiasociety.org/files/pdf/AS_CCS_TaskForceReport.pdf

Whilst a China specific roadmap is still undergoing completion, this document, and collaboration, was created as a result of joint commitments from the US and China at the July 2009 US-China Strategic and Economic Dialogue.

The first section of the document provides an overview of climate change and the dangers associated with it. The section also highlights the need for US-China cooperation in combating climate change, given the fact that the two countries are the world's two largest emitters of greenhouse gases, with coal energy production at 50% and 80% of current electricity generation. This collaboration provides the opportunity to build the confidence and trust necessary to drive progress towards a global solution.

Further, the document notes that neither country can currently meet its emission reduction targets without addressing its reliance on coal. This collaboration has committed both parties to create active channels for CCS cooperation, using this roadmap as a platform from which concrete and active cooperation can be formulated.

The document continues, presenting the CCS technology options, and three specific areas in which advancement should focus. These areas are:

- Demonstration plants: they are necessary to conduct real-world demonstration projects.
- Cost: generate accurate estimates of costs of CCS, reduction of costs and develop workable funding models.
- Commercial deployment: in order to make a significant impact on global emissions, both the US and China will need to scale-up deployment of CCS technologies, and also address questions concerning regulatory policy, legal framework and operational practice.

Next, the document states that the immediate aim of the roadmap is to catalyse US leadership by sketching a concrete and collaborative new plan of action for CCS that the US Government could consider adopting. The roadmap has been completed with the aim of working toward the creation of financial mechanisms to support large-scale projects at a low cost, and to accelerate the reduction of cost and provide the performance experience necessary for the scale-up to mass deployments. Furthermore, the roadmap is intended to complement other ongoing collaborations for both China and the US. The roadmap presents a 3-pronged approach to producing milestones. These include:

- Sequestration of available pure streams of CO2
- Retrofit research, development and deployment
- Catalyse markets for CCS

The roadmap then examines each of the stages of the 3-pronged approach, first highlighting China as a global leader in coal gasification development and deployment. They create a 'pre-captured CO_2', which is unavailable in the US and can store carbon at a low cost of $5-10/ton. There is also a discussion of the US contributing to a total of 5 projects in China, over a 5 year period. The projects would sequester 2-3 million tons of CO_2/year, with a total approximate cost of $100-200 million to the US.

The roadmap then calls out the need to retrofit existing plants with CCS capabilities in order to reach abatement targets. The document focuses on laying the groundwork for eventual broad-scale retrofitting by setting

up the preconditions for future CCS deployment without harming China's other energy priorities.

Furthermore, the document presents the concern that there are currently no markets established for CCS beyond secondary sources such as oil production. The assumption made is that such markets will eventually come into being through various cap-and-trade systems or a tax on carbon. In order to overcome key financing challenges, a bridge between the current situation and future markets must exist.

Moving forward, the roadmap presents the obstacles faced by both the US and China. Americans and their representatives refuse to support a price on carbon or mandatory emissions reductions for fear of creating a competitive disadvantage for the US. The challenges that arise from this thinking include:

- Congress will most likely oppose the use of US dollars to fund collaborative projects in China unless they bring substantial co-benefits to American workers.
- Congress's historic relationship with developing nations on climate change has been competitive and apprehensive.
- The Federal Government must address public concerns surrounding CCS.

For China, the main obstacles include:

- China's core interests are in energy security and economic development.
- Chinese climate negotiations expect developed countries to assume greater responsibility for emissions reduction.

On the positive, the roadmap also includes the benefits to overcoming these obstacles. For the US, collaboration with China may include the following benefits:

- Accelerate eventual CCS deployment in the US
- US job creation
- Reduction of US electricity prices
- Reduction of CCS costs in US
- Allow for US to share the risks with China

Overcoming the obstacles in China can be achieved by:

- China has become increasing proactive in addressing climate change and greenhouse gas emissions.
- Chinese government and commercial sector are making investments in CCS.
- China aspires to enhance its global reputation as a responsible and peaceful rising power.

The document concludes by reiterating the importance of this collaboration to the China-US relationship. Additionally, both countries have a long-term goal to attack the global climate problem, and this roadmap helps forge actions against climate change in a collaborative effort.

7. CLEANER FOSSIL POWER GENERATION IN THE 21ST CENTURY- MOVING FORWARD

UK Advanced Power Generation Technology Forum

http://www.apgtf-uk.com/files/documents/APGT%20Strategy_Report2013_web.pdf

This document provides a strategy with recommendations for RD&D efforts that primarily focus on the areas of:

- Whole systems and cross-cutting issues
- CO_2 capture
- Industrial CCS
- CO_2 transport
- CO_2 storage
- Knowledge exchange
- Skills development
- Capacity building and supply chain development
- International collaboration
- Public outreach/education

The document commences by presenting the background and the need for CCS in the UK and on and international level. The document reiterates the IEAs three time-specific goals, which include:

- By 2020, the capture of CO2 is successfully demonstrated in at least 30 projects.
- By 2030, CCS is routinely used to reduce emissions in power generation and industry.
- By 2050, CCS is routinely used to reduce emissions from all applicable processes in power generation and industrial applications at sites around the world.

The aim of the APGTF strategy is to 'ensure that the UK maintains a leading role in the development and commercialisation of carbon abatement technologies that can make a significant and affordable reduction in CO2 emissions from fossil fuel use.'

Moving forward, the document provides a prioritisation of needs and recommendations for RD&D activities for CCS. The document provides over 150 recommendations for the focus areas mentioned earlier, prioritising them as high, medium and low. The highest priority is specifically for topics which could benefit the commercialisation of CCS projects or policy. Most of the recommendations within the document fall into the medium priority category and should commence as soon as possible. Finally, the lower priority topics are those that can be delayed for a year or two in order to allow for other work to be completed first.

The document provides some conclusions which include:

- To maximise learning from publicly supported RD&D, the Commercialisation Programme projects and other full-scale projects, knowledge exchange/sharing should be encouraged (and funded) at several different levels.
- The project listing presented in Appendix 1[of the document] should be extended to a comprehensive online database with a portal to key results and hyperlinks to published reports.
- Given the challenges of achieving implementation on a relatively short timescale compared with much public-funded RD&D, public-sector funders of CCS RD&D should be more explicit in their requirements for knowledge sharing.
- The APGTF, in conjunction with the CCSA, should regularly assess skills needed, capacity shortages and specific supply chain opportunities.
- UK should continue to participate in international CCS bodies and initiatives such as the CSLF, Global CCS Institute, IEAGHE and ZEP.
- Consideration should be given to further extending Government support to RD&D projects that support the development of UK

industry through advancing the objectives set out in the UK CCS roadmap.

- The APGTF should continue to work alongside other organisations undertaking public outreach and education activities.

There is a plan for APGTF to develop an 'Action Plan' to help implement the recommendations found within this strategy document.