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People's Republic of China: Roadmap for Carbon Capture and Storage Demonstration and Deployment
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Component A–Work Package 1 Report: Review of CCS Roadmaps

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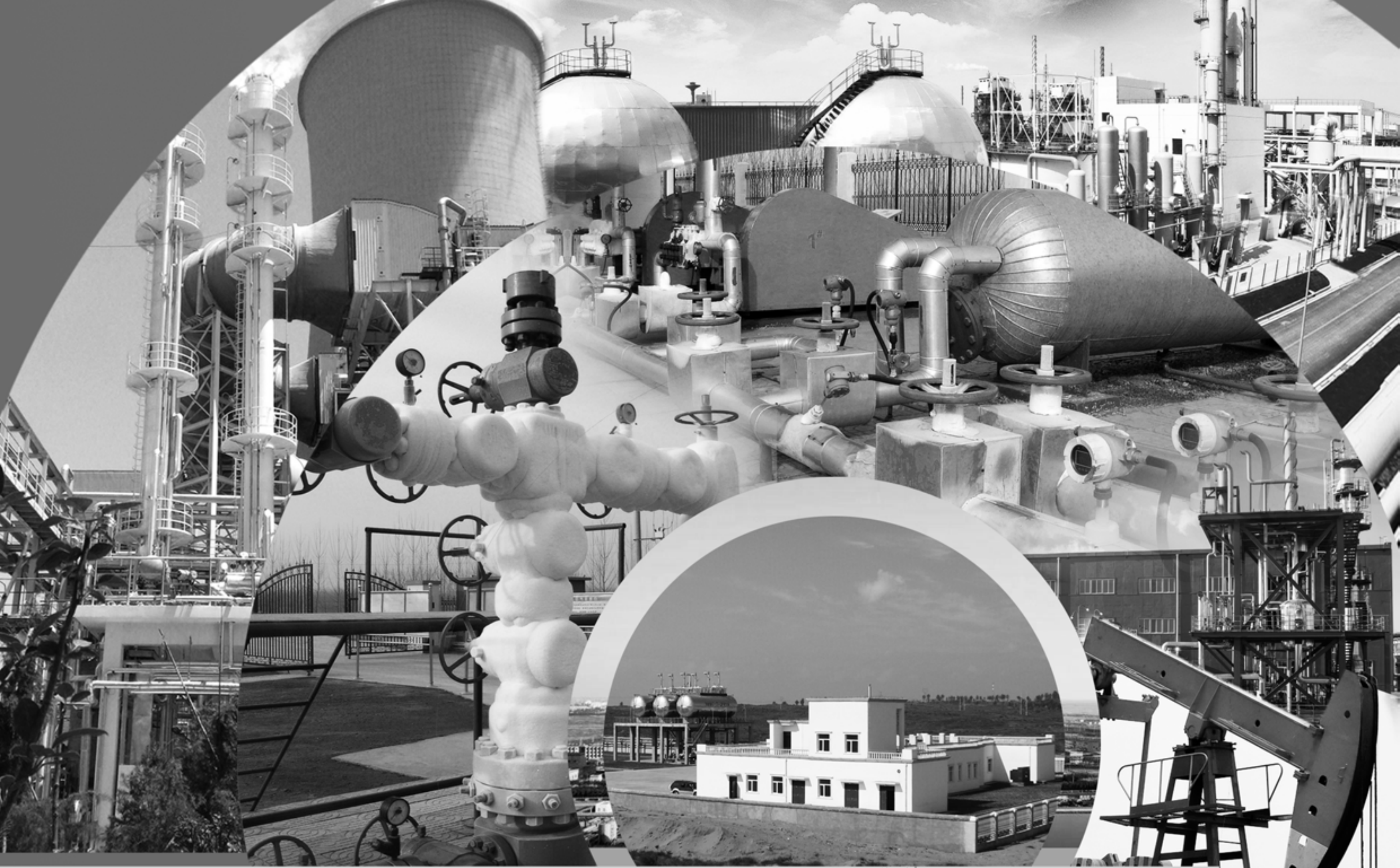

Road Map for Carbon Capture and Storage (CCS) Demonstration and Deployment in the People's Republic of China

WORK PACKAGE 1 REPORT:

Review of CCS Roadmaps

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Review of CCS Roadmaps

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Road Map for Carbon Capture and Storage Demonstration and Deployment

Component B: Oxy-fuel Combustion Technology Assessment

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Executive Summary

This report summarizes and compares Australia, Canada, the UK, the US, South Africa, Japan, Malaysia, and Poland's Carbon Capture and Storage (CCS) roadmaps. It also well as to provide suggestions for China's CCS roadmap based on this international CCS roadmapping experience. We analyzed the main focuses of these roadmaps, including visions and goals of CCS development and deployment, research program areas, implementation status, and policy and regulatory approaches.

The international CCS roadmaps share a common vision – to speed up the development and deployment of CCS technologies over the next 20 to 30 years. However, given their unique national context, each nation chooses a distinct technology focus and development approaches. Canada and the US clearly have the most ambitious goals for CCS development; their RD&D programs cover the gamut of technological areas and development stages. By presenting the newest technological gaps, organized according to specific technology programs sometimes with distinct funding sources, and with specific goals for different time/technology combinations, their roadmaps are like high-quality scientific a study with precise calculations. For example, Canada's roadmap described six approaches in a great detail to move CCS opportunities forward, including policy and regulatory frameworks, public outreach and education, international collaboration, science and technology R&D, demonstration, and national coordination. In the section of National Coordination, this document identifies stakeholders, the levels of coordination (international, national, and regional), the areas of coordination (policy and regulatory, education and outreach, and technology watch), and the outputs of the coordination.

The UK's roadmap focuses on introducing its government programs in CCS RD&D based on a core message – the government intervention is essential in the CCS development. For example, the UK government established a public-private Special Taskforce to work on the cost reduction of CCS technologies. Therefore, the UK's CCS roadmap does not have great technical details like the US and Canada's. Australia's CCS Roadmap is integrated into the national hydrogen economy plan. Additionally, Australia's document specifically maps all the stakeholders in the CCS value chain for the next 20-30 years. The South African CCS roadmap lacks detail of implementation, which is covered in separate work plan documents for each of the five major steps. Three work plans are available at this point. The CCS Roadmaps produced by the NGO Bellona for Poland and Hungary as well as the Malaysia CCS scoping study prepared by Global CCS Institute and Clinton Climate Initiative have some common characteristics. By using modeling techniques, the three international organizations are trying to give the nations a future energy picture in which CCS is an essential component.

However, implementation is not always linked to the visions, goals, and plans of the original CCS roadmaps. It is understandable that the implementation of CCS projects depends on a series of external factors, some of which are uncontrollable. Some nations do not even treat CCS roadmaps as an official CCS development guidance. Some CCS roadmaps are contracted to research organizations with a main purpose to understand the CCS potentials in their country. For example, CCS Roadmaps produced by Bellona for Poland and Hungary and the Malaysia CCS scoping study prepared by Global CCS Institute and Clinton Climate Initiative miss the details of technological status in these countries and thus, failed to provide comprehensive technology plans for R&D stage, demonstration stage, and deployment stage, respectively. None of these nations have directly tracked the actions proposed by these CCS roadmaps with national implementation. Please see the Table # below for the overall large-scale integrated project implementation of the selected nations in 2013.

Nation	Identify (Planning)	Evaluate (Planning)	Define (Planning)	Execute (Construction)	Operate (Operation)
Australia	0	3	1	0	4
Canada	0	1	1	4	1
China	6	3	3	0	0
Hungary	0	0	0	0	0
Poland	0	0	0	0	0
South Africa	0	0	0	0	1
UK	0	5	1	0	0

Table # Large-scale Integrated CCS projects of selected countries in this document (GCCSI, 2013) (Large scale integrated CCS projects are defined as those which involve the capture, transport, and storage of CO_2 at a scale of at least 800, 000 tonnes of CO_2 annually for a coal-base power plant or at least 400,000 tonnes of CO_2 annually for other emission-intensive industrial facilities)

China's CCS roadmap should follow the international highest quality, and achieve some fundamental criteria. China's roadmap should bescientific, comprehensive, manageable, and flexible. "Scientific & Manageable" is defined as collecting background information regarding China's CCS technology development status and the country's energy infrastructure for CCS deployment as detailed as possible. "Comprehensive" is defined building a holistic technology and policy approach as well as mapping all the stakeholders in the roadmap. “Flexible” is rodamapping in a way that recognizes that the technology innovation is a dynamic process, and China’s national development might need to be revised accordingly and timely. “Inclusive” is defined integrating the RD&D programs and goals with the policy framework necessary for deployment.

Table of Contents

Introduction

This report is to summarize and compare Australia, Canada, the UK, and the US, and South Africa's Carbon Capture and Storage (CCS) roadmap, as well as to provide suggestions on what China's CCS roadmap can learn from the others. This report, first introduces the main focus of each CCS roadmap, and then describes the implications for China's CCS roadmap. The table below summarizes the key features of the roadmaps included in this section.

Table 1. National and international CCS Roadmaps.

Jurisdiction	**Release dates**	**Focus (primary/secondary)**	**Author**
International	2009,2013	Deployment/Demonstration	International Energy Agency
Australia	2004, 2008	R&D/Deployment	CO2CRC, a government research organization
Canada	2006	Deployment	Canmet Energy Technology Center
China	2011	R&D/Demonstration	Ministry of Science and Technology
UK	2012	Deployment/R&D	Department of Energy and Climate Change
US	2002, updated regularly	R&D/deployment	NETL, a government research organization
South Africa	2004?	R&D/Demonstration	SACCS, a government research organization
Poland	2011	The role of CCS in the country's future energy structure	Bellona, a Norway-based Environmental NGO
Hungary	2011	The role of CCS in the country's future energy structure	Bellona, a Norway-based Environmental NGO

Major CCS Roadmaps

Australia

Australia's Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), the nation's leading collaborative research organization on CCS, produced the country's first CCS roadmap in 2004 and revised it in 2008[1]. This Roadmap, covering both capture and storage technologies, is carried out in four levels - Level 0: Develop Skills & Knowledge; Level 1 R&D; Level 2 Demonstration & Application; and Level 4 Advanced Systems. This roadmap indicates that Australia should have its demonstrations plants around 2010, and starts its commercial plants around 2015.

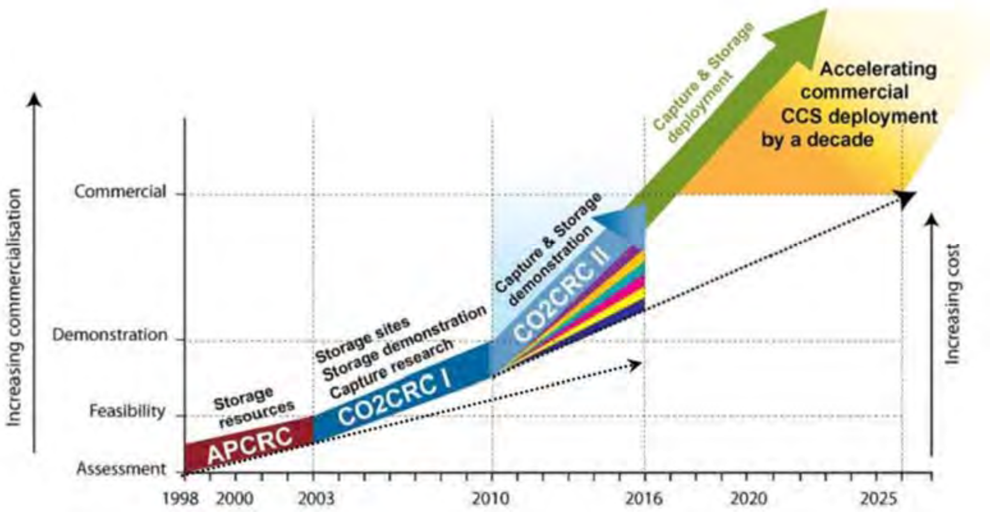

Figure 1 Australia's CCS Roadmap

The roadmap listed the barriers to accelerating commercial deployment of CCS in Australia. These barriers include lack of human capital, lack of CCS experience, lack of effective regulation, and most importantly, the economic competences of capture technologies. This roadmap is composed of three major sections: the R&D regarding capture and storage projects (Table 2), CCS pilot demonstration projects, and the integration of CCS in the nations' Hydrogen Economy long-term plan. It is worth noting that the development and deployment of CCS is regarded as the first step to achieve

[1]http://www.cslforum.org/publications/documents/SaudiArabia/T2_3_CSLF_PJC_DVP_Australia_Jan08.pdf

Australia's Hydrogen Economy. A timetable for different CCS-related technologies is presented in this Roadmap; the related actors who should participate in achieving this roadmap are discussed. These actors include the financial sector, equipment and infrastructure manufactures, industries, government, power sectors, coal and petroleum industry, and research organizations (Figure 2).

Capture R&D	***Storage and Utilization R&D***
Post-capture	Monitoring
Pre-Capture	Risk Assessment
Oxy	Oil
Membrane	Gas
Solvents	…
…	

Table 2 Capture, Storage, and Utilization R&D in Australia's CCS Roadmap

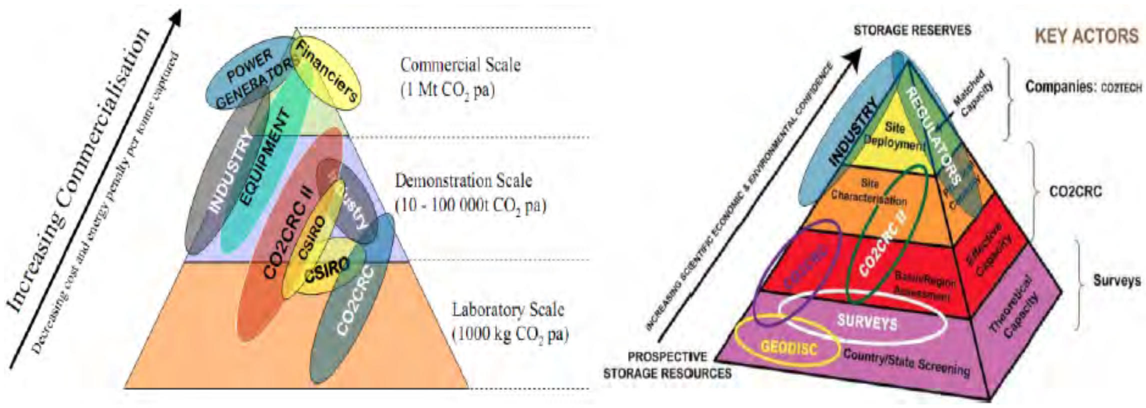

Figure 2 Pilot and Demonstration Projects in Australia

Canada

Canada's CCS Technology Roadmap (CCSTRM) was published in 2006 with an aim of identifying technologies strategies, processes and integration system pathways needed to a large-scale deployment of CCS in Canada. Like other CCS roadmaps, the CCSTRM starts with the advantages of Canada for CCS, and then discusses the rationale and challenges of CCS[2].

This roadmap primarily includes two sections: *Technology Pathways* and *The Way Forward*. The *Technology Pathways* section indicates that Canada needs to study CO_2 capture and storage as an integrated system although each component has its own research focus, goals and objectives. For example, the capture technology goals and research focus on cost reduction; and the roadmap recommends that the storage process should include both storage capacity estimates and infrastructure development. The roadmap concludes with "*The Way Forward*[3]," outlining six approaches that can enable Canada to capitalize its inherent opportunities for CCS. These include 1) policy and regulatory frameworks, 2) public outreach and education, 3) technology watch and international collaboration, 4) science and technology R&D, 5) demonstration, and 6) national coordination. Policy and regulatory frameworks are necessary components of deploying CCS infrastructure and systems, which will ensure that the industry grows in an appropriate, safe, and responsible manner. Public outreach and education is needed to provide public information on the benefits and challenges associated with CCS. Technology watch and international collaboration are both needed to stay connected to international activities, and to keep abreast of technology development around the world. Science and technology R&D is of critical importance because of the role it plays in tackling specific challenges faced by domestic energy industries (Figure 3&4). Demonstration of new science is one of the most important steps in installing new infrastructure and systems because it is the stage at which new technology and concepts are tested and proven to be technically and economically feasible. National coordination

[2] http://ccs101.ca/ccs_pro/canadas_ccs_roadmap

[3] http://canmetenergy.nrcan.gc.ca/sites/canmetenergy.nrcan.gc.ca/files/pdf/fichier/78713/ccstrm_e_lowres.pdf

of R&D and demonstration activities in Canada ensures a link to all the work being done on CCS and provide synergistic benefits to all stakeholders.

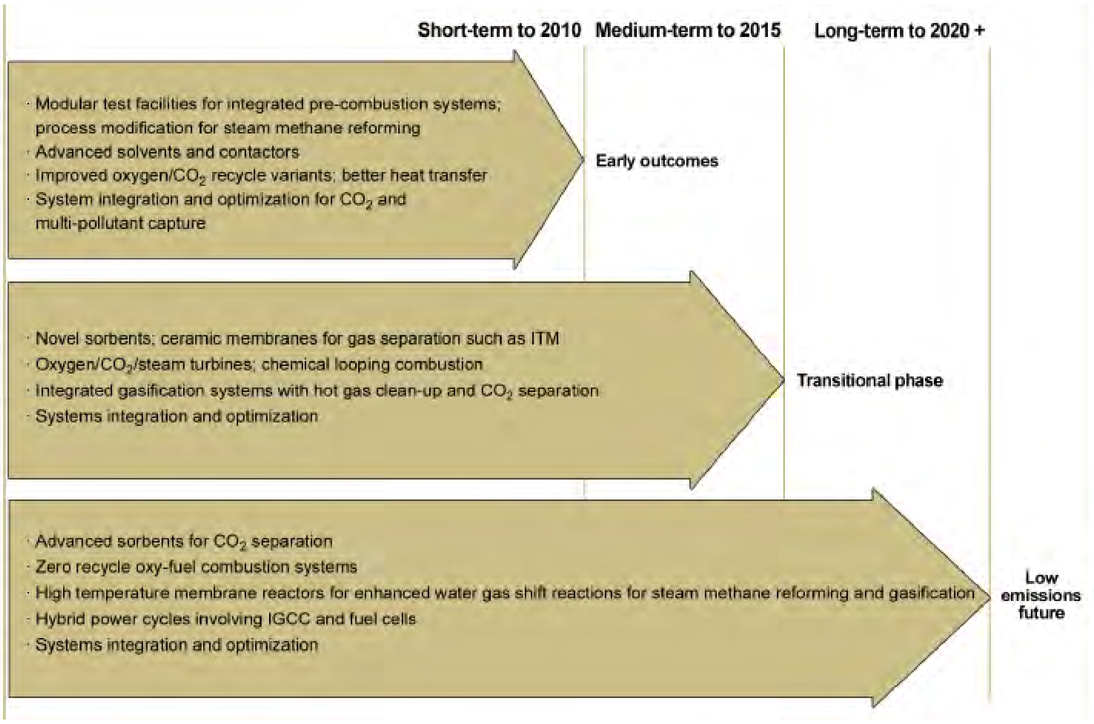

Figure 3 Canadian Capture R&D Needs

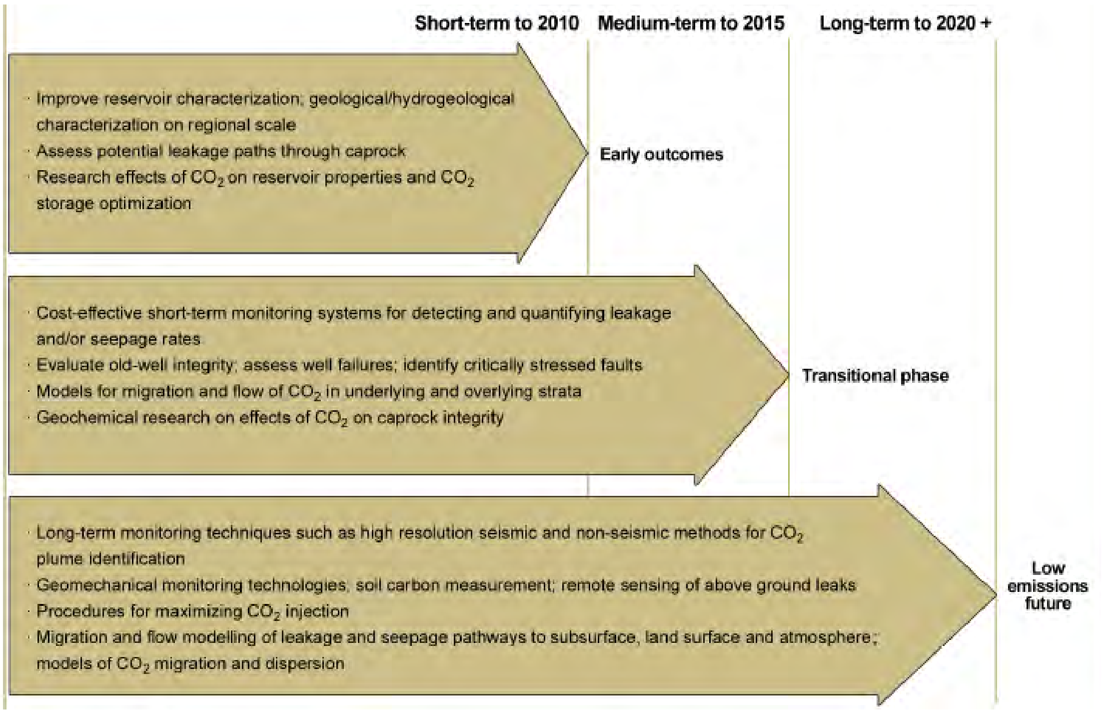

Figure 4 Canadian Storage R&D Needs

UK

Although the UK started its CCS research years ago, its first roadmap did not come out until 2012[4]. This CCS Roadmap sets out how the UK will achieve its goal of seeing commercial deployment of CCS in the country in the 2020s. The Roadmap lays out three advantages that UK has for advancing CCS: extensive storage capacity under the UK seabed, particularly under the North sea; existing clusters of power and industrial plants with the potential to share CCS infrastructure; expertise in the offshore oil and gas industry which can be transferred to the business of CO_2 storage; and academic excellence in CCS research. The UK Government hopes to enable CCS cost-competitive and to enable the private sector investment in CCS-equipped fossil fuel power stations by the 2020s, without government capital subsidy. Therefore low carbon fossil fuel power stations and industrial plants could be widely deployed in the UK in the 2020s.

In this Roadmap, three key challenges which need to be tackled are described as- reducing the costs and risks associated with CCS, putting in place market frameworks, and removing key barriers to the deployment of CCS. The comprehensive programs within the Roadmap are tied to the challenges. These programs include (1) a one billion British Pound in capital funding to support commercial-scale CCS, targeted specifically to learning-bydoing and knowledge sharing to reduce the cost of CCS such that it can be commercially deployed in the 2020s; (2) a $125m, 4-year, coordinated R&D and innovation program covering the range of R&D from fundamental research and understanding, to component deployment and pilot-scale testing, ensuring that the best ideas can be taken forward to the market (Figure 5); (3) development of a market for low carbon electricity through electricity market reform; (4) policy intervention to address key barriers to the deployment of CCS including work to support the CCS supply chain, develop transport and storage networks, prepare for the deployment of CCS on industrial applications and ensure the right regulatory framework is in place; and (5) international engagement. An office of Carbon Capture and Storage (OCCS), within the UK

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

Department of Energy and Climate Change, was created to help drive delivery of the Government's Climate and Energy objectives. The OCCS sets the strategic path for the development and wide-scale deployment of CCS in the UK. Among other things, it was established to create the policy and support arrangements to stimulate private sector investment in CCS; to work to maximize the global opportunities for UK businesses and the economy to benefit in the form of jobs and wealth creation; and to collaborate with stakeholders to remove barriers to investment and development in the UK and globally. Above all the OCCS aims to implement measures to help drive down the cost of CCS so it can be cost-competitive with other low carbon generation alternatives. The Government is asking industry to establish a CCS Cost Reduction Task Force to work alongside the Official of CCS to set out a path and action plan to reduce the costs of CCS. The taskforce identify potential reductions in the cost of deploying the technology; the scale of those reductions; and the actions required to deliver them.

R&D Theme	Short term R&D needs (5 – 10 years)	Medium term R&D needs (7 – 15 years)	Long-term R&D needs (10 – 20+ years)
Whole systems	• Investigate system operability and power plant interaction between CO_2 grid • Test flexibility to cope with change in demand • Develop CO_2 accounting	• Further Investigation of complex interaction of CO_2 from multiple sources (capture technologies, industrial sources)	
Capture	• Learn from demonstration projects • Develop understanding of environmental impact • Identify requirements for retrofitting • Adapt technology for range of fuel types • Specify CO_2 standards • Establish common measures and monitoring	• Provide validation of demonstration capture technologies • Develop and demonstrate 2nd generation capture agents and processes	• Develop commercially available systems with >85% capture rate for all fuel types • Develop capture systems with efficiency >45% including CO_2 capture
Industrial CCS	• Investigate extent to which CCS technologies could apply to industrial applications	• Identify sources with sufficient operational lifetime remaining to make retrofitting feasible	
Transport	• Understand potential hazards and risks to inform decisions on pipeline routes onshore • Develop techniques for leak mitigation and remediation • Develop ship-based transport option	• Gather best practice data • Identify novel pipeline materials and sealing and joining technologies • Develop technologies to reduce power and cost of compression	• Develop performance database for CO_2 transport networks to enable grid optimisation
Storage	• Improve understanding of geological seal integrity and subsurface CO_2 behaviour/ flow • Estimate UK CO_2 storage capacity • Develop and demonstrate low-cost and sensitive CO_2 monitoring technologies • Develop best practice guidelines for well construction, completion and remediation	• Test injection at significant scale at multiple sites • Investigate water production • Develop techniques for rapid, detailed appraisal of formation capacity • Improve monitoring technologies	• Develop techniques for high efficiency use of formation capacity

Table 2 UK CCS R&D Needs

The Impact the UK Electricity Market Reform on CCS

The UK electricity market reform is expected to play a critical role in developing CCS in the country. The electricity market reform aims to provide investors with a transparent, long-term, and stable investment environment for low-carbon energy technologies, as well as to ensure national energy security. Three policy instruments, *feed-in tariffs with contracts for difference (CfDs)*, *carbon price floor*, and *emission standard performance*, have the most direct impact on CCS.

The basic mechanism of CfDs is a pre-identified "*strike price*" to the generator for all eligible electricity generation. This strike price will operate against a *reference wholesale market price* – if the reference wholesale market price is lower than the strike price, the generator will be paid the difference between the two prices, whereas if the reference price is higher than the strike price the generator will have to pay back the difference. The carbon price floor, a part of the *Finance Act 2011*, is introduced from 1 April 2013. The initial price is set around 15.70 British Pounds/t CO_2, will be increased to 30 British Pounds/t CO_2 in 2020, and raised to 70 British Pounds per ton in 2030 (real 2009 prices). The carbon price floor aims to provide long-term certainty about the cost of carbon in the UK electricity generation sector, and send clear pricing signals towards low-carbon generation. Emissions performance standard (EPS) will initially be set at 450g CO_2/kWh – a level that will require that any new coal-fired power stations to use CCS technologies.

UK CCS Commercialization Program

The UK CCS Commercialization Competition makes available £1 billion capital funding, together with additional support through the UK Electricity Market Reforms, to support commercial-scale CCS projects in UK. The current competition started in April 2012 and the shortlist was made in October 2012. In March, 2013, the government announced two preferred bidders: Peterhead project in Aberdeenshire, Scotland and White Rose project in Yorkshire, England. Currently, an award was intended to make to the White Rose project by the UK Government in December 2013; and negotiations on the FEED study for the Peterhead project are still underway.

NER300

In the EU, the NER300 program provided 300 million allowances in the New Entrants' Reserve of the European Emissions Trading Scheme for subsidizing installations on innovative renewable energy technology and CCS. This financial program is managed by the European Commission (EC), European Investment Bank and Member States. In the first around of the NER300 program, no CCS projects were awarded funding. The official explanations include funding gaps and problems that Member States fail to address, and the lack of technological advance in proposed projects. In April 2014, the EC announced the second call for proposals. However, based on the newest official information, there is only 1 CCS project proposed from the UK.

USA

The US Department of Energy's National Energy Technology Laboratory (NETL) published the nation's first CCS Technology Roadmap in 2002, and it has been updated on an almost annual basis since then. The most recent US roadmap was released in September 2013[5]. The goal of this roadmap is to set out a plan for the US to solve key technology challenges and enable widespread deployment of CCS around 2030 (Figure 6). This Roadmap includes the US CCS research program plan and provides an overview of the US DOE's research, development, and demonstration (RD&D) efforts to supply cost-effective, advanced technologies to capture and store CO_2 from coal-based power systems. Under this Roadmap, some technologies are being demonstrated today, but other more advanced technologies (2nd Generation), including IGCC with CCS, Advanced IGCC Components, Post-combustion CO_2 Capture, and Oxy-combustion will be ready for full-scale demonstration between 2020-2025. Transformational technologies are currently in early stages of development and will be ready for commercial demonstration between 2030-2035. For carbon storage the goals are to develop and validate technologies to ensure 99 percent storage permanence while offsetting capture cost with utilization. Widespread commercialization of these utilization approaches should be underway by 2020, with all types of storage commercially deployed by 2035. Key challenges include reducing the cost and energy penalty of capture technologies, researching monitoring, verification, and accounting technologies, and strengthening public education and communication. This roadmap also includes a plan for IGCC, advanced turbines, fuels, and other related technologies. The DOE's Office of Fossil Energy established the Clean Coal Research Program to manage the RD&D activities regarding CCS. Again, this program is implemented by the NETL who manages the RD&D for the DOE Office of Fossil Energy. In 2011, DOE funding to support this RD&D effort totals approximately $2 billion for FY2011 through FY 2015. In addition, in 2009, the DOE's Fossil Fuel office received more than $3 billion from the American Recovery and Reinvestment Act.

5 http://www.netl.doe.gov/technologies/carbon_seq/refshelf/Program-Plan-Carbon-Storage-092013.pdf

Figure 5 The US CCS Roadmap Timeline (from 20011 roadmap)

Specific programs also compliment and provide results that support the CCS roadmap. The Clean Coal Power Initiative ($800 million is being used) provides government co-financing for new coal technologies that can help utilities cut sulfur, nitrogen, and mercury pollutants from power plants. New funding will help this program broad CCS commercial-scale experience by expanding the range of technologies, applications, fuels, and geologic formations that are tested. The Industrial Carbon Capture and Storage ($1.5 billion is being used) is for a two-part competitive solicitation for large-scale CCS from industrial sources. The second part of the solicitation includes innovative concepts for beneficial CO_2 reuse and CO_2 capture from the atmosphere. The Scale-Up of Current Projects is to accelerate scale-up and field-testing. The Geologic Sequestration Site Characterization ($100 million is being used) is to characterize a minimum of 10 geologic formations through the United States. The Geological Sequestration Training and Research ($40 million is being used) is to educate and train a future generation of geologist, scientists, and engineers with skills and competences in CCS-related geoscience. The FutureGen 2.0 ($1 billion is being used) is a clean coal repowering program and CO2 storage network being conducted by the FutureGen Alliance, Ameren Energy Resources, Babcock & Wilcox, and Air Liquide. The project will repower Ameren's 200-MW Unit 4 in Meredosia, Illinois, with advanced oxy-combustion technology. The Carbon Capture and Storage Simulation Initiative is to accelerate CCS technology development using advanced simulation and modeling techniques. The National Risk Assessment Partnership is to integrate CCS R&D activities and to develop the science base necessary to quantify potential risks associated with long-term geologic storage of CO_2.

In addition to the DOE technology roadmap, an interagency task force was established in 2010 which included 14 departments or agencies. The Task Force's recommendations were published in August 2010 and provide a roadmap for overcoming the barriers for CCS deployment that is wide-spread and cost-effective. The report highlighted that the commercial feasibility of CCS requires federal policies. Although the United States has not yet adopted an economy-wide national greenhouse gas policy, the following policies are worth noting. These policies are in addition to R&D funding: (1) proposed rules for new power plants would limit carbon emissions to 1,100 lbs or 499 kg/CO_2 per MWh. This would mean partial CCS for new coal-fired units and a proposal for existing plants is also expected in 2014; (2) tax incentives for CO_2 storage ($10/ton for EOR and $20/ton for storage) have been in place and are being refined/reconsidered; (3) loan guarantee programs have provided incentives for CCS and DOE has announced a new $8B loan guarantee program for clean fossil energy, which includes CO_2 capture for gasification and fuel reforming systems, as well as CO_2 capture from traditional coal and natural gas power plants.

South Africa

The South African Center for Carbon Capture and Storage (SACCS) produced a five-step roadmap towards full commercial uptake of CCS. Unlike the developed nations' CCS roadmaps, this one simply provides general steps and their parallel supporting programs. The five milestones are a measurement of CCS potential in 2004, a national Atlas on geological storage of CO_2 in South Africa in 2010, test injection sequestration of some tens of thousands of tonnes of CO_2 in 2016, demonstration plant sequestering some millions of tonnes of CO_2 around 2025, and full industrial operation in 2025[6]. At this point, the SACCS is working to achieve the third step - the test injection: determining an appropriate test injection site by apposite seismic surveys and drilling, testing inject some tens of thousands of tonnes of carbon dioxide, measuring the effect of that injection, adding to human capacity building by generating several post-graduate degrees, and producing results that will determine the future of CCS in South Africa. At the same time, the SACCS made human capacity plan, business plan, and establishing regulations to ensure to achieve the third milestone. For public engagement South Africa has developed both a national plan as well as local plan that can be implemented at the test injection site.

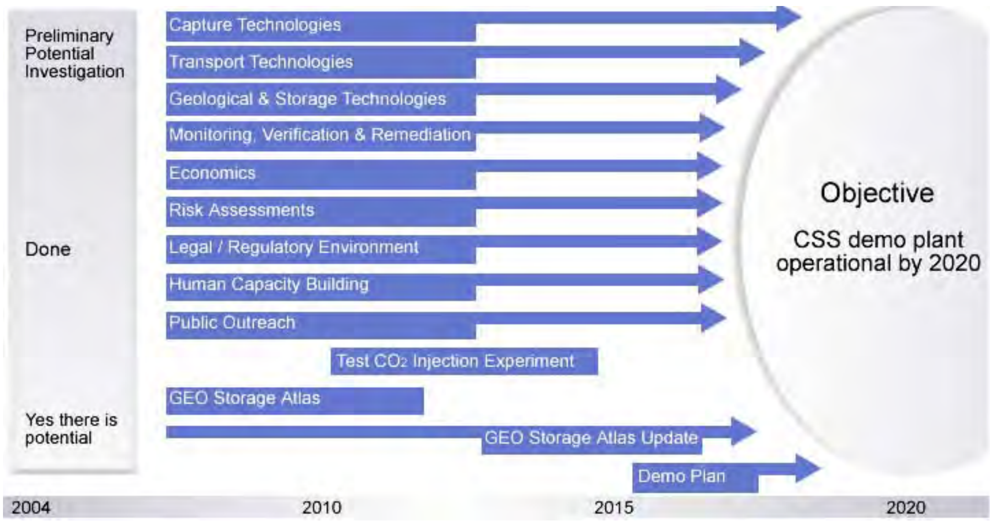

Figure 6 South Africa's Current Progress of CCS

[6] http://www.sacccs.org.za/roadmap/

Japan

The Ministry of Economy, Trade and Industry of Japan released a CCS technology roadmap in 2010 (Figure 8), which was deeply rooted in technology development. The roadmap gave a strong emphasize to cost reduction of various technologies. The capture cost in Japan 2010, was 4, 200 JPY ($52.5)/t-$CO_2$, estimated for new pulverized coal power plants. The target costs by 2015 is 2,000 JPY ($25)/t-$CO_2$, 1,000 JPY ($12.5)/t-CO_2 by 2020. The selected technologies for R&D include chemical absorption for post combustion, physical and chemical absorption for pre combustion, and oxy-fuel.

In addition, Japan CCS Co. Ltd (JCCS) was established in 2008 to carry out comprehensive investigations for large-scale CCS demonstration projects (Figure 9). This entity is comprised of 36 companies (11 electric power, 4 petroleum, 5 engineering, 4 petroleum resource developing, 4 general trading, 2 iron and steel, 2 city gas, 1 chemical, 1 non-ferrous metal and cement, 1 steel pipe, 1 special trading). At this point, JCCS is conducting surveys and studies on three candidate sites for CCS demonstrations.

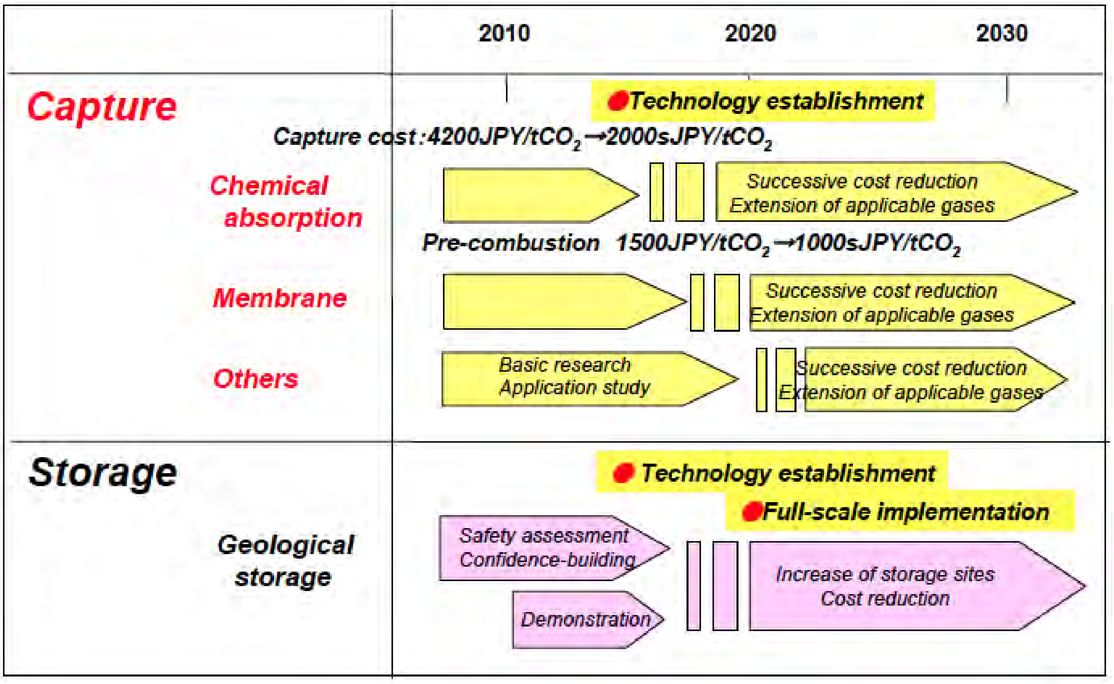

Figure 7 Japan's CCS Technology Strategy Roadmap (Ministry of Economy, Trade & Industry of Japan)

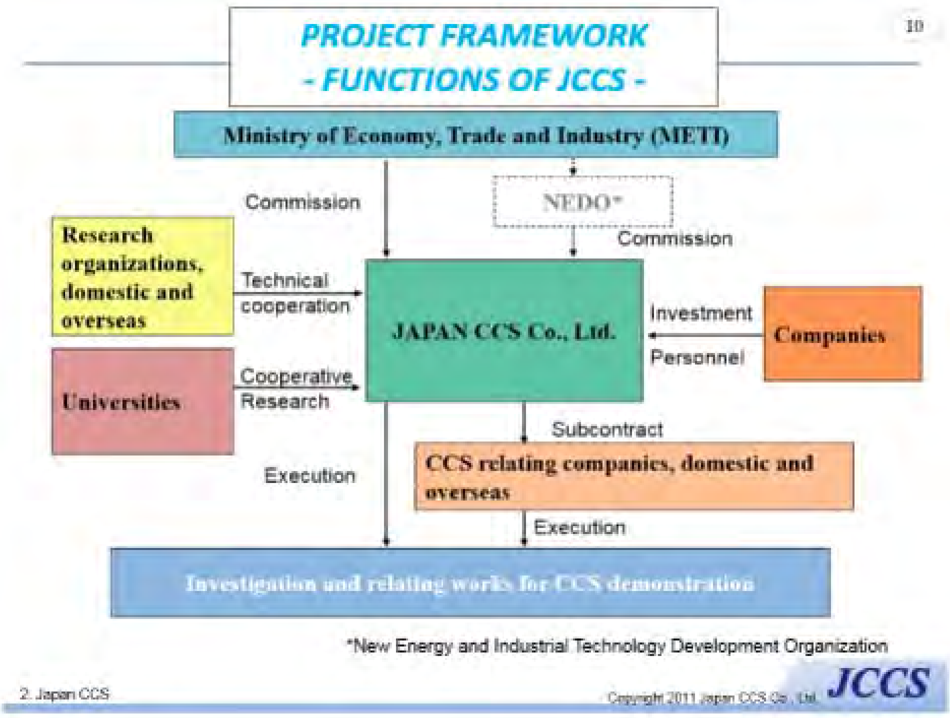

Figure 8 Japan CCS Ltd.

Malaysia

The Global CCS Institute and Clinton Climate Initiative, working with Malaysia's Ministry of Energy, Green Technology and Water, finished a CCS scoping study for this country in 2011. Strictly speaking, this document is not a technology roadmap given that it does not provide the goals and timeline of CCS development in Malaysia from official perspective. This study first provided a rationale for CCS investment in Malaysia; assessed CCS potential in this nation; analyzed CCS costs using information from specific sites in Malaysia; described funding and financial opportunities for emerging nations; and finally, recommended near-term actions.

Results show that CCS can help Malaysia to reduce CO_2 emissions in a long term while securing its energy industry and supply. Other important findings include 1) Malaysia should approach CCS with a long-term perspective to encourage strategic deployment and the potential for an integrated, expanded infrastructure network in the future; 2) CCS costs are broadly competitive with other identified mitigation opportunities and likely to reduce significantly with deployment; 3) early investment in characterization of a storage area is important; 4) retrofit of existing plants is typically more expensive on a unit basis that construction of a new plant, but requires a smaller upfront capital investment; 5) establishing effective financial support mechanisms will be of primary importance to the completion of a project by the private sector and will create incentives for industry to allocate resources to CCS. This study suggests Malaysia should further conduct a storage assessment; to develop CCS planning and implementation strategy; to design strategy for funding access; to review and prepare legal, regulatory, and community acceptance, and to establish a CCS workshop.

Poland

Bellona, an Environmental NGO based in Norway, helped Poland to produce the country's first CCS technology roadmap, named "*Insuring Energy Independence*," in 2011[7]. With goals of achieving future energy independence as well as reducing CO_2 emissions under Europe's new climate legislation, CCS can ensure Poland to freely choose between fossil fuels (primarily coal) or renewable energy in its near and medium term energy mix. This document spent large space modeling what energy needs Poland will have in the next several decades, what would happen under future EU climate policy, and how CCS can fit into different scenarios. Under all three scenarios – and across a wide range of possible EU climate & energy policies – this study shows that widespread CCS deployment in Poland is feasible, and that the activities to commercialize and deploy CCS in Poland are essential to ensure a secure economic future.

Poland can be a regional leader on CCS technologies with its two ambitious demonstration plants at Bełchatow and Kędzierzyn. However, further actions need to be taken: to develop and commercialize CCS technologies in the short term, and to build the best possible future energy sector (widespread deployment of CCS, significant improvement of energy efficiency, and rapid development of renewable energy).

Some updates: Poland has canceled its Bełchatow project and formally rejected EU's new climate policy twice. Speaking after the Energy Council of 22 February 2013, Minister of Environment Korolec said that the EU should abandon costly climate policy, which results in higher energy prices for consumers. Korolec also believes that CCS has no chance to be deployed on commercial scale. He added that the current rules are designed in a way that the heads of companies cannot choose to apply CCS, if the state does not guarantee to cover future losses.[8]

[7] http://www.bellona.org/reports/mapa_drogowa
[8] http://www.bellona.org/articles/articles_2013/1361807050.86

Hungary

Like the Polish CCS technology roadmap, the Norway-based environmental NGO, Bellona Foundation, prepared a CCS technology roadmap for Hungary – "*The Power of Choice*", in 2011[9]. This documents presented that Hungary has a very large CO_2 emissions reduction potential through CCS, given its 33% of CO_2 emissions from energy production, 25% from heavy industry, and sufficient underground CO_2 storage capacity. Hungary was the first country in Europe to undertake CO_2-EOR, which means an infrastructure for CO_2 transport has been in use for decades. However, challenges remain with building a new CCS demonstration, such as technological and financial uncertainties. The report suggests that, with the new EU and national emission reduction targets,Hungary's new national long-term energy planning strategy should provide a strong rationale for CCS. Subsequently, the government should set out an action plan that includes demonstration and deployment of CCS. Besides, the government needs to strategically consider the funding possibilities, and to make CO_2 storage legal.

9 http://www.globalccsinstitute.com/publications/power-choice-ccs-roadmap-hungary

The 2013 IEA CCS Roadmap

The 2013 IEA CCS Roadmap was published in July 2013[10]. It evaluated the global developments in CCS since the 2009 version, sets the vision for CCS deployment between 2013 and 2050, and most importantly recommended actions to facilitate CCS' deployment. This document summarized four major hurdles for CCS, including lack of economic drivers, lack of policy support, technical difficulties, and limited public understanding. This document again indicates that CCS is a critical component in a portfolio of low-carbon energy technologies. Around 30 large operating projects are needed by 2020, providing technology experience and enabling cost reductions. 70% deployment of CCS will need to occur in non-OECD, mainly in China.

The 2013 IEA CCS Roadmap laid out 7 key actions for the next 7 years:

Government

Action 1: Introduce financial support mechanisms for demonstration and early deployment of CCS to drive private financing of projects.

Action 2: Implement policies that encourage storage exploration, characterization, and development for CCS projects.

Action 3: Develop national laws and regulations as well as provisions for multilateral finance that effectively require new-build, based-load, fossil fuel power generation capacity to be CCS-ready.

Action 4: Significantly increase efforts to improve understanding among the public and stakeholders of CCS technology and the importance of its deployment.

Action 5: Encourage efficient development of CO_2 transport infrastructure by anticipating locations of future demand centers and future volumes of CO_2.

Industry/RD

Action 6: Reduce the cost of electricity from power plants equipped with capture through continued technology development and use of highest possible efficiency power generation cycles.

[10] http://www.iea.org/publications/freepublications/publication/name,39359,en.html

Industry

Action 7: Prove capture systems at pilot scale in industrial pilot applications where CO2 capture has not yet been demonstrated.

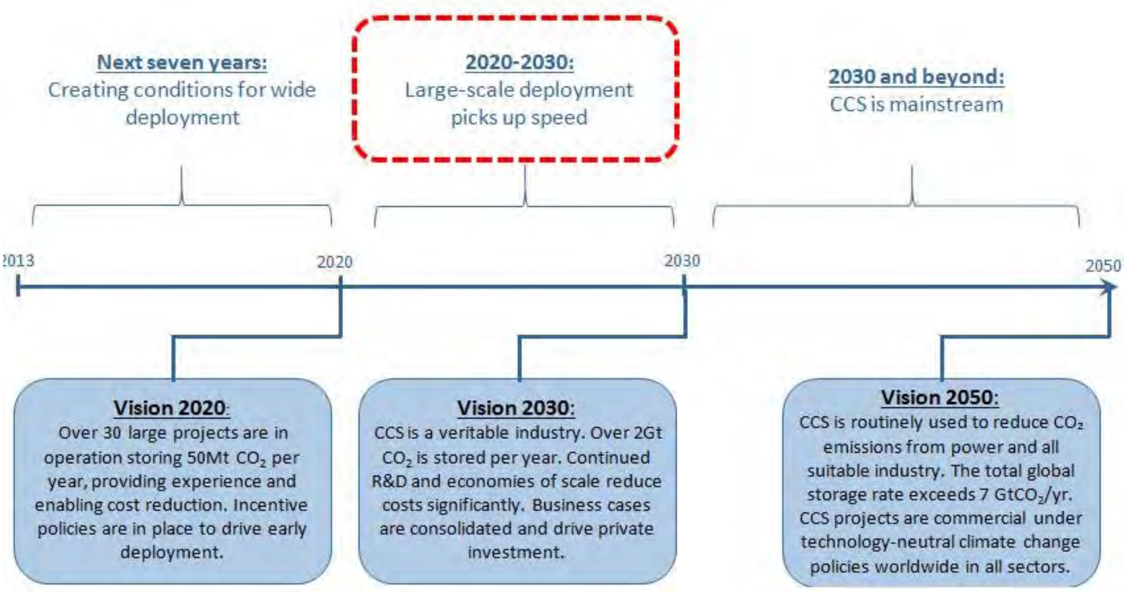

Figure 9 A Pathway for Wide Deployment of CCS

China

The Department of Social Development and the Administrative Center for China's Agenda 21 of the Ministry of Science and Technology of China developed China's first CCUS technology roadmap in 2011. This roadmap outlines the vision for the development of CCUS in China – providing technically viable and affordable options to combat climate change and facilitate the social-economic sustainability. It also has specific plans for three periods (by 2015, by 2020, and by 2030), and for specific technologies (capture, transportation, utilization, and storage) (Figure 11).

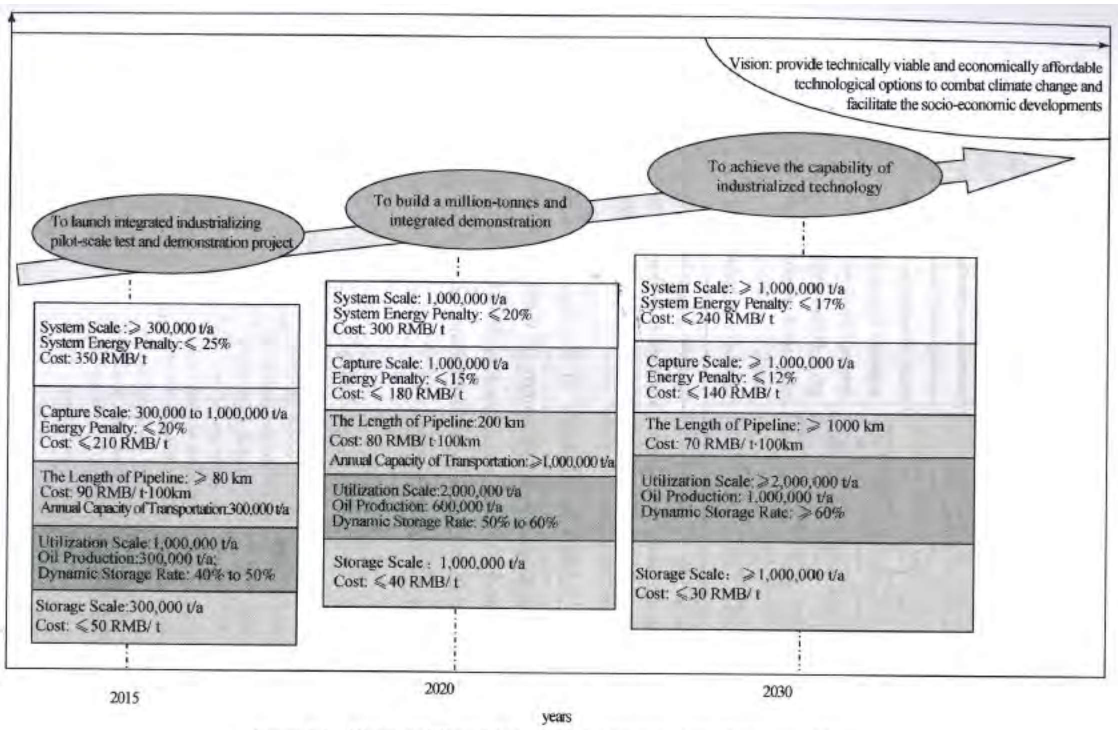

Figure 3-1 Vision and Phased Goals: CCUS Technology Development in China

Figure 5 Vision and Goals: CCUS Technology Development in China

This document presented China's efforts to achieve these goals, including all governmental programs. The public funded R&D activities on CCUS are mainly administered from the Ministry of Science and Technology and Natural Science Foundation of China, and through several national science and technology programs (National Basic Research 973 Program and National High Technology Development 863 Program). Technology status from capture to storage was also described in this roadmap in detail. Recommendations were made for R&DD and further deployment. For the stage of RD&D, this roadmap recommended to establish a coordination mechanism among CCUS-relevant stakeholders, to develop administrative regulations for CCUS demonstration projects, to enhance national financial support for RD&D activities, to strengthen the training for and introduction of related professionals, etc. To build a solid foundation for future deployment, research on laws and regulations needs to be done; better understanding on research collaboration among industrial chain needs to be built; financing and investment needs to be looked into; research on Intellectual Properties need to be conducted.

ADB CCS Roadmap for Demonstration in PRC

In 2011, the Asian Development Bank (ADB) supported China's National Development & Reform Commission (NDRC) to conduct a roadmap study for CCS demonstration, by using GreenGen as a case. This report included a CO_2 capture and storage demonstration strategic analysis. In addition, this project provided a view of the present level of preparedness for a CCS demonstration, identified technological, scientific gap and regulatory readiness, planed capacity building in all aspects of the CCS chain. It is worth noting that this document is not an official CCS roadmap for China and focuses at the demonstration scale.

CCS is considered as one of the important options to reduce CO_2 emissions in the future China's future energy mix in this document. The primary outcome of this report is "the Guideline for the Implementation of CCS." The guideline includes seven-phase implementation for a CCS project in China, including preparation, feasibility study, appraisal & approval, implementation, operation & monitoring, evaluation & closure, and post-closure management (see Figure 12). By describing major tasks and identifying relevant stakeholders in each stage, this guideline offers China's decision-makers and other stakeholders a comprehensive picture of the essential steps for a CCS demonstration project (Table 4).

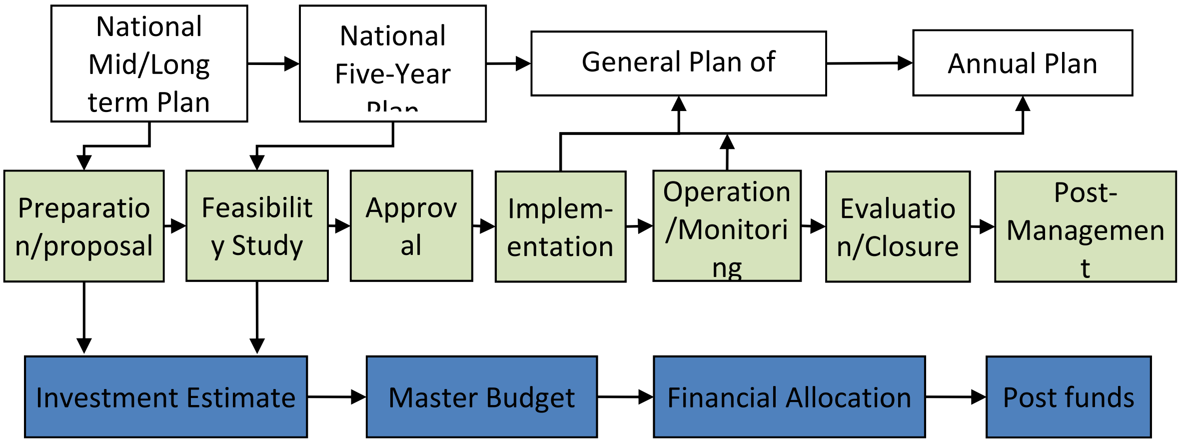

Figure 10 7-Phase Implementation procedure for a CCS demonstration project

Phase	Descriptions	Stakeholders
Preparation	- Perform preliminary study • *background information to be fully aware of topic* • *potential technical pathways* • *preliminary analysis on potential capture sources, storage sites, and available technology* • *risk/liability* • *Stakeholders consultation on FS Report* • *business partners and organization structures* • *limitations of the project* - Pre-feasibility report & proposal for permission - Approval of advancing to Feasibility Study	Project developer, national authorities (e.g. NDRC, MOST), investors
Feasibility Study	- Establish or entrust an executive agency - Entrust the consultant agencies - Convene project starting workshop - Capture-related feasibility study • *Survey and select a capture site – i.e. brown vs. Greenfield, national to local location, etc* • *Survey and Select plant type – IGCC, Post-Combustion coal power, NGCC, CTL, Coal Chemical, etc.* • *Research and decide on capture specifications and conditions – capture rate, capture technology, CO2 purity, etc.* - Storage-related feasibility study • *Regional survey of potential storage areas and select location(s)*	Project developer, engineering firms, investors, government authorities, public

- *Initial storage site geological characterization – subsurface mapping, geo models, injectivity estimates, containment estimates, capacity estimates from old data and new well logs, cores, and seismic imaging, or others.*

- *Storage plan - EOR vs. Saline Aquifer, storage capacity, CO_2 composition and pressure standards*

Initial economic estimates, risk assessment (including existing well and fault identification), monitoring plan, and remediation plan

- Transport-related feasibility study

- *Source-sink matching between selected &/or potential capture and storage sites to select optimal pair and potential routes*

- *transport method: pipeline vs. ship vs. truck*

- *Regulation issues on transport requirements – CO2 purity, pipeline materials, spacing of emergency shut-off valves, max/min pipeline pressure, pipeline burial depth, type of warning system, etc*

- *Transportation technology and materials*

- *Route design for pipeline*

- Environmental feasibility study

- *Assess environment impacts of CCS chain*

- Public acceptance feasibility study

- *Public communication and consultations*

- *Knowledge awareness promotion together with gov't.*

- Economics & Financial feasibility study

- *Cost estimates for best/worst/expected case scenarios – includes capital survey, characterization, & construction costs, increased cost of electricity, cost of injection, cost of accident remediation, cost of operation and maintenance, monitoring, etc.*

- *Cost-benefit assessment of the project*

- *Financial evaluation of resources necessary to operate the full project and manage post-operation costs as well as cover "insurance" in case of accidents*

- *Evaluate possible financing sources and reach out to identified financiers*

- *Prepare project investment plan and statements*

Prepare financial letters of intent from all financiers

- Project management & business organization structure

	• *Formation of the project owner & developer/operator* • *Organizational chart, employment predictions, and training programs* • *Measures to take for worker protection, health, and safety* • *Implementation/project plan* - Legal & regulatory feasibility study • *Study policies for CCS internationally* • *Examine existing laws for applicability* *Recommend policies needed from policy makers in order to make the project and subsequent projects viable* - Compile and present feasibility study report	
Appraisal & approval	- Form independent project appraisal committee - Local gov't & public consultations on capture site - Assess and permit land use plan for capture site, storage site, right of way for pipeline or other transportation form route - Assess and permit environment impact analysis report - Approvals of water consumption for plant and water protection at the pipeline and storage sites - Approval from government agencies for financial assistance， foreign capital investment， loan schemes from banks， etc - Issue special regulations or policies to fill in for legal and regulatory gaps - Form independent regulatory institution - Establish business and/or prepare business license & registration - Organize and supervise signing the letter of intent or contracts between main stakeholders - Issue licence for project design and construction	Project developer, third party assessor, government authorities
Implement-ation	- Establish project headquarter - Entrust project consultant agencies - Secure capital and operation funds - Project preliminary design and construction document design • *Capture facilities (plant) design* • *Pipeline route (networks) design* • *Infrastructure design for storage site* • *Injection well design & injection strategy design* - Approval of construction document - Site characterization – test injections to determine "Proved Storage Capacity"	Design engineering and construction companies, project developers etc.

	sufficient for planned storage volume - Update and optimize geo and simulation models - Develop project execution plan - Cost budget & control plan - Quality assurance and control plan - Schedule control plan - Human resource management plan - Risk analysis, monitoring and control plan - Procurement and contract administration plan - Security assurance and control plan - Final accounts, audit and transfer plan - Construction and monitoring	
Operation & monitoring	- Entrust or form project operator - Transfer control rights of assets - Measurement, monitoring, and validation plan - Contingency migration and remediation plan - Detailed injection plan (timing and staging) - Surface and groundwater monitoring plan - Stream purity, dehydration and corrosion control plan - Caprock, surface bulge, seismic activity and CO_2 plume monitoring plan - Operational logging and data collection inform operations plan - Geological model updating and implementation change plan - Regularly report on financial, technical, risk analysis, etc	Project developer and owner, engineering and construction companies, government authorities
Evaluation & closure	- Propose project closure proposal - Convene independent assessment committee - Conduct comprehensive environment safety and human non-endangerment assessment - Conduct long-term risk assessment of storage site - Conduct subsurface assessment for wellbore integrity - Conduct well plugging and abandonment feasibility assessment - Conduct assessment on post-monitoring, maintenance, contingency migration, and remediation plans - Entrust or form long-term administration entity - Record and register project lifetime data to public database	Project developer, operator, storage site monitoring and management firms, government authorities etc

	- Transfer assets and responsibility from operator to long-term administration entity - Certification of site closure	
Post-closure management	- Make and execute monitoring, maintenance, contingency migration, and remediation plans for the closed site - Conduct periodic measurement, monitoring, validation of closed site - Record and register site monitoring data - Long-term funding management and new mechanism development - Research on geological reuse of the closed site	storage site monitoring and management firms, government authorities etc

Table 3 Definition of contents of each phase for the CCS project

At the end, recommendations were made. Major recommendations include one or more integrated CCS project needed for China to master the CCS technologies in the Chinese context: for example, an IGCC-CCS demonstration can be one of the earliest starting choices; and establishing an electricity tariff or tax reduction to encourage project owners. At last, a coordinated national program is also recommended to integrate governmental support and share the experiences. Government leadership is critical in the early stage of CCS demonstration in China.

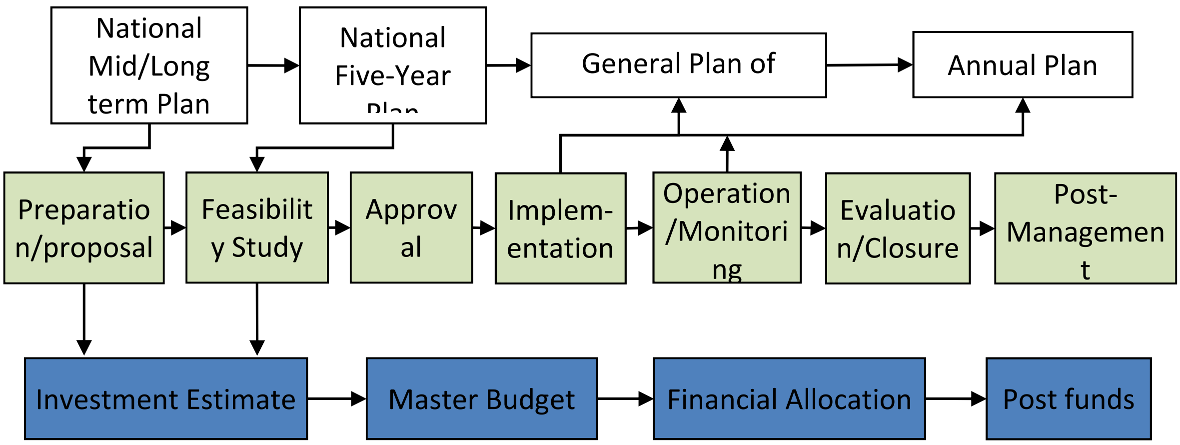

Figure 6 7-Phase implemention procedure for a CCS demonstration project

Summary and Conclusions

Roadmaps share a similar vision, while are diverse in contents.

All the CCS roadmaps share a similar vision – to speed up the development and deployment of CCS technologies in the next 20 and 30 years. However, each country has its own preferred approaches as well as own style of presenting its contents. The US and Canada's CCS roadmaps clearly have the highest quality in terms of scientific evaluation of CCS technologies in their own country and R&DD policy planning to achieve future commercialization. They provide the highest level of engineering information of each component of CCS and associated economic and police issues. For example in the 2011 US roadmap, the R&D timetables for each technology, capture technologies, storage technologies, utilization technologies, are precise to the level of a year. In addition, both the Canadian and US roadmaps introduced all government programs related to the CCS development, including the funding sources and amount. Overall, both nations' CCS roadmap can be regarded as a scientific work plan, in addition to a deployment roadmap.

The UK's roadmap focuses on introducing its government programs in CCS RD&D based on a core message – the government intervention is essential in the CCS development. For example, the UK government established a public-private Special Taskforce to work on the cost reduction of CCS technologies. Australia's CCS Roadmap is integrated into the national hydrogen economy plan. Additionally, Australia's document specifically mapped all the stakeholders in the CCS value chain in the next 20-30 years. The Canadian's approach emphasizes the full-integrated CCS system. Most interestingly, the Canada laid out the most complete policy approach, including policy and regulatory frameworks, public outreach and education, technology watch and international collaboration, science and technology R&D, demonstration, and national coordination. The South African CCS roadmap lacks detail of implementation, which is covered in separate work plan documents for each of the five major steps. Three work plans are available at this point.

The CCS Roadmaps produced by Bellona for Poland and Hungary and the Malaysia CCS scoping study prepared by Global CCS Institute and Clinton Climate Initiative have some common characteristics. By using modeling techniques, the three international organizations are trying to give the nations a future energy picture in which CCS is an essential component.

Institutional settings and implementation of Roadmap

1) Roadmaps are usually not official government documents, and do not necessarily be endorsed formally.

Table 1 clearly identifies the organization that authored the various roadmaps as well as topics covered and date of release. The authors of the selected CCS roadmap fall into three categories:

- government itself,
- agency affiliated with government
- and NGOs.

Unfortunately not all of the roadmaps were formally endorsed and the process for developing them is not generally included in the document itself. It may be interesting to investigate the institutional setting of these roadmaps, while it is outside the scope of this report that can be done without substantial additional effort via interviews, etc. Because of the long time period since the release of some of these roadmaps, such interviews may not even be possible. What is clear based on this analysis is that roadmapping efforts are undertaken by a variety of types of institutions with varying scopes and styles.

2) Implementation is often unrelated roadmap design and depends on a series of external factors. And unlike official government plans, there is usually no mandate to implement the roadmaps.

In many cases, the implementation of roadmap has nothing to do with the roadmap content, process or structure. There is a great variety in timing and types of roadmaps reviewed in the report. For example, unlike CCS technology roadmaps prepared by their own government or governmental-research institutes, CCS Roadmaps produced by

Bellona for Poland and Hungary and the Malaysia CCS scoping study prepared by Global CCS Institute and Clinton Climate Initiative omitted the details of technological status in these countries and thus, failed to provide comprehensive technology plans for R&D stage, demonstration stage, and deployment stage, respectively. None of these nations have closely followed the actions proposed by these CCS roadmaps. Please see the Table 4 for the overall large-scale integrated project implementation of the selected nations. Table 5 provides a summary of roadmap adoption/implementation according to country.

Nation	Identify (Planning)	Evaluate (Planning)	Define (Planning)	Execute (Construction)	Operate (Operation)
Australia	0	3	1	0	4
Canada	0	1	1	4	1
China	6	3	3	0	0
Hungary	0	0	0	0	0
Poland	0	0	0	0	0
South Africa	0	0	0	0	1
UK	0	5	1	0	0
US	0	5	6	2	7

Table 4 Large-scale Integrated CCS projects of selected countries in this document (GCCSI, 2013) (Large scale integrated CCS projects are defined as those which involve the capture, transport, and storage of CO2 at a scale of at least 800, 000 tonnes of CO2 annually for a coal-base power plant or at least 400,000 tonnes of CO2 annually for other emission-intensive industrial facilities)

Jurisdiction	**Roadmap Author**	**Number of Commercial-scale demonstrations (according to GCCSI, and not necessarily tied to roadmap)**	**Roadmap adoption/implementation**
International	International Energy Agency	65	Uncertain/TBD
Australia	CO2CRC, a government research organization	4	Progress of CCS demonstrations/deployment may be lagging behind the originally envisioned goals.
Canada	Canmet Energy Technology Center	7	Appears to be in implementation although there is no direct link to roadmap and project implementation.

China	Ministry of Science and Technology; ADB for GreenGen	12	MOST roadmap was endorsed and put in to action via the *Special S&T Plan for CCUS development in China in the 12th 5-year Plan*. The GreenGen-specific roadmap's implementation is TBD.
UK	Department of Energy and Climate Change	6	Although policy action supporting and funding CCS projects in the UK has been aggressive, project selection/construction has proven difficult.
US	NETL, a government research organization	20 (7 operating)	The roadmap is the official document for DOE's RD&D program and CCS demonstration in the US has followed it.
South Africa	SACCS, a government research organization	0	The roadmap is being used by SACCCS and the government to guide research and the test injection.
Poland	Bellona, a Norway-based Environmental NGO	0	Roadmap has not been endorsed or implemented.
Hungary	Bellona, a Norway-based Environmental NGO	0	Roadmap has not been endorsed or implemented.

Table 5 Summary of Roadmap implementation according to country

Perhaps the best example of implementation example comes from China regarding implementation of the CCUS Roadmap. After release of the CCUS Roadmap of China by department of social development of the ministry of science (MOST) and the administrative centre for China's agenda 21 in 2011, MOST issued a *Special S&T Plan for CCUS development in China in the 12th 5-year Plan*[11]. This special plan is mainly

[11] The plan could be found at: http://www.most.gov.cn/tztg/201303/t20130311_100051.htm

based on and follows the outcome of previous roadmap and will be implemented by MOST and other government departments. Several National S&T projects funded by MOST could be found now.

What China can learn?

Learning from these roadmaps, China's national CCS roadmap should achieve some basic criteria. The roadmap should be scientific, comprehensive, manageable, and flexible. China's CCS roadmap should use the US and Canada's CCS RD&D roadmap as references:

- Scientific & Manageable - Collecting background information regarding China's CCS technology development status and the country's energy infrastructure for CCS deployment as detailed as possible. Therefore, the roadmap is realistic and manageable.
- Comprehensive – Building a holistic technology and policy approach as well as mapping all the stakeholders in the roadmap. A public-private partnership is essential.
- Flexible – Given that the technology innovation is a dynamic process, China's national development might need to be changed accordingly.
- Inclusive – Integrating the RD&D program and goals with the policy framework necessary for deployment will help establish realistic milestones for China's demonstration and deployment of CCS.

A template is built in this memo (Table 2). The Structure of China's 2011 CCS Roadmap is:

1. Introduction
2. Current Status and Challenges
    - Basics for Development of CCUS in China
    - Current efforts
    - Assessment of technologies
3. Visions and Goals
4. Prioritized Technologies and Actions
    - Capture
    - Transportation
    - Storage
    - Strategy for Full-Chain CCUS Demonstration and Deployment
5. Supporting Policies

Overview	China's CCS Development Status and overall goals (Australia, Canada, US, UK, South Africa)
	China's current CCS related research programs (Australia, Canada, US, UK, South Africa)
	China's context for acting on climate change and co-benefits for local air pollution (IEA, Poland, Hungary)
	International Cooperation & Interagency Cooperation (Australia, Canada, US, UK)
Large-scale integrated projects	China's CCUS demonstration Program (US, IEA)
	International CCS/CCUS demonstrations at various scales (US)
Policy, Regulatory, & Market	National Policy & Regulatory Frameworks (Canada, UK, US)
CO_2 Capture	Pre-combustion 1. Current national and international status (IEA, Japan) 2. Cost & performance issues (Australia, US) 3. The Role of R&D (US, Canada) 4. The R&D Progress over time (US) 5. The R&D targets and goals (US)
	Post-combustion 1. Current national and international status 2. Cost & performance issues 3. The Role of R&D 4. The R&D Progress over time 5. The R&D targets and goals
	Oxy-combustion 1. Current national and international status 2. Cost & performance issues 3. The Role of R&D 4. The R&D Progress over time 5. The R&D targets and goals
CO2 Transport & Storage	CO2 Transportation (Canada, the US)
	CO2 Storage (Canada, the US)
	Monitoring, Verification, & Accounting (Canada, the US)
	Simulation & Risk Assessment (Canada, the US)
CO_2 Utilization	Enhanced resource recovery (EOR, ECBM) (US)
	Utilization in useful products such as cements, plastics, and algal fuels (US)
Outreach	Public engagement & education (Canada, UK, US)
	Future International Collaboration (Canada, UK, US)

Table 1 The Template for China's CCS Roadmap

Related sources

Australia: www.cslforum.org/publications/documents/SaudiArabia/T2_3_CSLF_PJC_DVP_Australia

Canada: http://ccs101.ca/ccs_pro/canadas_ccs_roadmap

USA: www.netl.doe.gov/technologies/carbon_seq/refshelf/Program-Plan-Carbon-Storage-092013.pdf

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

South Africa: www.sacccs.org.za/roadmap/

Poland: www.bellona.org/reports/mapa_drogowa

Hungary: www.bellona.org/articles/articles_2013/1361807050.86

IEA: www.iea.org/publications/freepublications/publication/name,39359,en.html

www.ccusChina.org.cn