International Journal of Greenhouse Gas Control 4 (2010) 396–409

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Accelerating the deployment of carbon capture and storage technologies by strengthening the innovation system

Klaas van Alphen[a,*], Marko P. Hekkert[a], Wim C. Turkenburg[b]

[a] Department of Innovation Studies, Copernicus Institute for Sustainable Development and Innovation, Utrecht University, P.O. Box 80115, 3508TC Utrecht, The Netherlands
[b] Department of Science, Technology and Society, Copernicus Institute for Sustainable Development and Innovation, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

ARTICLE INFO

Article history:
Received 28 April 2009
Received in revised form 21 September 2009
Accepted 28 September 2009
Available online 3 November 2009

Keywords:
Functions of innovation systems
Carbon dioxide capture and storage
Research, development and demonstration
Innovation policy
Energy transition
Climate change mitigation

ABSTRACT

In order to take up the twin challenge of reducing carbon dioxide (CO_2) emissions, while meeting a growing energy demand, the potential deployment of carbon dioxide capture and storage (CCS) technologies is attracting a growing interest of policy makers around the world. In this study we evaluate and compare national approaches towards the development of CCS in the United States, Canada, Norway, the Netherlands, and Australia. The analysis is done by applying the functions of innovation systems approach. This approach posits that new technology is developed, demonstrated and deployed in the context of a technological innovation system. The performance assessment of the CCS innovation system shows that the extensive knowledge base and knowledge networks, which have been accumulated over the past years, have not yet been utilized by entrepreneurs to explore the market for integrated CCS concepts linked to power generation. This indicates that the build-up of the innovation system has entered a critical phase that is decisive for a further thriving development of CCS. In order to move the CCS innovation system through this present difficult episode and deploy more advanced CCS concepts at a larger scale; it is necessary to direct policy initiatives at the identified weak system functions, i.e. entrepreneurial activity, market creation and the mobilization of resources. Moreover, in some specific countries it is needed to provide more regulatory guidance and improve the legitimacy for the technology. We discuss how policy makers and technology managers can use these insights to develop a coherent policy strategy that would accelerate the deployment of CCS.

1. Introduction

Energy experts now widely agree that carbon dioxide capture and storage (CCS) is indispensable in any credible CO_2 emission reduction portfolio, as CCS features prominently in all the main blueprints for reducing GHG emissions until 2050 (IEA, 2008a; IPCC, 2007). As well as being supported by the scientific community, CSS has attracted great interest from world leaders, particularly those whose countries depend heavily on fossil fuels for secure (coal based) electricity generation and export income, notably Western Europe, Australia, Canada and the US.

Despite the acknowledged urgency to demonstrate CCS technologies (see e.g., G8, 2008) and the increasing amount of funding, no fully integrated power plants with CCS have yet been built at commercial scale (de Coninck et al., 2009). In terms of deployment the past years have not been encouraging, as several flagship projects have been cancelled or postponed because of various reasons, including Statoil's Halten project in Norway, Saskpower's oxyfuel plant in Canada, Hydrogen Energy's CCS project in Kwinana (Australia), and the FutureGen project in Illinois (US) (Hawkins et al., 2009).

The rethinking of these high-profile CCS projects – which often have been portrayed as the gateway to a cleaner and secure energy future – outlines that new technologies, like CCS, are often not able to negotiate the various market and institutional barriers that confronts them (Murphy and Edwards, 2003). It shows that substantial investments in technological R&D and demonstration do not necessarily lead to successful innovations. Given the prominent role that CCS is now taking in global attempts to attain climate mitigation goals, it is essential to gain more insight in the CCS innovation process to investigate whether handholds for successful support strategies can be developed.

Failures in the market and new insights obtained from innovation theory deepen our understanding of innovation processes. Scholars such as Nelson and Winter (1977), Kline and Rosenberg (1986), Lundvall (1992), Freeman (1995), emphasised that organisations are not innovating in isolation but in the context of an innovation system. The basic idea of a technological innovation system is that the innovation process is strongly influenced by a network of actors that are developing, advocating

---

[*] *Corresponding author.* Tel.: +31 30 2537484; fax: +31 30 2532746.
E-mail address: k.vanalphen@geo.uu.nl (K. van Alphen).

1750-5836/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijggc.2009.09.019

Table 1
Functions of technological innovation systems (Hekkert et al., 2007).

F1. Entrepreneurial activity	At the core of any innovation system are the entrepreneurs. These risk takers perform the innovative (pre-)commercial experiments, seeing and exploiting business opportunities.
F2. Knowledge development	Technology R&D are prerequisites for innovations, creating variety in technological options and breakthrough technologies.
F3. Knowledge diffusion	This is important in a strict R&D setting, but especially in a heterogeneous context where R&D meets government and market.
F4. Guidance of the search	This function represents the selection process that is necessary to facilitate a convergence in technology development, involving policy targets and expectations about technological options.
F5. Market creation	This function comprehends formation of new (niche) market by creating temporary competitive advantage through favorable tax regimes, consumption quotas, or other public policy activities.
F6. Resource mobilisation	Financial and human resources are necessary inputs for all innovative activities, and can be enacted through, e.g. investments by venture capitalists or through governmental support.
F7. Creation of legitimacy	The introduction of new technologies often leads to resistance from established actors, or society. Advocacy coalitions can counteract this inertia and lobby for compliance with legislation/institutions.

or opposing the technology and by an institutional infrastructure that legitimizes, regulates and standardizes the new technology (Carlsson and Stankiewicz, 1991). A well performing innovation system accelerates technological development, while a poorly functioning innovation system hampers technological innovation (Hekkert and Negro, 2008).

Over the past few years further progress has been made in determining key processes, also known as system functions, that need to take place in innovation systems in order to perform well (see e.g. Hekkert et al., 2007; Bergek et al., 2008). These system functions are decisive processes that foster the shaping and development of a technology (Edquist, 2004). In earlier empirical work, this systems functions approach has been used effectively to deliver explanations for the success or failure of technological trajectories of sustainable energy technologies in various countries (see e.g. Jacobsson and Bergek, 2004; Foxon et al., 2005; Negro et al., 2007; van Alphen et al., 2008; Jacobsson, 2008; Suurs and Hekkert, 2009).

This study applies the functions of innovation systems framework to create insight into the wide range of processes that drive or hamper the development of CCS technologies in the United States, Canada, Norway, the Netherlands, and Australia. Furthermore, we aim to demonstrate how these insights can be useful to technology managers that wish to accelerate the development and deployment of CCS by strengthening the performance of the CCS innovation system.

The remainder of this article is structured as follows: Section 2 outlines the analytical framework and methods, which are applied in Section 3 to analyze and compare the performance of the CCS innovation systems. Section 4 identifies policy and management strategies; and Section 5 contains a concluding discussion.

2. Analytical framework and methods

There has long been a misconception that the process leading from invention to a new product is linear, starting with basic research, followed by applied R&D or demonstration, and ending with production and diffusion. The different stages of the linear model of innovation were considered as separate, both in terms of time and in terms of the actors and institutions involved. The technological innovation systems (TIS) approach, and the broader innovation literature it stems from (i.e. Lundvall, 1992; Freeman, 1995), rejects this model. Instead, it stresses that technological innovation involves continued interaction between numerous processes, with R&D, production and market formation all running in parallel and reinforcing each other through positive feedback mechanisms (Smits, 2002). If such feedbacks are neglected, whether by policy makers or entrepreneurs, this might as well lead to the development of undesirable technologies or the absence of technological development altogether (Klein Woolthuis et al., 2005).

A TIS is defined to comprise networks of actors (organisations) that operate under a particular institutional infrastructure (norms, regulations) and whose actions and interactions contribute to the development and diffusion of a new technology (Carlsson and Stankiewicz, 1991). For CCS, such a system needs to be built up in order to make successful demonstration and large-scale deployment possible. The TIS literature provides insights in the dynamics of this build-up process (Hekkert et al., 2007). This is done by studying a set of seven key activities or “system functions”, each of which covers a particular aspect of technological innovation, namely entrepreneurial activities, knowledge development, knowledge diffusion, guidance, market creation, resources mobilization and the creation of legitimacy (see Table 1 for definitions).

To some extent, system functions need to be realized simultaneously, since they can complement, or reinforce each other (Suurs and Hekkert, 2009), but an innovation system may very well collapse due to the absence of a single system function. For example, Kamp (2002) has shown that the Dutch wind energy innovation system was well developed in the 1980s but collapsed due to the absence of knowledge exchange between the emerging turbine industry and users, the latter being mainly energy companies. So, there may be particular (combinations of) functions that drive or block the growth of a specific technological innovation system. Therefore the seven system functions are considered a suitable set of criteria for the performance assessment of emerging CCS innovation systems in the US, Canada, Australia, the Netherlands and Norway.

2.1. Methods

In order to ascertain to what extent the functions of innovation systems have been fulfilled, we conducted semi-structured interviews with the main actors involved in the development of CCS in all the five countries under study. Hereby we made use of a number of indicative questions that provide insight in the fulfilment of the above TIS functions as they relate to the development and deployment of CCS technologies (see Table 2). The results of the interviews are verified and complemented by additional literature review of scientific as well as “grey literature” (e.g. professional journals, financial yearbooks, roadmaps and policy papers).

In total, more than a hundred interviews have been conducted with senior representatives from industry, research, government and environmental groups. Also, within stakeholder groups variety was sought (e.g. researchers involved in both capture and storage technologies; and representatives from natural resource companies as well as electric utilities; and policy makers at various government levels). With cross-referencing as well as external justification, the validity of the group of interviewees was guaranteed.

To minimise the personal bias of the researchers and to further assess the system’s performance, we have let interviewees reflect upon the ongoing activities in the system. The interviewees have been asked to rate their level of satisfaction with the fulfilment of a particular system function on a 5-point Likert scale where 1 = very weak, 2 = weak, 3 sufficient, 4 = good and 5 = very good. The respondents gave their view on what should be done to improve the fulfilment of those system functions that were seen as impeding a higher performance of the entire CCS innovation system. This provides the basis for advice on policy strategies to enhance the development of deployment of CCS.

3. Results

This section describes the fulfilment of the seven system functions in the Netherlands, Norway, Canada, the US, and Australia, and discusses the performance evaluation made by the 100 key-stakeholders that have participated in this study.

3.1. Entrepreneurial activity

Canada and Norway are hosting three of the four complete, end-to-end commercial CCS facilities in the world today (Dooley et al., 2009).[1] At Statoil's offshore Sleipner West gas field on the Norwegian continental shelf, 1 $MtCO_2$ is separated and injected into the Utsira saline formation each year, since 1996 (Torp and Gale, 2004). Twelve years later, Statoil started its Snøhvit project, whereby 0.7 $MtCO_2$/year is separated from a liquefied natural gas production facility and stored into a deep saline formation 2600 m below the seafloor (Estublier and Lackner, 2009). In Canada 1–2 $MtCO_2$ is injected annually to enhance oil recovery from the Weyburn field, since 2000. The CO_2 that is used in this project is a by-product from synthetic methane production at a coal gasification plant, located 325 km south of Weyburn, in North Dakota (US) (Preston et al., 2005). Since Sleipner, many smaller CCS projects have commenced in the countries that are the focus of this paper. For example, the Callide A oxyfuel project in Australia; the Frio Brine and Mountaineer CO_2 storage projects in the US; the offshore K12-B enhanced gas recovery project in the Netherlands; the CANMET Oxyfuel pilot plant in Canada; and the Zero Emission Norwegian Gas project in Norway. However, CCS projects of similar scale as Weyburn, Sleipner and Snøhvit, currently only exist in project plans (see Table 3).

Most experts interviewed for this study recognize the value of the significant amount of CCS pilot projects that have been carried out, or are still planned in the countries under study, and confirm the rapidly increasing amount of (industrial) organizations involved in these CCS projects. However, with an average score of 2.9, this function scores relatively low compared to the other functions. The latter can be explained by the relatively slow progress of CO_2 capture technologies compared to the experience gained in large-scale CO_2 storage facilities. It is argued that projects like Weyburn and Sleipner, have shown the world what is possible in terms of storage, and that this has triggered many other governments and enterprises to engage in CCS projects. However, most of the experts surveyed, would like to see that more entrepreneurs to take up CCS projects related to power production.

In contrast to the current storage projects, which make use of CO_2 from relatively pure industrial CO_2 streams, CO_2 capture from power plants is hardly tested at scale. The present high costs of power production with CCS are one of the main barriers to its application. Next to high prices for capture equipment, the energy penalty as well as the possible loss of availability of the power plant are important cost factors. It is argued by a large number of experts participating in this study that is too early to "pick winners" and that all three capture options – i.e. post-combustion, pre-combustion and oxy-combustion – should be demonstrated at pilot and commercial scale to advance technological learning and bring down the costs. Besides demonstrating capture facilities into new power plants, most of the interviewees point out that more efforts should be made to deploy retrofit options for existing power plants.

Table 2
Indicative questions that reflect the extent to which each function in the innovation system is fulfilled by the components of the system (see also Hekkert et al., 2007; Bergek et al., 2008).

F1: Entrepreneurial activity
The number and the degree of variety in entrepreneurial experiments?
The number of different types of applications?
The breadth of technologies used and the character of the complementary technologies employed?
The number of new entrants and diversifying established firms?

F2: Knowledge creation
The number and degree of variety in RD&D projects?
The type of knowledge (scientific, applied, patents) that is created and by whom?
The competitive edge of the knowledge base?
The (mis)match between the supply of technical knowledge by universities and demand by industry?

F3: Knowledge diffusion
The amount and type of (inter) national collaborating between actors in the innovation system?
The kind of knowledge that is shared within these existing partnerships?
The amount, type and 'weight' of official gatherings (e.g. conferences, platforms) organized?
Configuration of actor-networks (homo, or heterogeneous set of actors)?

F4: Guidance
Amount and type of visions and expectations about the technology?
Belief in growth potential?
Clarity about the demands of leading users?
Specific targets or regulations set by the government or industry?

F5: Market creation
What phase is the market in and what is its (domestic & export) potential?
Who are the users of the technology how is their demand articulated?
Institutional stimuli for market formation?
Uncertainties faced by potential project developers?

F6: Resource mobilization
Availability of human capital (through education, entrepreneurship or management)?
Availability of financial capital (seed and venture capital, government funds for RD&D)?
Availability of complementary assets (complementary products, services, network infrastructure)?
Level of satisfaction with the amount of resources?

F7: Legitimization
Public opinion towards the technology and how is the technology depicted in the media?
What are the main arguments of actors pro or against the deployment the technology?
Legitimacy to make investments in the technology?
Activity of lobby groups active in the innovation system (size and strength)?

In relation to power production with CCS, quite a few interviewees (particularly in North America) mention a lacking business interface between the producers of CO_2 – i.e. electric utilities – and those who will be injecting it into the subsurface; mainly oil and gas companies. According to Hawkings (2009), this role could be fulfilled by the CO_2 transportation companies, which can take care of both the physical as well as the contractual infrastructure between the CO_2 emitters and injectors. It was noted by several experts surveyed here that the lack of a "backbone" CO_2 infrastructure in industrial areas likely hampers the implementation of more entrepreneurial experiments with the technology.

---

[1] The fourth project is the In Salah project in Algeria, where up to 1.2 Mt/CO_2 is removed from natural gas and injected in a deep saline aquifer each year, since 2004 (IPCC, 2005).

Table 3
Major active and planned large-scale CCS projects commencing before 2015 in Norway, the Netherlands, United States, Canada and Australia (sources: ETP ZEP, 2008; NETL, 2008; CO2CRC, 2009; NrCan, 2009; IEA GHG, 2009; MIT, 2009).

Country	Name (location)	Project leader	Reservoir type	CO_2 source	Size (Mt/year)	Start
Norway	Sleipner	StatoilHydro	Saline	Gas processing	1	1996
Norway	Snøhvit	StatoilHydro	Gas	LNG production	0.7	2008
Norway	Husnes	Sargas	EOR	Coal – post combustion	2.6	2011
Norway	Karstø	Naturkraft	Saline	Gas – post combustion	1.2	2012
Norway	Mongstad	StatoilHydro	Saline	Gas – post combustion	1.5	2014
Netherlands	CGEN	CGEN NV	Oil & gas	Coal – pre combustion	2	2014
Netherlands	Magnum	NUON	Oil & gas	Various – pre combustion	±1	2015
Netherlands	Enecogen	Eneco	Oil & gas	Gas – post combustion	2	2015
Netherlands	Maasvlakte	EON	Oil & gas	Coal – post combustion	±5	2015
Canada	Weyburn	Pan Canadian	EOR	Coal gasification	1	2000
Canada	Fort Nelson	PCOR	Saline	Gas processing	1.6	2011
Canada	BoundaryDam	SaskPower	EOR	Coal – oxy combustion	±1	2015
Canada	Genesee	Epcor	Saline	Coal – pre combustion	±1	2015
Canada	Alberta Carbon Trunk Line	Enhance Energy	EOR	Oil sand upgrading	1.8	2015
Canada	Quest	Shell	EOR	Oil sand upgrading	±1.5	2015
US	Mt Simon	MGSC/MRCSP	Saline	Ethanol production	1	2009
US	Gulf Coast	SEACARB	Saline	Gas processing	1	2009
US	Entrada	SWP	Saline	Gas processing	1.1	2010
US	Oologah	AEL/Alstom	EOR	Coal – post combustion	1.5	2011
US	Antelope	Basin Electric	EOR	Coal – post combustion	1	2012
US	WA Parish	NRG Energy	EOR	Coal – post combustion	1	2012
US	Williston	PCOR	EOR	Lignite – post combustion	1	2012
US	Kimberlina	CES	Saline	Coal – oxy combustion	1	2012
US	Kern County	Hydrogen Energy	EOR	Petcoke – post combustion	2	2014
US	West Wyoming	BigSky	Saline	Gas processing	1.5	2011
Australia	Coolimba	Aviva Corp.	Oil & gas	Coal – post combustion	3	2015
Australia	Moomba	Santos	EOR	Gas processing	1	2010
Australia	Zerogen	Stanwell	Saline	Coal – pre combustion	0.5	2012
Australia	Gorgon	Chevron Texaco	Saline	Gas processing	3.3	2013
Australia	Monash CTL Project	Monash Energy	Oil & Gas	Coal to liquids – separation	13	2015

Table 4
Expert evaluation of "entrepreneurial activities" on a scale of 1–5.

Netherlands	Norway	US	Canada	Australia	Average
2.5	2.7	3.2	3.1	3.3	2.9

Table 4 shows that the fulfilment of this function is evaluated higher in North America and Australia then in the two European countries. This can be partly explained by the decades of experience with underground injection technology through acid gas disposal, and EOR by oil and gas companies in the US and Canada (see Bachu and Gunter, 2005). At present there are over 70 CO_2 EOR sites in North America (IPCC, 2005). Furthermore, CO_2 injection and storage has been tested for a variety of reservoir types in more than 20 small-scale pilot projects in the US and Canada, as part of the US-DOE Carbon Sequestration program (Litynski et al., 2008). Finally we observed more uncertainty on the future availability of public funding for integrated CCS projects in the Netherlands and Norway, than in than in North America and Australia, where billions of dollars have been granted to project developers of commercial scale CCS projects that will commence in the coming years. We will further elaborate on this issue in Section 3.6, where we discuss the fulfilment of the function "mobilization of resources".

3.2. *Knowledge development*

The 100 experts interviewed for this study are satisfied with the knowledge base that has been accumulated over the past decade. On average they scored this function with a 3.9, which is the highest of all functions (see Table 5). Despite this, it is argued to continue R&D of all components of the CCS chain. Below we will first describe the technological focus of the major CCS R&D programs in the countries under study and then we will discuss the main directions for future CCS research indicated by the interviewees.

3.2.1. *The United States*

The US DOE is taking a leading role in the advancement of CCS technologies. Through its Carbon Sequestration Program, DOE has divided more than USD 100 over 80 R&D projects in 2008 (NETL, 2008). The objective of the Program is to develop fossil fuel based power plants with over 90% CO_2 capture and 99% storage permanence, as well as less than a 10% increase in electricity costs by 2012. There are three main components to the US CCS activities: core R&D of nearly all possible CCS component technologies; major demonstration projects through the Clean Coal Power Initiative; and deployment through the Regional Carbon Sequestration Partnerships (RCSPs). Other major RD&D projects include:

- The public private Coal-Seq Consortium, led by Advanced Resources International, which studies the CO_2-storage/ECBM process by performing experimental and theoretical research on coal reservoir behavior, and validating the findings against the results from the field projects such as the work conducted in the Allison Unit (Reeves et al., 2009; IEA, 2008b).
- The Zero Emission Research and Technology Center (ZERT) is a research collaboration focused on understanding the basic science of underground CO_2 storage and safety issues associated with injected CO_2 (ZERT, 2009; IEA, 2008b).

Table 5
Expert evaluation of "knowledge development" on a scale of 1–5.

Netherlands	Norway	US	Canada	Australia	Average
3.7	3.8	3.9	3.9	3.7	3.8

- The Frio project was the first injection of CO_2 into a saline aquifer to demonstrate the feasibility of injection into high-permeability sandstone (Ghomian et al., 2008). The Lawrence Berkeley National Laboratory (LBNL) manages the related GeoSeq program, which among other things tests technologies to detect surface seepage of CO_2 of the Frio Brine injection site (IEA, 2008b).
- The CO_2 Capture Project, an international effort led by BP and co-funded by the US DOE, seeks to develop and test new breakthrough technologies to reduce the cost of CO_2 separation, capture, and transportation from combustion sources such as turbines, heaters and boilers by up to 75% (IEA, 2008b; Miracca et al., 2009).
- The FutureGen Alliance, led by the coal-fuelled electric power industry, intends to build a 275 MW coal-fired IGCC power plant with CCS and hydrogen production in Mattoon, Illinois (FutureGen Alliance, 2007). This flagship project, with an estimated cost of USD 1.5 billion, has been issue of debate since the DOE announced in January 2008 to discontinue support for FutureGen and decided to sponsor several smaller CCS pilot projects instead (US DOE, 2008). However, in June 2009, DOE reassessed that decision and reached agreement with the Alliance to complete a new preliminary design of the plant. Early spring 2010, a decision will be made whether to move forward with the project (FutureGen Alliance, 2009a,b).

3.2.2. Canada

In 2008, approximately 200 organizations were active in over 75 CCS R&D projects in Canada (Legg and Campbell, 2006). The most significant R&D project in Canada is the IEA Weyburn-Midale project at EnCana's EOR project site. The objectives of this project are to predict and verify the ability of an oil reservoir to securely store CO_2 and to develop a Best Practices Manual, for the design and implementation of other CO_2 storage projects (Preston et al., 2005, 2009). More applied research regarding EOR has been carried at the Zama and Pembina EOR Projects in Alberta (Lakeman et al., 2009; Smith et al., 2009). Furthermore, the Alberta CO_2-Enhanced Coal Bed Methane Recovery Project made a proof of concept for the injection of CO_2 and other flue gases into coal (Deng et al., 2008), and the Alberta Saline Aquifer Project identified the top three suitable deep saline formations in the province (IEA, 2008b). The Wabamun Aquifer Storage Project, which is conducted at the University of Calgary, has got a similar objective only then focuses on deep saline aquifers in the area of major coal-fired power plants in central Alberta (Keith and Lovoie, 2009). In terms of capture research there are two major Canadian test centers active, namely:

- The CANMET Energy Technology Centre, which leads the "Oxyfuel combustion for CO_2 capture project". This project involves a 300 kW oxyfuel pilot plant near Ottawa with the goal to achieve higher than 95% CO_2 purity and controlling other air pollutants (IEA, 2008b).
- The International Test Centre in Saskatchewan, has two main components: a pre-commercial-scale chemical absorption technology demonstration pilot plant at the Boundary Dam power facility near Estevan, and a post-combustion technology pilot plant at the Petroleum Technology Research Centre of the University of Regina (Wilson et al., 2004).

3.2.3. The Netherlands

In the Netherlands, CCS R&D is concentrated around one large heterogeneous national CCS consortium. This CATO (CO_2 Capture, Transport and Storage) program has a budget of nearly €25 million (=USD 35 million) and runs between 2004 and 2008 (Lysen et al., 2005). CATO is co-ordinated by the Utrecht Centre for Energy Research covers CO_2 capture, CO_2 storage, systems analysis and public outreach. The Dutch CAPTECH R&D program (2006–2009), led by the Energy Centre of the Netherlands (ECN), complements part of the capture research within CATO and aims to reduce the CO_2 capture cost with 50% (Jansen and van Egmons, 2009; Meerman et al., 2008). In order to achieve this, a wide portfolio of future capture technologies is being investigated. Furthermore, E.on, the Netherlands Organisation for Applied Scientific Research (TNO), and the University of Utrecht have installed a post-combustion pilot capture plant (CATO CO_2 Catcher) to test different solvents and membranes at the site of E.on's coal-fired power plant near Rotterdam (Nell, 2008). In the coming the budget of CATO will triple to €75 million and continue with a more applied research focus to support the planned CCS pilot projects in the Netherlands (Pagnier, 2009). These include: the SEQ Oxy fuel plant in the north of the Netherlands; NUON's IGCC pre-combustion CO_2 capture project and EnecoGen's Cryogenic project, which uses liquefied natural gas in a combined cycle gas turbine and freezes the flue gases (Stuij, 2008).

3.2.4. Norway

Norway's first R&D project related to CCS was initiated by SINTEF in 1987. Since then, more than 40 R&D projects have been implemented (van Alphen et al., 2009). The number and size of these R&D projects increased considerably in recent years, as in 2005, the government launched the CLIMIT national gas technology programme to foster coordinated research on natural gas-fired power plants that include CCS (Gassnova, 2006). In addition to this program, the Mongstad European test centre was established in June 2007 in conjunction with the future Mongstad combined heat and power station. The centre will have a capture capacity of 0.1 $MtCO_2$ per year and test amine and carbonate-based CO_2 capture technologies (de Koeijer et al., 2009). CO_2 storage research focuses mainly on deep saline aquifers, for example the SACS and CO_2Store programs, which are both related to Statoil's Sleipner project (Chadwick et al., 2007).

3.2.5. Australia

CCS R&D in Australia aims to achieve large cuts in coal-based GHG emissions. The research efforts in Australia centre around the industry based COAL21 consortium and a number of Cooperative Research Centres (CRCs), including the CRC for Coal in Sustainable Development (CCSD) and the CRC for Greenhouse Gas Technologies (CO_2CRC). The CO_2CRC has budget of AUD 140 million (=USD 120) and focuses on various CO_2 capture and storage technologies, regional CO_2 strategies and the implementation of pilot projects (Cook, 2009). The latter includes, the CO_2CRC Otway Project, and the Hazelwood and Loy Yang post combustion capture projects in Victoria, which involve the drying of brown coal and retrofitting CSIRO's mobile pilot post-combustion CO_2 capture facility (IEA, 2008b). Other CCS pilot projects in Australia include:

- The Callide Oxyfuel pilot project in Queensland is converting an existing 30 MW unit at Callide A for CO_2 capture. The second stage of this AUD 200 million project commences in 2010 and involves the injection and storage of up to 0.5 Mt of captured CO_2 (Cook, 2009).
- The Munmorah project in New South Wales investigates an ammonia based post combustion capture process, and the ability to adapt this process to suit Australian conditions (Cottrell et al., 2009; IEA, 2008b).
- The HRL IDGCC (integrated drying gasification combined-cycle) project in Victoria is a 400 MW brown coal power plant, of which CO_2 is captured at pilot scale initially (IEA, 2008b).

In general, the knowledge developed regarding CO_2 storage is considered by the 100 experts surveyed for this study as being of high quality. This is the result of a rich history of oil and gas activities as well as the scientific excellence of research institutes in all countries under study. In order to advance the current knowledge regarding CO_2 storage, these experts identified several research priorities for the future, including the development of advanced monitoring, measurement and verification (MMV) technologies. Furthermore, it is needed to improve and validate numerical models to determine the (long-term) integrity for a large variety of reservoir types. This would give a more reliable overview of the most suitable storage sites in a particular country or region. Furthermore, it is argued that even though 3400 miles of CO_2 pipelines are already laid out in the US alone, more research is needed into the regulatory, financing, siting and safety issues of CCS-dedicated CO_2 pipelines.

On the quality and diversity of CO_2 capture R&D a considerable number experts surveyed in this study are less satisfied. More basic research into new solvents, sorbents and membranes is needed to identify innovative cost-effective capture technologies. Furthermore, the interviewees in all countries stress the need to diversify CO_2 capture research. In Norway, for example, the possibility to increase R&D efforts into capture technologies for coal-fired power plants was mentioned several times, as these technologies would have a larger world market potential. While in the US, Canada and Australia it was recognized that R&D efforts should diversify towards CO_2 capture from gas-fired generators and retrofit options for existing power plants. The Netherlands is an exception to this trend; as some the surveyed experts from this country argued for more focus on pre-combustion technologies, as the R&D budget is too small to be a front-runner in all three CO_2 capture areas. Finally, it was noted that more attention should be given to developments in fuel cell technology as well as in commercial gasification processes, as these research areas offer considerable learning potential for the development pre-combustion CO_2 capture technologies.

Despite the above, it is argued by the experts surveyed here that the most important stimulus for this function is the implementation of more demonstration projects to test the developed knowledge under real world conditions. Not only to increase technological learning, but also to gain experience with the regulatory requirements of such projects and improve public outreach strategies.

3.3. Knowledge diffusion

Organizations in the field of CCS have two main reasons to establish partnerships and exchange knowledge. First, to share the relatively high costs (and investment risks) related to CCS RD&D. Second, the technological challenges involved in the development of CCS, as well as the integration of different fields of expertise, require shared knowledge and competences. Therefore, it is very much appreciated by most of the 100 experts surveyed in this study that strong national and international CCS consortia exist. Together with the increasing number of conferences, this is reflected in the relatively high average evaluation score of 3.7 (Table 6).

Examples of CCS knowledge networks are the earlier described CATO CCS consortium in the Netherlands and the Australian CO_2CRC, which both consists of more than 40 industrial, (non)governmental, and research organisations. The American RCSPs are also government-industry collaborative networks that involved, in 2008, more than 350 organizations covering 42 American states and four Canadian provinces (Litynski et al., 2008). Public private CCS consortia in Canada include, the Integrated CO_2 Network (ICO_2N) and the Canadian CO_2 Capture and Storage Technology Network (CCCSTN); both tasked with coordination of R&D and deployment efforts with the aim to establish large-scale integrated CCS systems. Furthermore, the major Norwegian RD&D projects, like the CO_2store program and the CO_2 test centre in Mongstad involve a large amount of national and international projects partners.

Table 6
Expert evaluation of “knowledge diffusion” on a scale of 1–5.

Netherlands	Norway	US	Canada	Australia	Average
3.7	4	4	3.2	3.5	3.7

There are many organizations participating in RD&D programs across national borders. For example, Dutch research institutes and companies are leading in a number of European projects, including RECOPOL and CO_2REMOVE. And in the same way Norwegian organizations, like StatoilHydro and SINTEF, joined various international research initiatives, such as: CASTOR; CO_2Sink and the CO_2 Capture Project (CCP). The fact that the latter project involves eight leading multinational energy companies and receives funding from the EU, the US-DOE as well as the Norwegian government elucidates the international nature of CCS knowledge networks.

The experts surveyed in this study agreed on the value of international CCS consortia and stress the need to intensify the exchange of experimental knowledge across borders. Several interviewees made the point that best practices should be made available in order to optimize technological learning, as no single company or nation can develop CCS in isolation. In relation to this point it was noted by several of the interviewees that the IEA GHG R&D program fulfils an important role for international knowledge diffusion in the field of CCS. This is done the research networks it sponsors (Beck and Aiken, 2009a, 2009b), and the organization of the bi-annual International Greenhouse Gas Control Technologies (GHGT) conference series. The largest GHGT conference until now was held in Washington DC, in November 2008 and hosted 1460 participants from 42 different countries (MIT, 2008). However, it is also recognized by our experts that current international collaborations are mainly established on a purely political or scientific level (e.g. the IEA GHG R&D program) and that more should be done to develop a complementary set of CCS demonstration projects around the world, including the growing coal based economies of India and China. The Carbon Sequestration Leadership Forum (CSLF) could take up such a coordinating role. This international ministerial-level panel is amongst other things tasked with the planning of joint projects (CSLF, 2008).[2] Moreover, the Global CCS Institute, established in July 2009 by the Australian Government, has been set up for the purpose to build a “central base” of CCS knowledge and expertise. The institute has obtained the support of more than 20 national governments and over 80 leading corporations, non-governmental organizations (NGOs) and research organizations to accelerate the commercial deployment of CCS projects all over the globe (GCCSI, 2009).

The vast majority of the interviewees recognized that the increasing amount of (inter)national CCS platforms and conferences have contributed significantly to the optimization of CCS knowledge networks. However, it was also noted that this is not always the case for knowledge networks around capture technologies. A number of these experts argue that R&D on capture technologies in private companies often occurs behind “closed doors”, since this knowledge can create a competitive advantage. It is argued by experts in all countries that commercial interest and

---

[2] At present, there are over 20 projects that have received CSLF recognition, including the RSCPs, the Frio project, the IEA GHG Weyburn-Midale CO_2 project and the Otway Basin project in Australia (CSLF, 2008).

Table 7
Mid-term GHG emission reduction targets in the Netherlands, Norway, US, Canada and Australia (VROM, 2007; Environment Canada, 2008; Government of Australia, 2008; NME, 2007; US EPA, 2009).

Country	Netherlands	Canada	Australia	Norway	US
Target	30%	20%	25%	Carbon neutral	17%
Target Year	2020	2020	2020	2030	2020
Reference year	1990	2006	2000	–	2005

the protection of intellectual property hinder an optimal flow of information between the actors involved in CCS R&D. This is mentioned as the most important barrier for the performance of this function, which could hamper the implementation of integrated CCS projects.

3.4. Guidance

On average, the experts participating in this study rated their satisfaction of this function with a moderate score of 3.0. They are satisfied with the clarity of technological demands articulated by industry towards scientific organizations, as well as the role of political and industrial leaders in advocating the promise of CCS. In all countries under study, CCS is bound to play a key role in the low emissions futures envisioned by the various governments (see Table 7). The latter is formally illustrated in several white papers (e.g. Australian Government, 2004, 2008; VROM, 2007) and technology roadmaps (e.g. Environment Canada, 2008; NETL, 2007), but also in speeches of political leaders, like the New Year speech of Norwegian Prime Minister Stoltenberg in 2007 wherein he calls the development of CCS technology for the Mongstad CCS plant ‘‘Norway's moon landing project’’ (Tjernshaugen, 2007). Or in the fall of 2008, at a campaign rally, Barack Obama said ‘‘We must find a way to stop coal from polluting our atmosphere without pretending that our nation's most abundant energy source will just go away. That's why we must invest in clean coal technologies’’ (Obama, 2008).

Guidance in the technology development process is not just about setting ambitious targets and the creation of visions. It also involves the introduction of an unambiguous regulatory framework supporting CCS. Such a framework not only comprises clear climate policy (which we will discuss further under the next function: ‘‘market creation’’), but also legislative solutions related to standardization, permitting and liability. There is wide agreement among the experts surveyed in this study that permitting capture and transportation facilities are not substantially different than for conventional industrial facilities. However, it is argued that a new set of rules is needed for underground injection and storage of CO_2. Below we will first describe the progress made regarding the development of supportive CCS regulations in the countries under study and then discuss the major outstanding regulatory issues.

In Australia, the Ministerial Council on Mineral and Petroleum Resources endorsed a set of Regulatory Guiding Principles for CCS (MCMPR, 2005). Designed to facilitate the development of consistent regulatory frameworks for CCS in all Australian jurisdictions, the principles address: assessment and approval processes; access and property rights; transportation issues; monitoring and verification; liability and post-closure responsibilities; and financial issues. Furthermore, the federal government released draft legislation, in May 2008, which amends the federal Offshore Petroleum Act of 2006 to allow for CO_2 injection and storage offshore. The legislation, which came into force in November 2008, provides for a system of access and property rights for the geological storage of CO_2 in offshore waters under Commonwealth jurisdiction. In March 2009, the first step in the process of providing these access and property rights was taken by the release of 10 offshore areas for the exploration of GHG storage areas (Australian Government, 2009a).

In Norway and the Netherlands the national governments are also working on a supportive legal framework, thereby approximating and complementing recent EU directives addressing CCS. Among other things, the CCS Directive proposed by the European Commission (EC, 2008) provides for the use of existing legislation where possible, in particular for capture and transport of CO_2, but also proposes new legislation to address CO_2 storage. This new legislative framework for CCS sets criteria for site assessment and permitting; requirements for the CO_2 stream; specifications for a CO_2 storage monitoring system; and liability measures, including the handling of EU Emission Trading Scheme (EU ETS) allowances for any leakage. The latter is of prime importance for the GHG inventories of the country wherein the storage operations take place.

In 2008, the US Environmental Protection Agency announced a regulation for commercial-scale CO_2 storage under the Underground Injection Control (UIC) program, with finalization targeted for early 2011 (US EPA, 2008). Just like the EU Directive, the regulation is expected to include site characterization, well construction and operation, monitoring, post-closure care and public participation. The proposed CO_2 injection rule specifically discusses the need for an ‘‘adaptive regulatory’’ approach as the science and engineering of CCS evolves (US EPA, 2008). Alongside EPA, a number of states are pressing ahead with rules for sequestration. Washington state was the first to propagate rules in the June 2008. At least six more states are close to adopting rules or at various stages in the process of scoping and developing them (Pollak and Wilson, 2009). Furthermore, the American Clean Energy and Security Act of 2009 would establish a task force to provide recommendations to Congress before 2012 that include a study of the ability of existing laws and insurance mechanisms to deal with subsurface property rights and to manage risks associated with CCS, including implications and considerations for different models for liability assumption (Waxman and Markey, 2009).

As in the US and Australia, the regulation of CCS in Canada also involves a complex interaction between federal and state laws. Existing federal and provincial oil and gas legislation covers certain aspects of CCS, including CO_2 capture and transportation-related issues. It is also anticipated that injection can be partly covered by existing legislation on CO_2 for EOR, natural gas storage and acid gas disposal. However, in most Canadian jurisdictions, issues around property rights and post-injection activities still remain to be addressed (Bachu, 2008). A number of activities have been undertaken to address the outstanding regulatory issues. For example, Alberta has established a government-industry CCS Development Council, which is among other things tasked with solving regulatory issues regarding CCS project implementation in Alberta. The provincial government of Saskatchewan is considering amending its oil and gas regulations to allow for CCS, and British Columbia has introduced legislation on CO_2 storage property rights (IEA, 2008b). The federal government is also funding several research projects that address regulatory issues. Although the Canadian experts participating in this study appreciate these efforts, the relatively preliminary status of regulation regarding CCS in this country, explains the relatively low score of this function compared to other countries (see Table 8).

In general we can conclude that current regulatory frameworks are a good platform to build from, but inadequacies in several areas indicate the need to change part of the current legislation. According to the experts surveyed here the gaps in existing regulatory frameworks relate to three main areas:

Table 8
Expert evaluation of "guidance" on a scale of 1–5.

Netherlands	Norway	US	Canada	Australia	Average
3.3	3	3.2	2.6	3	3.0

1. Legal issues around pore space ownership and its interaction with mineral rights, especially in North America.
2. Specification of requirements to cover the operation of CO_2 storage projects, including guidelines for site selection and MMV.
3. Articulation and assignment of timeframes and responsibility for the different liability types (operational, local, and global climate) in case of CO_2 leakage from the reservoir.

Although most experts participating in this study would like to see CCS regulation in place soon, some of them also note that the regulatory agencies will require time to complete this work, and that it is not practical to expect this to be accomplished before any projects can proceed. In addition, the experience gained from early projects will be helpful to inform the development of many of these new regulations. Therefore it was argued by several of our experts (mainly in North America) that regulatory agencies should therefore provide – after a thorough site selection procedure – approvals on a one-time basis to allow the first projects to move ahead.

3.5. Market formation

Within a decade CCS has advanced from a science-based technological concept to an option, of which its separate parts are widely demonstrated by industry. For example, in niche applications such as EOR, whereby relative pure CO_2 from industrial operations is utilized to gain extra oil revenues, but also in other entrepreneurial experiments as described in Section 3.1. Moreover, the existing integrated commercial CCS projects – like Sleipner, Snøhvit and Weyburn – are using a broad range of CO_2 capture technologies, CO_2 transportation pipelines, CO_2 injection systems and MMV tools. Thereby these projects prove that geologic CO_2 storage technologies are mature and capable of deploying at commercial scales (Dooley et al., 2009). However, it is unlikely that utilities will adopt CCS on a large scale until sound climate policies make CO_2 financially worth capturing and storing. It is argued that one of the main barriers standing in the way for a broader uptake of integrated commercial scale CCS projects is the absence of a clear regulatory framework that create economic drivers for CCS. Therefore, this function is rated with an average 2.2 (Table 9); the lowest score of all functions.

The fact that Norwegian experts rated the fulfillment of this function higher than interviewees in the other countries can be explained by the introduction of a carbon tax in 1993, which has proved to be an effective incentive to encourage CO_2 storage operations in the North Sea. Additionally, it triggered the development of capture solutions for initially offshore and later onshore gas-fired power plants (van Alphen et al., 2009). However, it appeared that until now the tax of approximately €40/tCO_2 has not been sufficient to initiate commercial CCS projects related to power generation. In order to provide such market incentives for CCS, governments in all countries under study are introducing climate policies, which we will discuss below.

Table 9
Expert evaluation of "market creation" on a scale of 1–5.

Netherlands	Norway	US	Canada	Australia	Average
2	2.9	2.2	2	2.1	2.2

In March 2008, the federal government of Canada released further details of its emissions trading scheme (ETS) for large emitters to support its Turning the Corner Plan (Government of Canada, 2008). The key concept in the scheme, which is proposed to be effective 1 January 2010, is that of emissions intensity. The emissions-intensity reduction target for each industrial sector, including the oil sands and electricity sectors, is based on an improvement of 18% from 2006 emission-intensity levels in 2010. Every year thereafter, a 2% continuous emission intensity improvement will be required. Where a facility improves its emissions intensity by more than the required annual amount it would be issued emissions credits, which could be traded with other participants in the scheme or saved for future use. There are several other options for firms to comply, including investments in pre-certified clean energy projects identified by the federal government for up to 100% of a firm's regulatory obligation through 2018. So far, CCS is the only certified investment option that has been identified for this compliance mechanism. Several of our Canadian experts argued that an ETS in combination with an increasing stringency of emission performance standards (EPS) for new facilities in the oil sands and power sectors could lead to a de facto mandatory use of CCS technologies by 2018 and trigger early investments in CCS "CCS-ready" installations on the short term. Eventually, the Government of Canada plans to transition from an emission-intensity based target system to a fixed emissions cap system in the 2020–2025 period. It has indicated that in determining the level of the cap, particular consideration will be given to regulatory developments regarding climate change in the US.

Climate change mitigation in the US has been primarily a technology-driven voluntary effort. Although on the state level, several initiatives have been taken that vary between being committed to reduce GHGs to introducing a multi-state cap-and-trade system, it was not until June 2009 that the first federal climate legislation was approved by the House of Representatives (Waxman and Markey, 2009). The American Clean Energy and Security Act of 2009 (ACES) would establish a cap and trade system for GHG emissions from all major emitting sectors including power producers.[3] Under these caps, GHG emissions must be reduced by 17% by 2020 and over 80% by 2050 compared to 2005 levels (EIA, 2009). The ACES Act combines regulatory requirements and financial incentives to ensure that new fossil fuel based power plants will operate with CCS. ACES requires all new coal plants with a capacity of 250 MW or greater that receive permits from 2009 to 2019 to emit no more than 500 kgCO_2/MWh no later than 2025 and potentially earlier depending on the level of commercial deployment of CCS technologies (Forbes, 2009). The EPS for new coal-fired power plants commencing after 2020 is set at 365 kg/MWh. Taking into account that the CO_2 emissions of a pulverized coal (PC) plant ranges from 736 to 811 kg/MWh and for an IGCC from 682 to 846 kg/MWh (Rubin, 2009), implies that the only way to comply with the standards for coal-fired electric power plants is to use CCS. In order to offset the financial burden for power producers and industries that need to apply CCS in their daily operations, the ACES Act sets aside bonus allowances up to USD to 90 per tonne of captured CO_2 for 10 years.

The Australian government also recognizes that if designed and implemented well, an ETS is a better approach to reduce its GHG emissions, than its current system of Mandatory Renewable Energy Targets (Australian Government, 2008). Australia's ETS will be established at the earliest in 2010 and recognizes CCS as an

---

[3] Despite the passage of ACES in the House, the future of the Act remains uncertain, as it faces both opposition and competing bills in the Senate. It is not expected that President Obama can sign this or a similar bill into law before early 2010 (Pew Center, 2009).

eligible way for firms to meet there obligations under the scheme. It is proposed that during the remainder of the Kyoto compliance period, to the end of 2012, permits should be sold at a fixed price (Garnaut, 2008). The sale of permits would generate substantial revenue, which could be allocated to support commercialization of CCS.

The Netherlands and to a lesser extend Norway, both rely on the proposal of the European Commission to bring CCS into its ETS, as it comes to creating a market for CCS. At present, a large gap exists between the CO_2 avoidance costs of CCS, which shows a range of €40–120/tCO_2 (IEA, 2008b), and the carbon price, varying between €10 and €16/tCO_2 in the first half of 2009 (ECX, 2009. This gap, in combination with the volatility of the carbon price, renders it likely that additional policies will be needed to ensure large-scale deployment of CCS in Europe (Groenenberg and de Coninck, 2008). Therefore, the European Commission has outlined the possibility of a "CO_2 emissions fade out", implicating the obligation of CCS for all new fossil-fuel-fired power stations from 2020 onwards (which is similar to the proposed EPS' for power plants in the US ACES Act and Canada's Turning the Corner plan). However, making CCS obligatory also implies financial support for demonstration of CCS to bring down its costs. For that reason, the European Council's plans to co-finance 10–12 CCS demonstration projects in commercial electricity generation by 2015 (ETP ZEP, 2008).

The importance of financing the first large-scale CCS demonstration projects that have not yet benefited from scale economies and technological learning was been noted by large number of the interviewees in all countries. They argued that besides creating a clear market for CCS, it is of prime importance that the technology becomes "market ready" and that additional public investments are needed. We will further elaborate on this issue in the following section.

3.6. *Mobilization of resources*

Although investments in CCS RD&D have grown substantially over the past years, the 100 experts surveyed in this study rate their satisfaction on the availability resources with an average score of 2.8 (see Table 10). The most widely shared opinion is that the current availability of financial resources is not sufficient to realize commercial-scale integrated CCS demonstration projects. Interviewees (especially from private firms) argued that financial risks are too high for firms to justify CCS investments to shareholders. Taking into account that the carbon price in the early years might not be high or stable enough to trigger enough CCS investment, additional incentives will likely be needed.

To provide investor certainty, it is believed by most of the experts participating in this study that public private partnerships are the way to go. In these partnerships government agencies should fund a substantial part of the billions of dollars necessary to deploy the first set of commercial-scale CCS projects. Several of the experts surveyed here recognize that supporting the fossil-fuel industry with public money could meet resistance from environmental NGOs and the certain societal groups (an issue that we will discuss further under the last function: "creation of legitimacy"). Despite this possible risk, it is argued that this approach would offer the highest incentives to early projects that have not yet benefited from scale economies, and technological learning; e.g. improved materials and technology design, standardization of applications, system integration and optimization. In order to get these first projects off the ground, Governments in all the countries under study announced additional funding for the demonstration projects.

Table 10
Expert evaluation of "mobilization of resources" on a scale of 1–5.

Netherlands	Norway	US	Canada	Australia	Average
2.5	2.7	3.0	3.1	2.9	2.8

The majority of Australia's AUD 500 million Low Emissions Technology Demonstration Fund has been allocated for CCS deployment in public private partnerships (Cook, 2009). Furthermore, the AUD 600 million COAL21 Fund established by the coal industry and the State of Queensland also supports the development of low emission coal technologies (State of Queensland, 2007). On top of that, in May 2009, the Australian Government announced AUD 2.4 billion in low emissions coal technologies, including new funding of AUD 2 billion for industrial-scale CCS projects under the CCS Flagships program, potentially including a CO_2 storage hub (see Table 3, Section 3.1 for the planned commercial scale CCS projects in Australia) (Australian Government, 2009b).

Since 2006, the federal government of Canada has allocated CAD 375 million in financial support to CCS-related activities, including CAD 125 million (=USD 115 million) under the ecoENERGY Technology Initiative (NrCan, 2009). Furthermore, CAD 250 million is made available in 2008 for the commercial demonstration of CCS in the coal-fired Boundary Dam power plant in Saskatchewan, which funding has been matched by he provincial government (Campbell, 2009). In its 2009 budget, the federal government instituted tax breaks for CCS projects and committed an additional CAD 1 billion over five years for demonstration clean energy technologies, with only CCS explicitly identified as a recipient of this funding (Department of Finance Canada, 2009). Moreover, the Alberta government has committed CAD 2 billion to fund a portion of the construction costs of 3 large-scale CCS projects in its province by 2015 (Government of Alberta, 2009). Between Federal and Alberta budgets, public funding for CCS is nearly CAD 3 billion, which is expected to leverage at least the same amount of investments from industry.

In the US, the DOE awarded nine grants representing over 500 million to the Regional Carbon Sequestration Partnerships to conduct large-scale field tests whereby over 1 MtCO_2 will be injected into deep geologic formations (Litynski et al., 2009). Major investments into demonstration of CO_2 capture related to power generation are also expected through the US DOE sponsored FutureGen efforts and Clean Coal Power Initiative (FutureGen Alliance, 2009a,b; US DOE, 2009). The budgets of these support programs increased substantially by the US government's Recovery Act funds for CCS research and demonstration. Much of the USD 3.4 billion designated for fossil fuel RD&D – about five times what the DOE now spends annually on such research – will finance industrial-scale CO_2 capture installations at coal-fired power plants and oil refineries (CRS, 2009; Charles, 2009). However, Secretary of Energy Steven Chu said shortly after the announcement of the funds: "It sounds like a lot of money, but it doesn't go that far..." Thereby he referred to the FutureGen project, which price tag rose to USD 1.7 billion (Charles, 2009). The ACES Act of 2009 may provide extra financial incentives as it proposes the establishment off a Carbon Storage Research Corporation to be run by the Electric Power Research Institute. The Corporation would use funds collected through levy on fossil fuel based electricity to issue grants up to USD 1 billion per year for at least 5 early commercial-scale CCS demonstrations (Pew Center, 2009; Forbes, 2009).

Compared to the billions of dollars allocated to CCS in North America and Australia, the €92 million provided by the Dutch government for three small-scale capture pilot plants and two storage projects seems a bit low. The amount of money that has been made available by the Norwegian government for the capture demonstration projects at Mongstad and Karstø are of the same order of magnitude. Explaining the relatively low rating on the fulfillment of this function in these countries (see Table 10). However the Norwegian and Dutch projects will be implemented before 2013, while the budgets mentioned above stretch over a longer period of time (Stuij, 2008; de Koeijer et al., 2009). Furthermore, the Dutch and Norwegian governments expressed their willingness to co-finance one of the European flagship projects, if sited in their countries. So far the EU made available €1.05 billion for 7 CCS projects as part of their European Economic Recovery Plan (EC, 2009). Furthermore, it has allocated the revenues from the auctioning of 300 million emissions allowances in the new round of the EU ETS to the construction large-scale CCS projects (European Parliament, 2009). At a price of €20/tCO_2 this would total to €6 billion. The competition and selection of CCS projects will take place in 2010 and a final funding decision is expected to be made somewhere in 2011 (ETP ZEP, 2008).

Next to the current lack of financial resources, most of the interviewees in all countries recognize that the increasing scarcity of skilled (technical) personnel in CCS may cause problems, as CCS has the potential to become an industrial sector that is comparable to the current oil and gas industry. This concern is compounded by reports that petroleum-engineering departments are already operating up or above capacity and that there is competition for qualified personnel within the energy industry (Bryant and Olson, 2009). Experts participating in this study see the solution for this potential problem by introducing educational programs at universities to get future engineers acquainted with specific CCS knowledge. They also stress the need to retrain current managers and technicians in the industry.

3.7. *Creation of legitimacy*

The current fulfillment of this function is scored 3.1. Although moderate, the creation of legitimacy is a somewhat difficult function in the various CCS innovation systems. The legitimacy for CCS is different for each of the stakeholders, ranging from politicians, environmental NGOs, industry lobby groups and communities that are encountered with storage projects under their back yards. Below we will discuss the legitimacy for CCS as seen by different stakeholder groups.

In all countries considered in this study, CCS is favored by a powerful coalition of industrial organizations. For example the Norwegian Confederation of Trade Unions and Federation of Norwegian Industries are closely aligned with the regional electrochemical industries, being interested in using more natural gas in their production processes. Together with the national oil companies, these resources-based industrial interest groups occupy a privileged role in Norwegian politics where they perform a powerful lobby for CCS deployment (van Alphen et al., 2009). Similar lobby activities can be found in Australia, it was noted by most Australian experts participating in this study that the coal industry is strongly in favor of deploying CCS technologies in order to stay in business in a low-carbon economy. Furthermore, the majority of Canadian experts we surveyed agree that there are influential coalitions advocating CCS in Canada. They noted that industrial consortia like the Canadian Coal Power Coalition (CCPC) and ICO_2N invest heavily in a lobby for CCS in political arenas. Oil and Gas industry associations also have a relatively large influence in Dutch as well as in American politics, as they are responsible for a large share of jobs and generate a substantial amount of income for the treasury through the payment of royalties. Adding the financial power of the energy industry to its influential role in politics, this is seen by most experts surveyed in this study as a benefit for CCS technologies over renewable alternatives, like wind and solar.

On the other hand, the support of the fossil fuel based industry for CCS might be the reason that several vocal environmental NGOs as well as some politicians oppose public support for CCS. Some of them argue that continued production of electricity from fossil fuels with CCS lengthens the dependence on non-renewable resources and that giving public dollars to the “rich” energy industry is a farce in itself (see e.g. Greenpeace International, 2008). Furthermore, it was noted by some experts participating in this study that CCS is far from the silver bullet to all the problems related to the coal mining activities and the development of tar sands (in the case of Canada), as it fails to address many non-CO_2 related environmental impacts, like acid rain, destruction of wildlife habitat, and depletion and contamination of fresh water. According to most stakeholders in all of the countries that are the focus of this paper, one of the major bottlenecks in the fulfillment of this function lies in possible public resistance towards CCS because of similar reasons as currently given by some environmental interest groups. It is argued by interviewees in all the five countries in focus that a public backlash against the technology in general, or in opposition towards the siting of a specific project, can stall the development of CCS by many years.

In all countries under study, research has been carried out in order to better understand the public attitudes towards CCS. See for example: de Best-Waldhober and Daamen (2006) and Sharp et al. (2009) for their research on informed public opinions in the Netherlands and Canada; Curry (2004) and Reiner et al. (2006) for their survey studies in the US; and Ashworth et al. (2009a) for an overview of all the Australian research activities regarding public perceptions of CCS. These studies confirm that despite a growing awareness of climate change, CCS remains relatively unknown to the lay public. If additional information on CCS is provided to the respondents, a slight support for CCS is found in all countries (Ashworth et al., 2009b). In Canada, CCS is even perceived to be less risky than many other commonly used energy technologies, including oil and gas refinery operations and nuclear power (Sharp et al., 2009). Furthermore, several researchers found that if the technology is developed and managed in a way that addresses the public’s preferences and concerns then support could increase significantly (de Best-Waldhober and Daamen, 2006; Sharp et al., 2009). Moreover, the majority of respondents in these studies have indicated that they would support the use of CCS as part of broader GHG reduction strategy that also includes energy efficiency and renewable energy technologies.

Despite the moderate support for CCS, it is not possible to accurately predict the public reaction to future large-scale CCS development as it will be strongly dependent upon the way the public debate evolves, the way in which CCS projects are managed, and whether a strong NIMBY (Not In My Backyard) movement develops in reaction to specific siting decisions (Ashworth et al., 2009b). The latter happened by the siting of the first onshore CO_2-storage pilot project in the Netherlands. The local government and citizens of Barendrecht—a town situated above the projected storage reservoir—strongly opposed siting the pilot project in their densely populated area. They felt cost and efficiency had weighed more when choosing Barendrecht for the pilot than their safety and the possible devaluation of their homes. The affair became front-page news, received prime time television coverage and provoked questions in Parliament (Chazan, 2009).

It is argued by the experts surveyed here that in order to increase public support, more should be done to engage the public and (environmental) interest groups in an early development phase of CCS projects and incorporate their concerns in the design of the project. In Norway, for example, the combined public outreach activities of various industrial and environmental interest organizations (e.g. Bellona) created more legitimacy for the technology among citizens (van Alphen et al., 2009). This was confirmed by Shackley et al. (2009) in their survey of opinion regarding the role of CCS in Europe’s energy future among 500

Table 11
Expert evaluation of "creation of legitimacy" on a scale of 1–5.

Netherlands	Norway	US	Canada	Australia	Average
3	4	2.9	2.9	2.8	3.1

stakeholders in Europe, Norwegian stakeholders stand out as extremely optimistic regarding the deployment of CCS in their country. This partly explains the relatively high rating of 4.0 in this country (see Table 11).

The experts surveyed in this study recognize that when developing public outreach strategies it is of prime importance to pay attention to the significant body of literature that is available on public perception of CCS and to take advantage of successful public outreach strategies applied in other CCS projects, like FutureGen (Hund and Judd, 2008) and the Otway Basin storage project (Anderson, 2007). It is argued that (risk) communication on CCS cannot start early enough and that without public engagement, implementation of CCS projects risk being delayed or even cancelled. Therefore, some of the interviewees note that experts should engage more often in open dialogue with the public about benefits, risks and other legitimate concerns about CCS. Finally it was noted that in any communication on CCS, it needs to be portrayed as part of a wider portfolio of climate mitigation options and not at the expense of renewables.

4. Strengthening the innovation systems' performance: implications for policy

The performance assessment and comparison of CCS innovation systems in Canada, the US, the Netherlands, Norway and Australia, shows that the extensive knowledge base and CCS knowledge networks, accumulated over the past years, have not yet been utilized by entrepreneurs to explore markets for CO_2 capture concepts linked to power generation. In order to advance the overall performance of the innovation systems and accelerate the deployment of more advanced CCS technologies, it is necessary to direct policy initiatives at the identified weak system functions, i.e. entrepreneurial activity, market formation and resources mobilization. Moreover, in most countries regulatory guidance and the creation of legitimacy may also be improved (see Fig. 1). Below we will discuss a general policy strategy that would help alleviate the current barriers to the technology's future deployment.

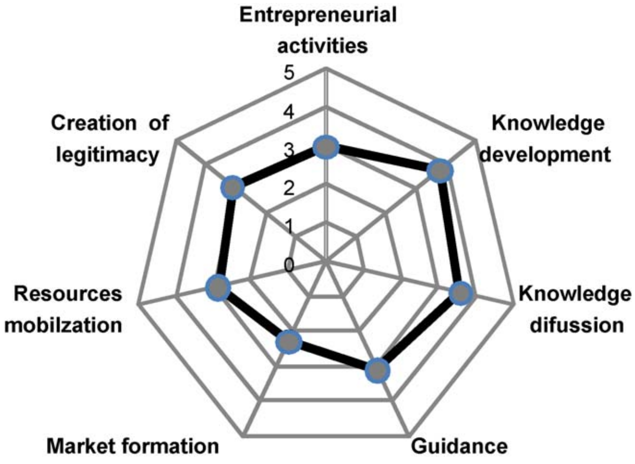

Fig. 1. Spider diagram depicting the overall score on the functions of innovation systems by a hundred experts in Norway, Netherlands, United States, Canada and Australia.

While continuing basic research, there is great need to implement more large-scale CCS projects that integrate power production with CCS. CCS component technologies (capture, transport, storage and MMV) all exist at industrial scale, but full integration and application of these components in commercial facilities is still largely missing. Commercial scale demonstration projects that integrate the whole CCS chain are necessary to gain practical experience with the technologies and reduce the technical as well as financial risks of such projects. To facilitate the deployment of a complementary set of large-scale CCS projects, changes in (inter) national collaborative networks may be required. In order to solve intellectual property issues, integrate the CCS chain, and take optimal advantage of the available learning potential, improved coordinated action is necessary. Hereby, domestic CCS consortia, as well as international CCS network organizations like the CSLF and the Global CCS institute could play an important role.

The implementation of sound climate policies and legislation is vital for the development of commercial scale CCS projects, as strong economic drivers for CCS are currently lacking. The industrial sectors that may apply CCS in their daily operations should be able to rely on a long-lasting change in the institutional infrastructure of the innovation system that creates a clear market for CCS. The temporal subsidies and tax credits that have been applied so far are a necessary first step, but do not seem to be strong enough to deal with the relatively high costs of power generation with CCS. Therefore, it is necessary that governments change "the rules of the game". It is believed that the introduction of emissions cap-and-trade systems in all countries under study – possibly with bonus allowances for CCS projects in combination with EPS' for power plants could be a strong policy mechanism to create a market for CCS on the mid- and longer term.

However, taking into account that the carbon price in the early years might not be high or stable enough to trigger enough CCS investment, additional incentives will be needed to remove the financial disadvantage created by CCS. Many of the 100 interviewees argued that public private partnerships are the way to go in establishing early commercial-scale CCS demonstration projects. The billions of dollars that have been made available by the governments of Australia, Canada and the US as well as the billions of Euro's that will become available for CCS demonstration in the EU (including Norway and the Netherlands) after auctioning 300 million emission allowances, would offer a significant incentive for early projects that have not yet benefited from scale economies, technological improvement and learning. Although essential, we would argue that such investments are futile in the absence of an overarching long-term climate policy. Sound alteration of near-term financial stimuli to push the demonstration of CCS technologies and longer-term technology pull strategies that create a clear market for CCS are therefore of prime importance to accelerate the deployment CCS in all countries under study.

Besides implementing sound climate policies, solving the outstanding regulatory issues regarding CCS is one of the most important actions to be taken in order to get large-scale CCS projects online. First, legal issues around pore space ownership and its interaction with mineral rights need further attention (especially in North-America). Second, timeframes and responsibility for the different liability types (operational, local, and climate) need to be articulated and assigned. Third, requirements to cover the operation of CO_2 storage projects, including guidelines to site selection and MMV need to be further specified. The experience gained from early projects might be used in the development of these new guidelines and regulations. Regulatory agencies should therefore provide approvals on a one-time basis to allow the first projects to move ahead; then they should use the subsequent learning to develop legislation and guidelines for broader application of future CCS projects.

Finally we would argue that a strong regulatory framework could minimize concerns of CCS being a "risky technology", thereby building public trust in CCS applications. It is clear that without enough support from a broad coalition, the development of the technology may suffer from resistance. Therefore, such a regulation should include mechanisms to support CCS projects that engage a wide range of stakeholders and incorporate public outreach efforts. It is argued that an open two-way communication with stakeholders, including (environmental) interest groups, the media and members of the local community should be an integral of CCS projects. Thereby it is of prime importance to take advantage of successful public outreach strategies applied in other CCS projects. Any communication on CCS needs to be in the context of climate change and portray CCS as part of a broader portfolio of climate mitigation options, including renewable and energy efficiency measures.

5. Discussion of results and concluding remarks

In this study we have evaluated and compared the performance of CCS innovation systems in the US, Canada, the Netherlands, Norway and Australia. By the assessment made in this study the strengths and weaknesses of the innovation systems are identified, which is vital for the development of coherent long-term policy strategies that may enhance the successful deployment of CCS technologies.

The analysis allows for a cross-national comparison on a function level; e.g. differences in focus of R&D programs and variation in regulatory frameworks. Thereby it provides an opportunity for technology managers to learn from a broad range experiences regarding the development of CCS technologies in other countries. However, one should be aware that new and more influential innovation system dynamics may start off as part of developments in other countries than the ones included in this study, like the United Kingdom, Germany or China. Furthermore, this study focuses on a wide variety of aspects that are decisive for successful CCS deployment. Although this is one of the strengths of taking an innovation system perspective, one should not neglect the in depth studies that focus on a single aspect of technology development. See for example, Groenenberg and de Coninck (2008) on policies related to the creation of a market for CCS in Europe; Pollak and Wilson (2009) on providing regulatory guidance for CCS in the US; Wade and Greenberg (2009) regarding the creation of legitimacy and public acceptance of CCS; or de Coninck et al. (2009) on knowledge diffusion and global technological learning. We would argue that these in depth studies could help to fill in the general deployment strategy outlined in this study based on interviews with more than 100 experts in five different countries and an extensive literature review.

It is realized by the majority of the experts that participated in this study, that the extensive knowledge base and knowledge networks, which have accumulated over the past years in North America, Western Europe and Australia, have not yet been utilized by entrepreneurs to explore the market for power generation with CCS. Therefore, it is argued that the build-up of a CCS innovation system has entered a critical phase that is decisive for a further thriving development of CCS technologies in the countries under study. In order to move the CCS innovation systems through this present difficult episode and deploy more advanced CCS concepts at a larger scale it is necessary direct policy initiatives at the identified weak system functions; i.e. entrepreneurial activity, market formation and the mobilization of resources. Moreover, in some specific countries regulatory guidance and the creation of legitimacy require more attention.

In order to remedy malfunctioning in the assessed CCS innovation systems the following general deployment strategy has been abstracted from our analysis:

- Short-term investor certainty needs to be provided by establishing public private partnerships combined with a direct subsidies for a variety of commercial scale integrated CCS projects whose level declines as cumulative deployment increases. It is believed that the creation of such public private partnerships would offer the highest incentive to early projects that have not yet benefited from scale economies and technological improvement.
- In order to bring down the costs of the first generation CCS projects and advance technological learning in these commercial scale applications, (international) coordination and knowledge exchange is of prime importance. Such a coordinated effort should not be limited to the development of a complementary set of roadmaps and demonstration projects, but also target regulation and standards that will enable safe and effective CCS projects.
- Clear legislation regarding site selection, safety standards, monitoring, ownership and liability are not only crucial for project developers, but may also help to gain public trust in CCS. Open communication with stakeholders, the media and the lay public about benefits, risks and other legitimate concerns should be an integral part of every CCS project plan.
- Although necessary, we would argue that the abovementioned efforts are futile in the absence of overarching long-term climate policies. Governments need to change "the rules of the game" by implementing cap-and-trade systems – possibly with bonus allowances for CCS projects – in combination with EPS' for emitting facilities. Sound alteration of short-term financial incentives to stimulate learning by doing and long-term market incentives is key in the development and commercialization CCS technologies.

Acknowledgements

This research is part of CATO (the Dutch knowledge network on CO_2 Capture, Transport and Storage) and KSI (the Dutch knowledge network on system innovations and transitions). The authors are especially grateful to the interviewees for their willingness to participate and for their valuable contributions, which have formed the empirical foundation of this article.

References

Anderson, C., 2007. Social research Otway CCS project, in CCSA Seminar. CO_2CRC, Melbourne.

Ashworth, P., Wade, S., Reiner, D., Daamen, D., Itaoka, K., 2009a. Recent developments in public attitudes and acceptance of CCS: an overview of research activities and results in recent years. IOP Conf. Series: Earth and Environmental Science 6, 172011.

Ashworth, P., Boughen, N., Mayhew, M., Millar, F., 2009b. An integrated roadmap of communication activities around carbon capture and storage in Australia and beyond. Energy Procedia 1 (1), 4749–4756.

Australian Government, 2004. Securing Australia's Energy Future. Australian Government, Canberrra. Available via: www.pmc.gov.au/energy_future.

Australian Government, 2008. Carbon Pollution Reduction Scheme: Australia's low pollution future. Australian Government, Canbera. Available via: http://www.climatechange.gov.au/whitepaper/report/index.html.

Australian Government, 2009a. Initial Release of Offshore Areas for Assessment of GHG storage sites-Guidance notes for applicants. Australian Government, Canberrra.

Australian Government, 2009b. $4.5 billion clean energy initiative. Media release 12 May 2009. Available via: http://www.environment.gov.au/minister/garrett/2009/budmr20090512i.html.

Bachu, S., 2008. Legal and regulatory challenges in the implementation of co_2 geological storage: an Alberta and Canadian perspective. International Journal of Greenhouse Gas Control 2 (2), 259–273.

Bachu, S., Gunter, W.D., 2005. Overview of acid gas injection operations in Western Canada. In: Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies.

Beck, B., Aiken, T., 2009a. An introduction to the IEA GHG international research network on risk assessment. Energy Procedia 1 (1), 2581–2586.

Beck, B., Aiken, T., 2009b. An introduction to the IEA GHG international research network on monitoring. Energy Procedia 1 (1), 2383–2387.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: as scheme of analysis. Research Policy 37, 407–429.

Bryant, S., Olson, J., 2009. Training carbon management engineers: why new educational capacity is the single biggest hurdle for geologic CO_2 storage. Energy Procedia 1 (1), 4741–4748.

Campbell, K., 2009. Canada's Saskatchewan investing in carbon capture and storage demo plant. Mining Weekly, 21 March 2008. Available via: http://www.miningweekly.com/article/canada039s-saskatchewan-investing-in-carbon-capture-and-storage-demo-plant-2008-03-21.

Carlsson, B., Stankiewicz, R., 1991. On the nature, function and composition of technological systems. Journal of Evolutionary Economics 1 (2), 93–118.

Chadwick, A., Arts, R., Bernstone, C., May, F., Thibeau, S., Zweigel, P., 2007. Best Practice for the Storage of CO_2 in Saline Aquifers – Observations and Guidelines from the SACS and CO2STORE Projects. British Geological Survey 267, Nottingham, UK.

Charles, D., 2009. Stimulus gives DOE billions for carbon-capture projects. Science 323, 1158.

Chazan, G., April 21, 2009. Shell's plan to lead in storage of carbon dioxide hits a snag. Wallstreet Journal 2009.

CO_2CRC, 2009. CCS activity in Australia 2009. Cooperative Research Centre for Greenhouse Gas Technologies, Canberra.

Cook, P.J., 2009. Demonstration and deployment of carbon dioxide capture and storage in Australia. Energy Procedia 1 (1), 3859–3866.

Cottrell, A.J., McGregor, J.M., Jansen, J., Artanto, Y., Dave, N., Morgan, S., Pearson, P., Attalla, M.I., Wardhaugh, L., Yu, H., Allport, A., Feron, P.H.M., 2009. Post-combustion capture R&D and pilot plant operation in Australia. Energy Procedia 1 (1), 1003–1010.

CRS, 2009. Energy Provisions in the American Recovery and Reinvestment Act of 2009 (P.L. 111-5). Washington, DC: Congressional Research Service. See also: http://fpc.state.gov/documents/organization/121927.pdf.

CSLF, 2008. Carbon Sequestration Leadership Forum Recognized Projects. CSLF, Washington, DC. Available via: www.cslforum.org.

Curry, T.E., 2004. Public Awareness of Carbon Capture and Storage: A Survey of Attitudes toward Climate Change Mitigation. MIT, Cambridge, MA.

de Best-Waldhober, M., Daamen, D., 2006. Public Perceptions and Preferences Regarding Large Scale Implementation of Six CO_2 Capture and Storage Technologies. Centre for Energy and Environmental Studies. University of Leiden, Leiden, The Netherlands.

de Coninck, H., Stephens, J.C., Metz, B., 2009. Global learning on carbon capture and storage: a call for strong international cooperation on CCS demonstration. Energy Policy 37 (6), 2161–2165.

de Koeijer, G., Enge, J.O., Thebault, C., Berg, S., Lindland, J., Overå, S.J., 2009. European CO_2 test centre mongstad—testing, verification and demonstration of post-combustion technologies. Energy Procedia 1 (1), 1321–1326.

Deng, X., Mavor, M., Macdonald, D., Gunter, B., Wong, S., Faltinson, J., Li, H., 2008. ECBM Technology Development at Alberta Research Council. Presented at the Coal-Seq VI Forum, Houston, US.

Department of Finance Canada, 2009. Canada's Economic Action Plan: Budget 2009. Government of Canada, Ottawa, Canada.

Dooley, J.J., Davidson, C.L., Dahowski, R.T., 2009. An Assessment of the Commercial Availability of Carbon Dioxide Capture and Storage Technologies as of June 2009. Joint Global Change Research Institute. Pacific Northwest National Laboratory. Available via: http://www.pnl.gov/science/pdf/PNNL-18520_Status_of_CCS_062009.pdf.

European Commission, 2008. Proposal for a Directive of the European Parliament and of the Council on the geological storage of carbon dioxide. EC, Brussels.

EC, 2009. Call for proposals concerning a program to aid economic recovery by granting community financial assistance to projects in the field of energy. European Commission, directorate-general for energy and transport, Brussels, Belgium. Available via: http://ec.europa.eu/energy/grants/2009_07_15_en.htm.

ECX, 2009. ECX EUA Daily Futures (Spot) Contract: Historic Data 2009. Available via: www.ecx.eu.

Edquist, C., 2004. Reflections on the systems of innovation approach. Science and Public Policy 31 (6), 485–489.

EIA, 2009. Energy Market and Economic Impacts of H.R. 2454, the American Clean Energy and Security Act of 2009, report nr. SR/OIAF/2009-05. Available via: http://www.eia.doe.gov/oiaf/servicerpt/hr2454/pdf/sroiaf(2009)05.pdf.

Environment Canada, 2008. Turning the Corner: Regulatory Framework for Industrial Greenhouse Gas Emissions. Available via: ec.gc.ca/doc/virage-corner/2008-03/541_eng.htm.

Estublier, A., Lackner, A.S., 2009. Long-term simulation of the Snøhvit CO_2 storage. Energy Procedia 1 (1), 3221–3228.

ETP ZEP, 2008. EU Demonstration Programme for CO_2 Capture and Storage (CCS) – ZEP's proposal. European Technology Platform for Zero Emission Fossil Fuel Power Plants, Brussels.

European Parliament, 2009. Report on the proposal for a directive of the European Parliament and of the Council amending Council Directives 77/91/EEC, 78/855/EEC and 82/891/EEC and Directive 2005/56/EC as regards reporting and documentation requirements in the case of merger and divisions (COM(2008)0576 – C6-0330/2008 – 2008/0182(COD)). European Parliament, Brussels, Belgium. Available via: http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//NONSGML+REPORT+A6-2009-0247+0+DOC+PDF+V0//EN.

Forbes, S., 2009. Carbon Capture and Storage and The American Clean Energy and Security Act. World Resources Institute, Washington, DC.

Foxon, T.J., Gross, R., Chase, A., Howes, J., Arnall, A., Anderson, D., 2005. UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures. Energy Policy 33 (16), 2123–2137.

Freeman, C., 1995. The 'National System of Innovation' in historical perspective. Cambridge Journal of Economics 19 (1), 5–24.

FutureGen Alliance, 2009. FutureGen Cooperative Agreement with the U.S. Department of Energy. FutureGen Fact Sheets & Presentations, 1 September. FutureGen Alliance, Washington, DC. Available via: www.futuregenalliance.org/publications.stm.

FutureGen Alliance, 2009. FutureGen Initial Conceptual Design Report. FutureGen Alliance, Washington, DC. Available via: www.futuregenalliance.org/publications.stm.

G8, 2008. Joint Statement by G8 Energy Ministers. Aomori, Japan: June 8, 2008.

Garnaut, R., 2008. The Garnaut Climate Change Review – Final Report. Cambridge University Press, Melbourne, Australia.

Gassnova, 2006. Norwegian Gas Power Technology RD&D Program CLIMIT: Work Programme 2006. Gassnova and the Research Council Norway.

GCCSI, 2009. Global CCS Institute Overview Booklet. Global CCS Institute, Canberra.

Ghomian, Y., Pope, G.A., Sepehrnoori, K., 2008. Reservoir simulation of CO_2 sequestration pilot in Frio brine formation. USA Gulf Coast. Energy 33 (7), 1055–1067.

Government of Alberta, 2009. Government moves forward on carbon capture projects. Government of Alberta Information Bulletin, June 30, 2009. Available via: http://www.energy.gov.ab.ca/Initiatives/1438.asp.

Government of Canada, 2008. Turning the corner: Regulatory Framework for Industrial Greenhouse Gas Emissions. ISBN 978-0-662r-r05525-9.

Greenpeace International, 2008. False Hope, Why Carbon Capture and Storage Won't Save the Climate. Greenpeace, Amsterdam, the Netherlands.

Groenenberg, H., de Coninck, H., 2008. Effective EU and member state policies for stimulating CCS. International Journal of Greenhouse Gas Control 2 (4), 653–664.

Hawkins, D., Perida, G., Steelman, J., 2009. Twelve years after Sleipner: moving CCS from hype to pipe. Energy Procedia 1 (1), 4403–4410.

Hekkert, M., Negro, S., 2008. Functions of innovation systems as a framework to understand sustainable technological change: empirical evidence for earlier claims. Technological Forecasting and Social Change 76 (4), 584–594.

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: a new approach for analysing technological change. Technological Forecasting and Social Change 74 (4), 413–432.

Hund, G., Judd, K., 2008. Stakeholder Acceptance Issues Concerning CCS — Lessons Learned from FutureGen, paper presented at the Ninth International Conference on Greenhouse Gas Control Technologies, Washington, DC, US.

IEA, 2008a. World Energy Outlook 2008. International Energy Agency, Paris.

IEA, 2008b. CO_2 Capture and Storage: a key abatement option. International Energy Agency, Paris, France.

IEA GHG, 2009. CO_2 Capture and Storage RD&D Projects Database. IEA Greenhouse Gas R&D Program, Cheltanhan (UK). Available via: http://www.co2captureandstorage.info/co2db.php.

IPCC, 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. Intergovernmental Panel on Climate Change, New York. Available via: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf.

IPCC, 2007. IPCC, Climate Change Mitigation. Working Group III's Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Jacobsson, S., 2008. The emergence and troubled growth of a 'biopower' innovation system in Sweden. Energy Policy 36, 1491–1508.

Jacobsson, S., Bergek, A., 2004. Transforming the energy sector: the evolution of technological systems in renewable energy technology. Industrial and Corporate Change 13 (5), 815–849.

Jansen, D., van Egmons, S., 2009. Recent developments in the Dutch CAPTECH programme. Energy Procedia 1 (1), 1451–1456.

Kamp, L., 2002. Learning in Wind Turbine Development — A Comparison Between the Netherlands and Denmark. Utrecht University, the Netherlands.

Keith, D., Lovoie, R., 2009. An overview of the Wabamun Area CO_2 Sequestration Project (WASP). Energy Procedia 1 (1), 2817–2824.

Klein Woolthuis, R., Lankhuizen, M., Gilsing, V., 2005. A system failure framework for innovation policy design. Technovation 25 (6), 609–619.

Kline, S.J., Rosenberg, N.R., 1986. An overview of innovation. In: Landau, R., Rosenberg, N. (Eds.), The Positive Sum Strategy Harnessing Technology for Economic Growth. National Academic Press, Washington, DC, US.

Lakeman, B., Gunter, W.D., Bachu, S., Chalaturnyk, R., Lawton, D., van Everdingen, D., Lim, G., Perkins, E., 2009. Advancing the deployment of CO_2 monitoring technologies through the Pembina Cardium CO_2 Monitoring Project. Energy Procedia 1 (1), 2293–2300.

Legg, J.F., Campbell, F.R., 2006. Carbon Dioxide Capture and Storage: A Compendium of Canada's Participation. Prepared under NRCan Office of Energy Research and Development Ottawa, Ontario, Canada Catalogue No.: M4-39/2006E-MRC ISBN: 0-662r-r43044-1.

Litynski, J.T., Plasynski, S., McIlvried, H.G., Mahoney, C., Srivastava, R.D., 2008. The US Department of Energy's regional carbon sequestration partnerships program validation phase. Environment International 34 (1), 127–138.

Litynski, J., Plasynski, J.S., Spangler, L., Finley, F., Steadman, E., Ball, D., Nemeth, K.J., McPherson, B., Myer, L., 2009. US Department of Energy's regional carbon sequestration partnership program: overview. Energy Procedia 1 (1), 3959–3967.

Lundvall, B.A., 1992. National Systems of Innovation—Toward a Theory of Innovation and Interactive Learning. Pinter Publishers, London, United Kingdom.

Lysen, E., Faaij, A., Hendriks, C., 2005. The CATO programme in the Netherlands on CO_2 capture, transport and storage. Paper presented at the 7th International Conference on Greenhouse Gas Control Technologies, September 4–9, Vancouver, Canada.

MCMPR: Ministerial Council on Mineral and Petroleum Resources, 2005. Carbon Dioxide Capture and Geological Storage: Australian Regulatory Guiding Principles. Available via: www.industry.gov.au.

Meerman, H., Kuramochi, T., van Egmond, S., 2008. CO_2 Capture Research in the Netherlands. Available via: www.co2-cato.nl.

Miracca, I., Åsen, K.I., Assink, J., Coulter, C., Curran, L., Lowe, C., Moure, G.T., Schlasner, S., 2009. The CO_2 capture project (CCP): results from phase II (2004–2009). Energy Procedia 1 (1), 55–62.

MIT, 2008. GHGT-9 conference summary. 9th International Conference on Greenhouse Gas Control Technologies, 16–20 November 2008, Washington, DC, US. Available via: http://mit.edu/ghgt9/.

MIT, 2009. Carbon Dioxide Capture and Storage Project Database. MIT, Cambridge, MA Available via: http://sequestration.mit.edu/tools/projects/index.html.

Murphy, L.M., Edwards, P.L., 2003. Bridging the Valley of Death: Transitioning from Public to Private Finance. National Renewable Energy Laboratory NREL/MP-720-34036, Golden (CO), US.

Negro, S.O., Hekkert, M.P., Smits, R.E.H.M., 2007. Explaining the failure of the Dutch innovation system for biomass digestion—a functional analysis. Energy Policy 35 (2), 925–938.

Nell, L., 2008. CATO CO_2 catcher pilot plant factsheet. TNO Science and Industry, Delft, The Netherlands. Available via: www.co2-cato.nl.

Nelson, R.R., Winter, S.G., 1977. In search of useful theory of innovation. Research Policy 6 (1), 36–76.

NETL, 2007. Carbon Sequestration Technology and Program Plan. National Energy Technology Laboratory, Albany (OR).

NETL, 2008. Carbon Sequestration Project Portfolio. Available via: www.netl.doe.gov/technologies/carbon_seq.

NME, 2007. Norwegian climate policy. Summary in English: Report No. 34 (2006–2007). Ministry of the Environment, Oslo, Norway.

NrCan, 2009. EcoENERGY Technology Initiative. Natural Resources Canada, Ottawa, Canada. Available via: http://www.nrcan.gc.ca/eneene/science/etiiet-eng.php.

Obama B., 2008. Barack Obama and Joe Biden: New Energy for America. Available via: http://www.barackobama.com.pdf/factsheet_energy_speech_080308.pdf.

Pagnier, H., 2009. The National CCS knowledge and innovation program 2009–2014. Presented at the 4th Dutch CCS symposium, Driebergen, The Netherlands.

Pew Center, 2009. Summary of H.R. 2454: American Clean Energy and Security Act of 2009 (Waxman-Markey). Pew Centre on Global Climate Change, Arlington (US). Available via: http://www.pewclimate.org/docUploads/waxman-markey-detailed-summary-july2009.pdf.

Pollak, M.F., Wilson, W.J., 2009. Regulating geologic sequestration in the united states: early rules take divergent approaches. Environmental Science and Technology 43, 3035–3041.

Preston, C., Monea, M., Jazrawib, Brown, K., Whittaker, S., White, D., Law, D., Chalaturnyk, R., Rostron, B., 2005. IEA GHG Weyburn CO_2 monitoring and storage project. Fuel Processing Technology 86 (14–15), 1547–1568.

Preston, C., Whittaker, S., Rostron, B., Chalaturnyk, R., White, D., Hawkes, C., Johnson, J.W., Wilkinson, A., Sacuta, N., 2009. IEA GHG Weyburn-Midale CO_2 monitoring and storage project–moving forward with the Final Phase. Energy Procedia 1 (1), 1743–1750.

Reeves, S., Gonzalez, R., Harpalani, S., Gases, K., 2009. Results, status and future activities of the coal-seq consortium. Energy Procedia 1 (1), 1719–1726.

Reiner, D., et al., 2006. An international comparison of public attitudes towards carbon capture and storage technologies. In: Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies, Trondheim, Norway.

Rubin, E.S., 2009. A Performance Standards Approach to Reducing CO_2 Emissions from Electric Power Plants. Pew Centre on Global Climate Change, Arlington Available via: http://www.pewclimate.org/docUploads/Coal-Initiative-Series-Rubin.pdf.

Shackley, S., Reiner, D., Upham, P., de Coninck, H., Sigurthorsson, G., Anderson, J., 2009. The acceptability of CO_2 capture and storage (CCS) in Europe: An assessment of the key determining factors: Part 2. The social acceptability of CCS and the wider impacts and repercussions of its implementation. International Journal of GHG Control 3 (3), 344–356.

Sharp, S.D., Jaccard, M.K., Keith, D.W., 2009. Anticipating Attitudes toward underground CO_2 storage. International Journal of Greenhouse Gas Technologies 3, 641–651.

Smith, S.A., Sorensen, J.A., Steadman, E.N., Harju, J.A., 2009. Acid gas injection and monitoring at the Zama oil field in Alberta, Canada: a case study in demonstration-scale carbon dioxide sequestration. Energy Procedia 1 (1), 1981–1988.

Smits, R., 2002. Innovation studies in the 21st century: Questions from a user's perspective. Technological Forecasting and Social Change 69 (9), 861–883.

State of Queensland, 2007. Clean Coal Technology Special Agreement Act 2007 – Act No. 30 of 2007. Available via: http://www.legislation.qld.gov.au/LEGISLTN/ACTS/2007/07AC030.pdf.

Stuij, B., 2008. Towards Large Demo's – the first practical steps. Highlights from recently funded projects. Presented at the 3rd Dutch CCS symposium, Rotterdam, The Netherlands.

Suurs, R.A.A., Hekkert, M.P., 2009. Cumulative causation in the formation of a technological innovation system: the case of biofuels in the Netherlands. Technological Forecasting and Social Change 76 (8), 1003–1020.

Tjernshaugen, A., 2007. Gasskraft, Tjuears klimakamp. Paxforlag, Oslo.

Torp, T.A., Gale, J., 2004. Demonstrating storage of CO_2 in geological reservoirs: the Sleipner and SACS projects. Energy 29 (9–10), 1361–1369.

US DOE, 2008. DOE – Fossil Energy Techline: DOE Announces Restructured FutureGen Approach to Demonstrate CCS Technology at Multiple Clean Coal Plants. Available via: http://www.fossil.energy.gov/news/techlines/2008/08003-DOE_Announces_Restructured_FutureG.html.

US DOE, 2009. Secretary Chu Announces Two New Projects to Reduce Emissions from Coal Plants. US Department of Energy, Washington, DC Available via: http://www.energy.gov/7559.html.

US EPA, 2008. Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO_2) Geologic Sequestration (GS) Wells; Proposed Rule. Federal Register 73 (144), 43492–43541.

US EPA, 2009. EPA Analysis of the American Clean Energy and Security Act of 2009 H.R. 2454 in the 111th Congress. US Environmental Protection Agency, Washington, DC, June 2009.

van Alphen, K., Hekkert, M.P., van Sark, W.G.J.H.M., 2008. Renewable energy technologies in the Maldives – realizing the potential. Renewable and Sustainable Energy Reviews 12 (1), 162–180.

van Alphen, K., van Ruijven, J., Kasa, S., Hekkert, M.P., Turkenburg, W.C., 2009. The performance of the Norwegian carbon dioxide capture and storage innovation system. Energy Policy 37, 43–55.

VROM, 2007. Clean and Efficient: New energy for climate policy. Report nr. 7421. Ministry of Housing Special Planning and the Environment, the Hague, the Netherlands.

Wade, S., Greenberg, S., 2009. Afraid to start because the outcome is uncertain? Social site characterization as a tool for informing public engagement efforts. Energy Procedia 1 5641-4647.

Waxman, H.A., Markey, E.J., 2009. H.R. 2454, the American Clean Energy and Security Act of 2009. See also: http://energycommerce.house.gov/Press_111/20090515/hr2454.pdf.

Wilson, M., Tontiwachwuthikul, P., Chakma, A., Idem, R., Veawab, A., Aroonwilas, A., Gelowitz, D., Barrie, J., Mariz, C., 2004. Test results from a CO_2 extraction pilot plant at boundary dam coal-fired power station. Energy 29 (9–10), 1259–1267.

ZERT, 2009. A national resource for geologic sequestration science. Zero Emission Research and Technology Center, Bozeman (MT), US. Available via: http://www.montana.edu/zert/index.html.