Accelerating the Development and Deployment of Carbon Capture and Storage Technologies

– An Innovation System Perspective

Printed by: Proefschriftmaken.nl || Printyourthesis.com

Published by: Uitgeverij BOXPress, Oisterwijk

Cover design by: Claire Ginn

ISBN /EAN 9789088912528

Accelerating the Development and Deployment of Carbon Capture and Storage Technologies

– An Innovation System Perspective

Het versnellen van de ontwikkeling en het inzetten van technologie ter bevordering van afvangst, transport en opslag van koolstofdioxide

– Een innovatiesysteem benadering

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de rector magnificus, prof.dr. G.J. van der Zwaan, ingevolge het besluit van het college voor promoties in het openbaar te verdedigen op dinsdag 29 maart 2011 des ochtend te 10.30 uur

door

Klaas van Alphen

geboren op 16 oktober 1980, te Amstelveen

Promotoren: Prof. Dr. M.P. Hekkert

Prof. Dr. W.C. Turkenburg

Prof. Dr. Ir. R.E. H. M. Smits

This research was carried out at the Innovation Studies Group, Copernicus Institute for Sustainable Development and Innovation, Utrecht University (The Netherlands), financially supported by the Ministry of Economic Affairs of the Netherlands and consortium partners in the CATO R&D Programme.

Preface

The work presented in this thesis has been carried out within the CATO programme (CATO: CO_2 Afvang, Transport en Opslag), partly financed by the Dutch Ministry of Economic Affairs (Nowadays called Ministry of Economic Affairs, Agriculture and Innovation). The CATO programme created the main knowledge network in the field of CO_2 Capture and Storage (CCS) in the Netherlands, developing and assessing new knowledge, technologies, systems and approaches in this field. New technologies, like CCS, meet many market and institutional barriers before becoming mature. In the recent past, rapid diffusion of sustainable innovations mainly occurred when environmental problems were considered extremely urgent. A good example is the CFC free cooling technology that was to restore the hole in the ozone layer, back in the eighties and nineties. But in many other cases – like technologies that address climate change – the market uptake is slow. The question of how to accelerate the development and implementation of CCS technologies is of great importance for technology managers and policy makers all around the world.

This thesis is centered around the question of how to accelerate the development and deployment of CCS technologies, using an Innovation System perspective. After all, the innovation process is not only influenced by technological characteristics. The social-economic environment in which a technology is developed and diffused – called the 'Technological Innovation System' - is of great importance. A well functioning Innovation System would greatly support the final market uptake of CCS technologies. So identifying strengths and weaknesses in the present Innovation System is of crucial importance to technology managers and policy makers that wish to accelerate the innovation process. For a better understanding of the innovation processes, this thesis contains a comparison of CCS Innovation Systems in the United States, Canada, Norway, Australia, and of course the Netherlands. Such a comparison offers the possibility to learn from each other's experiences regarding the development of CCS and strategies that could accelerate the deployment of CCS technologies in the Netherlands and abroad.

Most of the analyses presented in this thesis have already been published in peer reviewed scientific journals and presented at (inter)national conferences. Furthermore, some components of this research have informed policy making on a national and international level. For example, results presented in this thesis have been used by the Global CCS Institute in its report on the Global Status of CCS for input to the Muskoka (Canada) 2010 G8 Summit.

Contents

List of abbreviations

ACES	American Clean Energy and Security Act
ARC	Alberta Research Council
ASAP	Alberta Saline Aquifer Project
AUD	Australian Dollar
CAD	Canadian Dollar
CATO	CO_2 Capture, Transport and Storage (in Dutch)
CICERO	Center for International Climate and Environmental Research Oslo
CMU	Carnegie Mellon University
CCCSN	Canadian CO_2 Capture and Storage Technology Network
CCS	CO_2 Capture, transport and Storage
CCSD	Cooperative research centre for Coal in Sustainable Development
CCP	Carbon Capture Program
CCPC	Canadian Clean Coal Power Coalition
CETC-O	CANMET Energy Technology Centre-Ottawa
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CO_2CRC	Cooperative Research Centre for Greenhouse Gas Technologies
CoP	Conference of the Parties
CRUST	CO_2 Re-use through Underground Storage
CSIRO	Australian Commonwealth Scientific and Research Organization
CSLF	Carbon Sequestration Leadership Forum
CTL	Coal-To-Liquids
DCMR	Environmental Protection Agency Rijnmond (in Dutch)
DOE	(United States) Department of Energy
EC	European Commission
ECBM	Enhanced Coalbed Methane Recovery
ECN	Energy Centre of the Netherlands
EGR	Enhanced Gas Recovery
EIA	Environmental Impact Assessment
EOR	Enhanced Oil Recovery
EPA	(United States) Environmental Protection Agency
EPS	Emissions Performance Standards
ETP ZEP	European Technology Platform for Zero Emission Fossil Fuel Power Plants
ETS	Greenhouse gas Emission allowance Trading Scheme
EU	European Union
EZ	The Dutch Ministry of Economic Affairs (in Dutch)
FoE	Friends of the Earth
GDDS	Group Decision Support System
GESTCO	Geological Storage of CO_2 From Fossil fuel Combustion
GHG	GreenHouse Gas
GHGT	Greenhouse Gas Control Technologies
HARP	Heartland Area Redwater Project
ICO_2N	Integrated CO_2 Network
IEA	International Energy Agency
IEA-GHG	International Energy Agency Greenhouse Gas R&D programme
IGCC	Integrated coal Gasification Combined Cycle power plant
IPCC	Intergovernmental Panel on Climate Change
IPE	Interdepartmental Project bureau Energy transition
KSI	Dutch Knowledge Network on System Innovations and Transitions (in Dutch)
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkely National Laboratory
LLNL	Lawrence Livermore National Laboratory
LNG	Liquefied Natural Gas

MIT	Massachusetts Institute of Technology
MGSC	Midwest Geological Sequestration Consortium
MMV	Monitoring, Measurement and Verification
MNP	Dutch Environmental Planning Bureau (in Dutch)
MRCSP	Midwest Regional Carbon Sequestration Partnership
NAM	Dutch Oil Company (in Dutch)
NETL	National Energy Technology Laboratory
NGCC	Natural Gas Combined Cycle power plant
NGO	Non Governmental Organization
NIMBY	Not In My Backyard
NME	Norwegian Ministry of Environment
NOK	Norwegian Kroner
NTNU	Norwegian University of Science and Technology (in Norwegian)
NVE	Norwegian Water Resources and Energy Directorate (in Norwegian)
OCAP	Organic Carbon dioxide for Assimilation of Plants
OECD	Organization for Economic Co-operation and Development
OED	The Royal Norwegian Ministry of Petroleum and Energy (in Norwegian)
O&M	Operating and Maintenance
PC	Pulverized Coal-fired power plant
PCOR	Plains CO_2 Reduction Partnership
PPM(V)	Parts Per Million (on Volume basis)
PTAC	Petroleum Technology Alliance Canada
PTRC	Petroleum Technology Research Centre
RCI	Rotterdam Climate Initiative
RCSP	Regional Carbon Sequestration Partnership
R&D	Research & Development
RD&D	Research, Development and Demonstration
ROAD	Rotterdam Capture and Storage Demo project (in Dutch)
SACS	Saline Aquifer CO_2 Storage
SD	Standard Deviation
SECARB	Southeast Regional Carbon Sequestration Partnership
SINTEF	The Foundation for Scientific and Industrial Research (in Norwegian)
SWP	Southwest Regional Partnership on Carbon Sequestration
SOP-CO_2	Integrated Research Programme on Carbon Dioxide Recovery and Storage (in Dutch)
TNO	Dutch Organization for Applied Scientific Research (in Dutch)
TIS	Technological Innovation System
TPES	Total Primary Energy Supply
UIC	Underground Injection Control
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USD	US Dollar
UU	Utrecht University
VROM	Dutch Ministry of Housing, Physical Planning and Environment (in Dutch)
WASP	Wabamum Area Sequestration Project
WCI	Western Climate Initiative
WESTCARB	West Coast Regional Carbon Sequestration Partnership
ZECA	Zero Emission Coal Alliance
ZEP	Zero Emissions Platform
ZEPP	Zero Emission Power Plant
ZERT	Zero Emission Research and Technology Center

1. Introduction

1.1. Background

Global warming is a problem that requires urgent action. The increasing anthropogenic emissions of greenhouse gases (GHG) into the atmosphere are expected to result in global climate change with potentially severe consequences for ecosystems and mankind [1]. Scientists expect changing weather patterns, melting glaciers, sea level rise and the extinction of species. The impact of a changing climate for humans can be severe as more extreme droughts and floods are expected, which may have major consequences for e.g. coastal communities, land-usage and fresh water supplies. Even though, direct relation between natural disasters that may have been caused by climate change and the emission of anthropogenic GHG is hard to prove due to the complexity of the climate system. Nevertheless, the dominating view in scientific research is that most probably global warming observed over the past few decades is for a substantial part caused by human activities [1-3].

Already in 1992 the United Nations Framework Convention on Climate Change (UNFCCC), signed by 165 countries stated that stabilisation of GHG concentrations in the atmosphere needs to be achieved at a level that would prevent dangerous anthropogenic interference with the climate system [4]. The current level of greenhouse gases in the atmosphere is equivalent to approximately 430 parts per million (ppm) and is rising by around 2 ppm each year [1].[1] This is to be compared to a 280 ppm pre-industrial level. Based on scientific assessments of dangerous anthropogenic interferences for different temperature increases [1, 5-8], the Conference of the Parties (COP), which is responsible for the international efforts to implement the UNFCCC, aims to keep global temperature increase below 2°C [9]. To keep temperature increase between 2-2.4°C above pre-industrial level, it is estimated that GHG emissions have to stabilise at 445-490 ppm CO_2-equivalent [1]. This requires GHG emissions to be cut back with 50-85% annually in 2050 compared to the 2000 level [1].

The most dominant source of CO_2 contributing to the rise in atmospheric concentration since the industrial revolution is the combustion of fossil fuels. Since 1971, the global primary energy supply has more than doubled as demand rose driven by a growing population and global economic growth[10]. Despite the increase of non-fossil energy generation (e.g. wind, biomass and solar), the share of fossil sources in overall energy production remains relatively constant at about 80% due to this a strong rise in demand [1, 11, 12]. Given that around one hundred new conventional thermal power plants are still being constructed each year -the majority of them in China [11, 13]- the emission level is very likely to increase in the coming decades under a business as usual scenario.

The strong link between the energy supply and CO_2 emissions should thus be broken, or at least be bent, in order to meet future energy demand with reduced CO_2 emissions. According to many scenario studies, a portfolio of technologies will be needed to achieve very large

[1] Carbon dioxide (CO_2) is one of the most important greenhouse gases, as it represents approximately 77 % of the greenhouse gases emitted [1]. Other greenhouse gases include methane (CH_4), nitrous oxide (N_2O) and F-gases (HFCs, PFCs, and SF_6).

GHG emission reduction. A promising group of technologies that could be included in such a portfolio is brought together under the term CCS, Carbon dioxide Capture and Storage. CCS can be defined as the separation of CO_2 from industrial and energy-related sources, transport of the CO_2 to an (underground) storage site, and long-term isolation of the CO_2 from the atmosphere [14]. The ultimate goal of CCS is to store the otherwise emitted CO_2 for geological times in the deep underground. By reaching its goal CCS can significantly cut back CO_2 emissions from burning carbon-containing fuels which are expected to dominate the primary energy supply until at least the middle of the 21st century [11, 14].

At present, CCS is the only technological solution that has the potential to substantially reduce carbon emissions from fossil fuel fired power plants, as well as plants (co-)firing biomass. As such CCS is essential as coal and gas are at present the predominant fuel for electricity production and responsible for no less than 40% of global CO_2 emissions[11]. Furthermore, the combination of biomass with CCS would result in a net removal of CO_2 from the atmosphere[15]. This makes biomass with CCS a potentially important option if a very rapid reduction of CO_2 emissions is needed [16, 17]. A further 25% of the current global CO_2 emissions come from large-scale industrial processes such as iron and steel production, cement making, natural gas processing and petroleum refining. All processes wherein CCS can be integrated. Given its broad application and with world energy demand projected to grow by more than 40% over the next two decades it is no surprise that CCS features prominently in the main blueprints for reducing GHG emissions until at least 2050 [1, 18, 19].

Together with renewable energy technologies, nuclear energy and greater energy efficiency, CCS contributes significantly to the least-cost route of reducing and stabilising CO_2 emissions in the atmosphere [18]. The Energy Technologies Perspectives BLUE Map scenario of International Energy Agency (IEA) [19], which assessed strategies for reducing GHG emissions by 50% by 2050, concluded that CCS will need to contribute one-fifth of the necessary emissions reductions to achieve stabilization of GHG concentrations in the most cost-effective manner (see figure 1-1), roughly the same percentage as renewable energy. Three years before, the IPCC Special Report on CCS assessed that CCS could provide 15% to 55% of the cumulative mitigation effort up to 2100 [14].

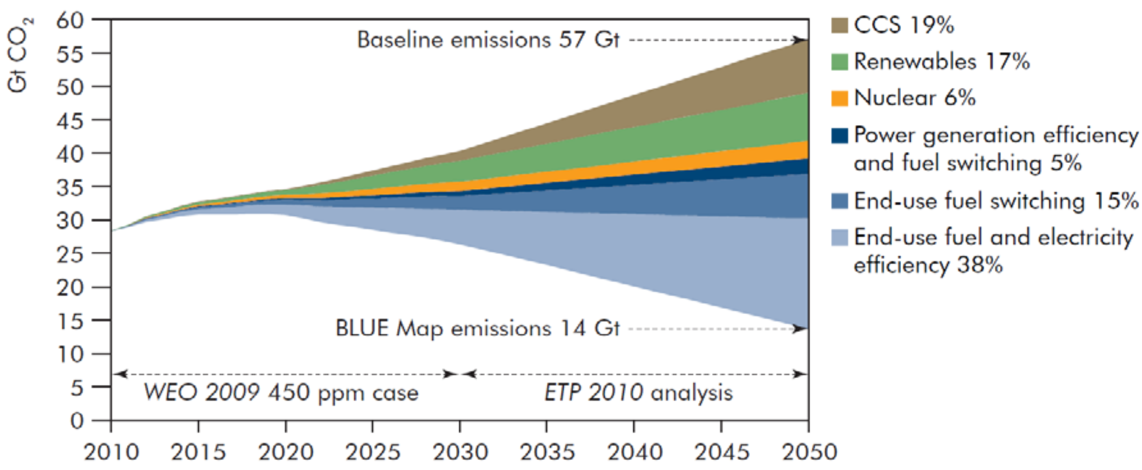


Figure 1-1: CCS delivers one-fifth of the lowest-cost GHG reduction solution in 2050 [20]

The Stern Review suggests that omitting CCS would, on average, increase overall GHG abatement costs [21]. The IEA quantified this number and revealed that if CCS technologies are not available, the overall cost to achieve a 50% reduction in CO_2 emissions by 2050 would increase by 70% [22]. CCS should therefore be an essential part of the portfolio of technologies to be applied to achieve substantial global GHG emission reduction. However, for CCS to play its part as key climate change mitigation option, more than 3,000 large-scale CCS projects need to get off the ground over the next four decades [22], capturing, transporting and storing a volume of CO_2 equivalent to twice the volume of oil and gas the world currently extracts each year [23].

As a technology that renders coal, oil and gas industry expansion and GHG reduction no longer mutually exclusive, CCS enjoys government and industrial support in most countries that depend heavily on fossil fuels for their secure (fossil fuel based) energy supply and export income. This follows from the recognition of the scale-up challenge and the need to speed up the commercial deployment of CCS technologies at the Gleneagles Summit in 2005, where G8 leaders[2] committed to "work to accelerate the deployment and commercialisation of Carbon Capture and Storage technology". Foremost among the recommendations was the launch of 20 large-scale CCS demonstration projects by 2010. In 2008, at the Hokkaido Toyako Summit, G8 leaders expressed strong support for this initiative, "… with a view to beginning broad deployment of CCS by 2020".

In the remainder of this introduction chapter, first the global development status of CCS technologies and the challenges encountered in its broad deployment are discussed in further detail. Then the concept of Innovation System Functions is introduced. This framework will be used throughout this thesis to provide insight in the CCS innovation process and forms the basis of which support strategies can be developed that aim to accelerate the development and (commercial) deployment of CCS technologies worldwide. Next, the main research questions are formulated. Finally, scope and outline of thesis are presented.

1.2. The development and deployment of CCS technologies: status and challenges

CCS can reduce CO_2 emissions from large industrial sources and power stations using carbonaceous fuels by approximately 85 %. As such, it is a key technology within a suite of low carbon solutions for mitigating climate change. In general, CCS can be seen as a set of technologies that integrates three stages: CO_2 capture at large point sources, transport of CO_2 to a suitable storage location, and injecting the CO_2 deep underground for long-term storage. The sections below provide a short overview of each of the stages in the CCS process.

Stage 1: Capture

In the first stage of CCS, CO_2 is isolated and captured. CO_2 capture technologies have long been used by industry to remove CO_2 from gas streams where it is not wanted or to separate

[2] Ministers from G8 countries: Canada, France, Germany, Italy, Japan, Russia, the United Kingdom and the United States.

CO_2 as a product gas [22]. In industrial processes such as natural gas sweetening for example, CO_2 is removed from natural gas streams to meet specific natural gas quality standards. Similarly in plants that produce ammonia or hydrogen.

There are three generic process routes for capturing CO_2 from fossil fuel power plants: post-combustion, pre-combustion and oxy-combustion. Each of these processes involves the separation of CO_2 from a gas stream by using chemical absorption, physical adsorption, or physical separation [14]. Post-combustion involves scrubbing the CO_2 out of flue gases from the combustion process. Oxyfuel combustion involves combusting fuel in recycled flue gas enriched with oxygen to produce a CO_2-rich gas. Pre-combustion uses a gasification process followed by CO_2 separation to yield a hydrogen rich fuel gas. Of these methods, post-combustion CO_2 capture using amine solvent scrubbing is one of the more established methods for CO_2 capture, as this is used to capture significant flows of CO_2 from flue gas streams in several facilities [22]. Oxyfuel combustion has been demonstrated in the steel manufacturing industry at plants up to 250 MW in capacity, and the related oxy-coal combustion method is currently being demonstrated at smaller scales [15]. Pre-combustion CO_2 capture from an integrated gasification combined cycle (IGCC) power plant has yet to be demonstrated; however, elements of the pre-combustion capture technology have already been proven in other industrial processes [14, 24, 25]. In other industrial activities, such as steel mills and cement plants, processes to capture CO_2 are being developed [14]. Adaptations to post-combustion, pre-combustion and oxy-fuel combustion processes have been proposed for these types of industrial facilities [26].

Stage 2: Transportation

Once separated, the CO_2 is compressed, and transported to a suitable storage site. CO_2 is already being transported today by high-pressure pipelines – primarily for use in industrial applications or in depleting oil fields, where it is used to increase the production of oil; a process also known as enhanced oil recovery (EOR). In North America for example over 30 million tonnes (Mt) CO_2 from natural and anthropogenic sources are transported per year through 6200 km of CO_2 pipelines in the USA and Canada [27]. Ships, trucks and trains have also been used for CO_2 transport in early demonstration projects [22].

Stage 3: Storage

The final stage of CCS sees the CO_2 injected into, and contained within, suitable subterranean geological structures, often at depths of one kilometre or more. Appropriate storage sites include depleted oil or gas fields, unmineable coal beds or deep porous saline aquifers, which have impermeable rock (also known as a 'seal') above them. The seal prevents the CO_2 from returning to the surface and forces the CO_2 to slowly permeate through the porous rock. These sites have securely contained fluids and gases for millions of years, and with careful selection, they offer confidence in the integrity of storage. Of the three, it is expected that saline formations will provide the opportunity to store the greatest quantities of CO_2, followed by oil and gas reservoirs [15].

Once injected, a range of technologies is used to monitor the behaviour of CO_2 in the storage site. This monitoring, as well as the associated reporting and verification processes, provide an additional safeguard to storage activities. Monitoring data from projects involving injection into depleted oil and gas fields and saline formations have shown that the CO_2 performs as anticipated after injection with no observable leakage [14]. A number of other projects have been conducted, primarily in the USA and Canada. Most of these projects use the CO_2 for EOR, but some also intentionally store and monitor CO_2 concurrently with EOR operations [22].

First estimates for the total global CO_2 storage capacity by reservoir type are given in Table 1-1. The total storage capacity ranges between 2 and 11 Tt. It should be stressed that high uncertainties still persist regarding the estimation of storage capacity due to the use of incomplete data or simplified assumptions on geological settings, rock characteristics, and reservoir performance [28]. This explains the large range in estimated storage capacity, especially for deep saline aquifers. Nevertheless, even in the most conservative scenario whereby 2 Tt of storage capacity is available for CCS activity, there is an opportunity to store all the CO_2 emissions from fossil fuel use in the coming 60 years (based on 2008 emission levels).

Table 1-1: Estimated storage capacity for several geological storage options [29].[3]

Reservoir type	Lower estimate of storage capacity (Gt)	Upper estimate of storage capacity (Gt)
Oil and gas reservoirs	675	900
Unminable coal seams (ECBM)	3 to 15	200
Deep saline formations	1000	10000

Integration and Scale-up

In 2010, there are nine fully integrated large-scale CCS projects in operation [23].[4] The Sleipner and Snøhvit (Norway) and In Salah (Algeria) projects involve CCS where the CO_2 content of the extracted natural gas is too high. The Weyburn-Midale project in Canada involves the capture of CO_2 from a coal-based synfuels plant in North Dakota (United States). The captured CO_2 is compressed and sent via a pipeline to an oil field in Canada, where it is used for EOR as well as storage. The other 5 projects are all located in the United States and use the CO_2 that is captured at fertilizer and natural gas processing plants for enhanced oil recovery (EOR). Currently, over 10 Mt CO_2/year is stored and/or used for EOR in these projects operation [23]. In addition to these projects, there are over 70 other large-scale integrated projects in planning stages across the world (See Figure 1-2).

[3] Note that these estimates include non-economical storage capacity.
[4] An integrated CCS project links together the whole CCS chain of capture, transportation and storage. Large-scale for a coal-fired power plant is capturing and storing at least 80 % of 1 Mt of CO_2 per year. For a natural gas-fired power plant, an industrial or natural gas processing installation, 'large-scale' is capturing and storing at least 80 % of 0.5 Mt of CO_2 per year.

Figure 1-2: The 85 active or planned large scale integrated projects by capture facility, storage type and region [30].

Figure 1-2 provides a global snapshot of planned and operational large-scale CCS projects by project type and region. For integrated large-scale projects, there is approximately 176 Mt/year of stored CO_2 in projects under development or in construction [23]. Considering activities across all technologies, the United States and Europe together account for nearly 70% of all large-scale integrated project activity. Most of the project activity in Europe is concentrated in the Netherlands, Norway and United Kingdom. Australia and Canada account for another 25%, while the remaining projects are located in North Africa, Asia and the Middle East [23].

The regional spread of planned CCS projects reflects the ongoing funding availability for CCS by governments. Internationally, nearly US$25 billion in support of CCS projects has been announced since 2005 with the majority of this occurring during the global financial crisis and subsequent recessions in North America and in Europe [30, 31].[5] Approximately 40% of funding announced in 2008 and 2009 is related to stimulus spending during the financial crisis. Commitments by the European Union are the largest level of single government funding blocks, and when additional funding commitments by the United Kingdom and Norway are accounted for, the European funding accounts for 47% of the total commitments. Funding from the North American governments represents 37% of the funding available for CCS [31]. The majority of the available funding is targeted to support integrated CCS facilities in the power industry, as there are currently no large-scale CCS facilities in this sector [23].

1.2.1. The (commercial) deployment of CCS technologies: a global challenge

Even though CCS technologies are commercially available today and have been integrated and demonstrated on a commercial scale, the deployment of CCS the Mt to Gt per year scale amounts to a tremendous global challenge. To meet the CO_2 savings achieved from CCS deployment in one of the IEA's key scenario's that stabilizes CO_2 emissions at 450ppm, around 3 400 projects will be required worldwide by the year 2050. It requires an additional investment of over USD 2.5-3 trillion from 2010 to 2050, which is about 6% of the overall investment needed to achieve a 50% reduction in GHG emissions by 2050 [19, 22]. This number makes more sense when realizing that these projects will be capturing, transporting and storing a volume of CO_2 equivalent to twice the volume of oil and gas the world currently extracts each year.

Figure 1-3 shows that nearly half of this total number of projects will be deployed in the power sector. The capture of emissions from industrial sources will account for over 1000 projects by 2050, with over 600 located in upstream sectors. This implies that CCS is more than a strategy for "clean coal." In order to play its part in the lowest-cost GHG mitigation portfolio, the IEA [22] suggests that CCS technology also needs to be adopted by biomass and gas power plants; in the fuel transformation and gas processing sectors; and in emissions-intensive industrial sectors like cement, iron and steel, chemicals, and pulp and paper [22].

---

[5] Excluding the electricity levy announced by the United Kingdom.

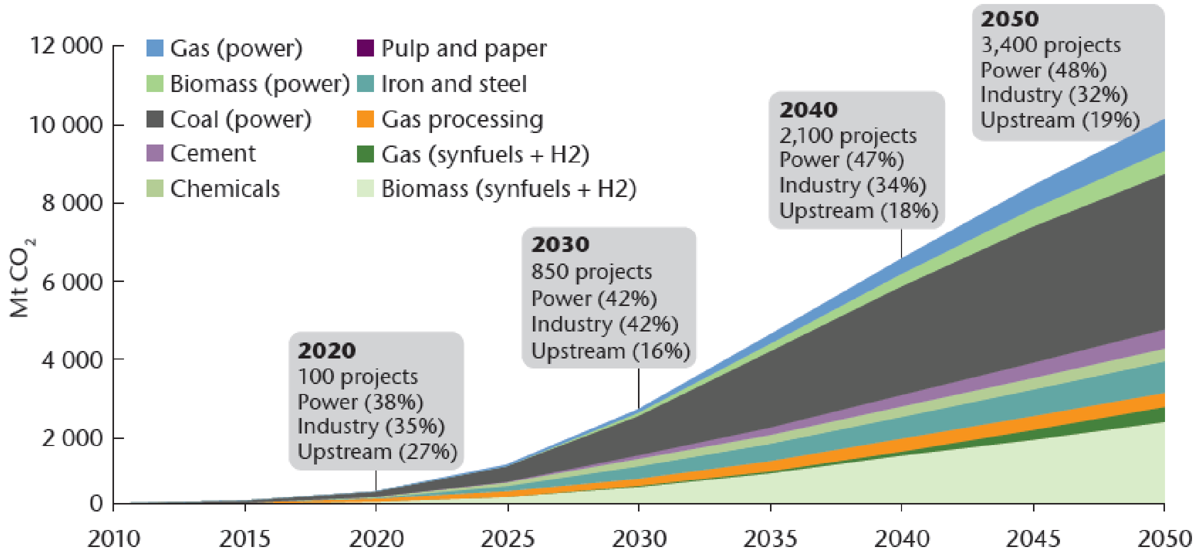


Figure 1-3: Global deployment of CCS by sector [22].

Even though, the majority of the early projects will be deployed within OECD countries, the share of CCS deployment within non-OECD regions will need to increase dramatically around 2025 to 2030 and beyond to effectively mitigate emissions from new coal-fired power plants built in emerging economies. To meet the emissions-reduction objectives of the BLUE Map scenario of IEA, capture of emissions from plants in China and India alone will need to account for over 30% of global CCS deployment in power generation over the 2010 to 2050 time period [22].

Within the coming decade, about 100 projects are needed; a significant ramp-up from today's levels of CCS deployment [22, 31]. While the current operating projects offer evidence that CCS technologies are viable at scale, many more commercial scale demonstration projects are needed in a number of countries and settings.

Even though the global status update of CCS projects showed that in 2010 there were around 85 large-scale integrated CCS under development or in operation (see Figure 1-2), it is notable that most of the 9 operating projects stem from before the year 2000 and that over the last five years, only one additional project has become operational, i.e. Snøhvit in Norway (2007). Furthermore, one additional project has progressed into the construction stage, which is the Gorgon Liquefied Natural Gas (LNG) project in Western Australia. This in contrast to the number of flagship projects that have been cancelled or postponed when nearing a final investment decision, including Statoil's Halten project in Norway, Saskpower's oxyfuel plant in Canada, and Hydrogen Energy's CCS project in Kwinana (Australia).

The rethinking of these high-profile CCS projects – which often have been portrayed as the gateway to a cleaner and secure energy future [32] – outlines that new technologies, like CCS, are often not able to negotiate the various market and institutional barriers that confront them [33]. On top of the significant technical challenges and investment requirements for these large-scale projects, the commercial risk is further increased by the existing uncertainties around legal and regulatory frameworks for CCS and the availability of long-term market incentives (like a guaranteed CO_2 price) [26]. Moreover the public and in particular communities in close proximity of a CCS project have legitimate concerns about CCS that must be addressed in order to obtain a 'social license to operate' [34].

Innovation scholars have argued that the transitional period between R&D, demonstration and commercialization is very complex and characterized by high technological uncertainty, high capital requirements and many social and political forces that interact and influence the final outcome of this phase. It's often argued that if this part of the innovation process is not well managed, either by policy makers, project managers or other stakeholders, this may lead to the development of technologies that do not match market demands or to absence of technological innovation altogether [35, 36]. On the other hand, if this process of sustainable technical change is well understood and subsequently well managed, it may allow for shaping and accelerating the development and deployment of the technology.

Understanding sustainable innovation processes requires a multi-disciplinary research focus since both technology characteristics and the social-economic environment in which the technology is developed and deployed influence the innovation process. The Innovation System approach, which has become a well-established heuristic framework in the field of innovation studies, provides such a focus and has been adopted as an analytical framework and as guideline for innovation and technology policy by numerous public organizations around the world [37-42]. Given the prominent role that CCS is now taking in global attempts to attain climate mitigation goals and the lack of knowledge regarding the CCS innovation process, the first contribution of this thesis is to provide insight into the wide range of processes that drive or hamper the development of CCS technologies by applying an Innovation System perspective.

1.3. Managing sustainable innovation processes: an Innovation System perspective

As became clear from the previous sections, CCS is a key solution within a portfolio of low carbon technologies for mitigating climate change. Together with renewable energy technologies -like wind energy, solar energy and biomass- greater energy efficiency and nuclear energy, CCS technologies play an important role in the so called 'energy transition' to the sustainable energy systems that should emerge this century to limit the long-term global average temperature rise to between 2.0ºC and 2.4ºC. Despite the enormous technological and economic potential of low emission technologies shown in various assessment studies [see e.g. 43, 44, 45], the fact is that from 1973 to 2005 the share of renewables in the total primary energy supply (TPES) in OECD countries has increased by 1.7%; from 4.5% to 6.7% of TPES [46]. Moreover, the role of CCS in mitigating climate change is still insignificant. If these technologies are to achieve dominance over conventional ways of fossil fuel use in order to meet future energy demand with reduced CO_2 emissions, this trend needs to be broken.

Underneath the trend of slowly diffusing technologies lies a world of companies, consumers, governments, scientists, regulatory frameworks and even other technologies, all interrelated [47]. This world has been well described by Unruh [48] who provides an overview of the causes underlying what he calls a ‘carbon lock-in’. Unruh explains how, over the past decades, an energy system has evolved into an interlinked complex set of actors, technologies and institutions. In the case for mobility for example, the usefulness of a car is determined by the presence of roads and the access to a fossil fuel based refuelling infrastructure. All of these technological structures are in turn embedded in institutional structures such as lease agreements, logistics and commuting patterns [47]. This illustrates the problematic situation for low carbon energy technologies to break through, due to having to compete with an incumbent technological system based on fossil fuels that benefits from long periods of experience, leading to high efficiency, low costs, conducive institutional arrangements, and many vested interests [48].

For an emerging technology like CCS, the alignment with its surrounding structures is by definition weak, hence its ability to break through and be deployed widely on global scale is complicated. For example, existing markets do not fully account for the (current and future) costs of carbon-emitting energy technologies and for the potential benefits of emerging low-carbon technologies. Furthermore, when continuing Unruh’s reasoning, developing a transportation and storage infrastructure for CCS is not only a matter of engineering and relative price of the technology, but requires amongst others companies willing to build, own and invest in such an infrastructure, governments to conduct regional planning exercises and to develop operational standards, as well as local communities living close to pipeline corridors to accept the associated risks.

These examples show that technological innovations can be understood as the development of a set of interlinked technologies and institutions being shaped (and reshaped) through the activities of actors [49]. With these technological and institutional structures in place, the innovation process typically gains more direction and speed [50]. This coincides with the basic idea behind the concept of Innovation Systems, namely that the innovation process is strongly influenced by a network of actors that are developing, advocating or opposing the technology and by an institutional infrastructure that legitimizes, regulates and standardizes the new technology [51].

As Bergek [52] states in her thesis: “It is the character of such systems that we need to comprehend if we are to understand how an energy system is transformed and how new industries emerge”.

1.3.1. Innovation Systems and System Functions

Failures in the market and new insights obtained from innovation theories deepened the general understanding of innovation processes. Scholars such as Nelson and Winter [53], Freeman [54], Lundvall [55] and Kline and Rosenberg [36] emphasised that organisations are not innovating in isolation but in the context of an Innovation System. It has become a well-established heuristic framework in the field of innovation studies, as it presents insight in factors that explain processes of innovation [55]. The Innovation System approach is a reaction to the linear model of innovation, which starts with basic research, followed by applied R&D and demonstration, and ending with production and diffusion of the innovation. The different stages of the linear model of innovation were in general considered as separate activities, both in terms of time and in terms of the actors and institutions involved (see Godin [56] for a discussion on this topic). The Innovation System approach and the evolutionary economics literature it stems from reject this model [47]. 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 [57].

From the 1980s onwards, Innovation System studies have pointed out the influence of the social system on innovative performance, and indirectly on long-term economic growth, within nations, sectors or technological fields. Hence, the existence in literature of different Innovation System approaches, like National Innovation Systems [55, 58, 59], Regional Innovation Systems [60, 61], Sectoral Innovation Systems [62] and Technological Innovation Systems [51, 63-65]. Conceptually, the various Innovation System approaches are comparable since the difference between them is largely a matter of geographical and/or techno-economical delineation, i.e., of system boundaries.

A number of scholars have adopted the Innovation System framework to study processes of socio-technical change and in many studies the focus was on emerging sustainable energy technologies [47, 50, 52, 63, 65-74]. More specifically these authors have adopted the Technological Innovation System (TIS) approach as introduced by Carlsson and Stankiewicz [51] as ‘A dynamic network of agents interacting in a specific economic/ industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology.’ The focus of the TIS approach on the institutions and networks of agents involved in the generation, diffusion, and utilization of a specific technology fits best with the major interest of this thesis: i.e. to understand and analyze technological innovation in terms of the structures and processes that support (or hamper) the development and (commercial) deployment of CCS.

Besides being less broad than the National and Sectoral Innovation System approaches, the TIS framework sets itself apart because of two main aspects [47]. The first is that the TIS approach emphasizes the ability to develop and exploit new business opportunities, as a crucial aspect of technological innovation. Instead of focusing solely on the generation and exchange of knowledge, it stresses the need to exploit this knowledge, or to actively recombine knowledge in order to create new business opportunities. The second feature that distinguishes TIS studies from other IS approaches is a more serious focus on system dynamics. The focus on entrepreneurial action and system dynamics has encouraged scholars to consider a TIS as something to be build-up over time.

Since Carlsson and Stankiewicz introduced the concept of a TIS, an increasing number of scholars have provided insights in the dynamics of this build-up process [50, 52, 65, 68, 72, 73, 75, 76]. This literature stresses that emerging technologies will pass through a so-called formative stage, before they can be subjected to a market environment [50].[6] During this

[6] This formative stage includes a ‘predevelopment phase’, which is the first phase in the build-up of an Innovation System. The phase ends when a working prototype is available on the market. The subsequent ‘take off phase’ is characterised by a small but increasing demand for the new technology. The formative stage is

formative stage actors are drawn in, and their networks grow in terms of size and density. Furthermore, institutions are designed and adjusted with the aim of increasingly aligning them to the emerging technology. On the other hand, when a TIS grows the rate of technological progress generally increases which in turn leads to increased chances of success for the technology in question. A TIS approach may focus on these changes in structure and their effects on technological innovation, but it may also focus on the processes underlying the structural build-up of the system [77].

This focus on process or 'function' is a relatively novel addition to the TIS approach and has not been addressed in a systematic manner in earlier work on Innovation Systems [78].[7] Galli and Teubal [67] started some thinking in this direction, which was followed up by Johnson [69], Jacobsson and Johnson [65], Liu and White [70], and Rickne [76], and tested and further developed by the Innovation Studies Group of the Utrecht University [47, 68, 78]. They argue that the primary goal of an Innovation System is to contribute to the development and diffusion of innovations. The novelty of the work by the authors above is that they reflected on different sub-functions, which are considered to be important for an Innovation System to develop and grow and, thereby, to increase the success chances of the emerging technology.

In this thesis, the term "system function" refers to these sub-functions instead of to the goal of an Innovation System. These system functions – e.g. knowledge diffusion and market creation – are decisive processes that have a direct impact on the development and diffusion of new technologies. The premise is that the structural components of the system – i.e. actors, their networks and institutions– should be successfully arranged to bring about an optimal fulfilment of a set of system functions, each of which covers a particular aspect of technological innovation. Therefore, a well-functioning Innovation System accelerates technological development and increases the success chances of a new technology, while a poorly performing Innovation System hampers technological innovation [78].

A number of studies have applied the Innovation System Functions approach, which has led to several lists of system functions in the literature [50, 52, 63, 65-67, 69, 70, 74]. Below the recently developed list of system functions at Utrecht University [71-73, 79] is presented.[8] This list has been applied to map, describe and explain the dynamics of a number of Technological Innovation Systems for low-carbon technologies.

Function 1: Entrepreneurial Activities. The existence of entrepreneurs in Innovation Systems is of prime importance. Without entrepreneurs innovation would not take place and the Innovation System would not even exist. The role of the entrepreneur is to turn the potential of new knowledge development, networks and markets into concrete action to generate and take advantage of business opportunities.

---

followed by an acceleration phase, which features strong growth in diffusion of the technology in question and a stabilization phase, which is characterised by the stabilisation of the demand or the technology.

[7] The use functions is an attempt to relate Innovation Systems explicitly to general systems theory, which has been used much more in natural sciences than in social sciences. This has led to a strong focus on Innovation System functioning since one of the characteristics of a 'system' from a general system perspective is that it has a function, i.e. it is performing or achieving something [78].

[8] This list of System Functions has been, to a large extent, developed in agreement with researchers from Chalmers University (Sweden), to be applied to empirical work both in the Utrecht and the Chalmers group [47].

Function 2: Knowledge Development. Mechanisms of learning are at the heart of any innovation process. For instance, according to Lundvall: "the most fundamental resource in the modern economy is knowledge and, accordingly, the most important process is learning"[55]. Therefore, R&D and knowledge development are prerequisites within a TIS. This function encompasses 'learning by searching' and 'learning by doing'.

Function 3: Knowledge Diffusion. According to Carlsson and Stankiewicz [51] the essential function of networks is the exchange of information. This is important in a strict R&D setting, but especially in a heterogeneous context where R&D meets government, competitors and market. Here policy decisions (standards, long term targets) should be consistent with the latest technological insights and, at the same time, R&D agendas are likely to be affected by changing norms and values. For example if there is a strong focus by society on renewable energy it is likely that a shift in R&D portfolios occurs towards a higher share of renewable energy projects. This way, network activity can be regarded as a precondition to 'learning by interacting'. When user producer networks are concerned, it can also be regarded as 'learning by using'.

Function 4: Guidance. The activities within the Innovation System that can positively affect the visibility and clarity of specific wants among technology users fall under this system function. An example is the announcement of the policy goal to aim for a certain percentage of renewable energy in a future year. This grants a certain degree of legitimacy to the development of sustainable energy technologies and stimulates the mobilisation of resources for this development. Expectations are also included, as occasionally expectations can converge on a specific topic and generate a momentum for change in a specific direction.

Function 5: Market Creation. A new technology often has difficulties to compete with incumbent technologies. Therefore it is important to create protected spaces for new technologies. One possibility is the formation of temporary niche markets for specific applications of the technology [50, 80, 81].This can be done by governments but also by other agents in the Innovation System. Another possibility is to create a temporary competitive advantage by subsidies, favourable tax regimes, or minimal consumption quotas, as a result of public policy.

Function 6: Resource Mobilisation. Resources, both financial and human, are necessary as a basic input to all the activities within the Innovation System [51]. Specifically for renewable energy technologies, the availability of the renewable energy resource itself is also an underlying factor determining the success or failure of an investment in specific conversion technologies.

Function 7: Creation of legitimacy. In order to develop well, a new technology has to become part of an incumbent regime, or has to even overthrow it. Parties with vested interests, or societal groups, may oppose this force of 'creative destruction'. In that case, advocacy coalitions can function as a catalyst to create legitimacy for the new technology and to counteract resistance to change.

1.3.2. System dynamics and performance

The system functions are types of processes necessary for a TIS to build-up. They may also be considered as criteria to be used for evaluating the performance of a TIS in the formative stage. This is important since, in the formative stage of technology development, data about output measures, such as market diffusion, and environmental or techno-economic features, are usually absent or pre-mature. The system function approach makes it possible to analyze and evaluate the development of TISs in dynamic terms.

Both the individual performance of each system function and the interaction dynamics between them are of importance. Positive interactions between system functions could lead to a reinforcing dynamics within the TIS, setting off virtuous cycles that lead to the diffusion of a new technology. An example of a virtuous cycle that can be expected regularly in the field of sustainable technology development is the following. The virtuous cycle starts with F4: Guidance of the Search. In this case, environmental problems are identified and government goals are set to limit or solve the problem. These goals legitimise the mobilisation of resources to finance R&D projects in search of solutions (F6), which in turn, is likely to lead to Knowledge Development (F2) and increased expectations about technological solutions (F4). Thus, the fulfilment of the individual functions is strengthened through interaction (Figure 1-4) and if such positive dynamics between functions were understood better, this could point out how a TIS is to be directed through its formative stage into a stage of market expansion [50].[9]

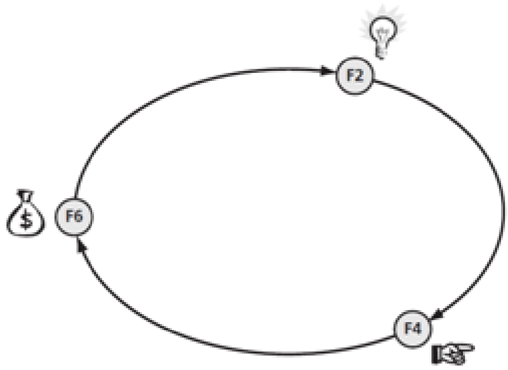


Figure 1-4: A reproduction of a positive feedback loop of system functions [47].

Given the interdependency of the system functions, one can say that a well-developing TIS is characterized by one or more virtuous cycles. A system in decline is, however, also characterised by one or more vicious cycles, where the system functions interact and reinforce each other in a negative way. For example, Kamp [82] has shown that the Dutch wind energy Innovation System was well developed in the 1980s but collapsed as a result of the absence of knowledge exchange between the emerging turbine industry and users, the latter being mainly energy companies. In this sense, technological innovation is a complex outcome which is determined by its weakest element(s). Evaluative studies therefore typically point out the

[9] In his thesis, Suurs [47] has made an attempt to generalize such findings in order to establish a more theoretical understanding of TIS dynamics.

relative strengths and weaknesses of particular TISs, usually on the basis of national or sectoral comparisons.

As mentioned above, in the formative stage, technology diffusion has hardly taken place and thus it is important to take into consideration intermediate criteria of system performance. It is expected that as actors, institutions, and technologies are successfully arranged to increase their ongoing contribution to system functions, the chances of (eventual) technology diffusion will increase; see also Bergek [83]. Therefore, system functions make suitable performance criteria for a TIS in the formative stage. As Bergek suggests: 'System performance may be evaluated in terms of the "functionality" of a particular Innovation System, i.e. in terms of how well the functions are served within the system' [52].

There is no standard yet for appraising the performance of each individual system function in terms of some kind of threshold that needs to be surpassed. Instead, success or failure may be determined on the basis of expert opinions. Several indicators or so-called diagnostic questions for different system sub-functions have been proposed for performance assessment (see Table 1-3). This way, evaluation will emerge as a socially constructed judgement that arises from within a TIS. The researcher has the task of collecting all these value judgements, making an overview of them. It is also the task of the researcher to relate successes and failures, via events, to the seven system functions. This way, the set of system functions provides a framework for the evaluation of a TIS in the formative stage, in terms of activities that contribute to its build-up (or breakdown).

Based on a combination of these evaluative approaches it will be possible to formulate strategies for policy makers and other practitioners that aspire to understand and influence emerging energy technologies. These strategies can be directed at strengthening the performance of specific system functions.

In sum, quite some progress has been achieved in order to make the Innovation System concept operational for the analysis of technological change. However, as the nature of this research is mostly descriptive and the case examples are rather limited, it is difficult to compare Innovation Systems and explain the observed differences. Therefore, Markard and Truffer [84] argue that additional refinement and alignment is needed with regard to performance assessment of emerging Innovation Systems (e.g. indicators for different functions). What seems to be missing is an objective bench mark that gives an indication of the performance of an emerging TIS and allows for system comparison. Therefore, this thesis aims to contribute to the Innovation System Functions literature by applying several methods of performance assessment of emerging Technological Innovation Systems that allow for system comparison and to demonstrate how the insights it generates can be useful to technology managers that wish to accelerate the future (commercial) deployment of CCS technologies.

1.4. Research objectives & questions

The research objectives that can be abstracted from the above are threefold and very much intertwined:

1. The first objective of this thesis is to provide insight into the range of processes that drive or hamper the development of CCS technologies in a number of selected countries: the United States, Canada, Norway, the Netherlands, and Australia, by applying the Innovation System Functions approach.
2. The second objective is to demonstrate how these insights in the dynamics and performance of CCS Innovation Systems can be useful to technology managers that wish to steer the future (commercial) deployment of CCS.
3. The third objective is to contribute to the Innovation System Functions literature by providing original and rich case study material, as well as by applying new methods of performance assessment of emerging Technological Innovation Systems.

Consequently, three exploratory research questions have been formulated to meet the overall objectives of this thesis:

1. How did the Innovation System around CCS technologies build-up up over time in the United States, Canada, Norway, the Netherlands and Australia and what are the main drivers and barriers encountered for further growth?
2. How can the development and deployment of CCS technologies be accelerated based on these insights into the historical dynamics and current performance of CCS Technical Innovation Systems in industrialized countries?
3. How can the assessment of dynamics and performance of Technical Innovation Systems be improved based on methods from other fields of innovation research?

1.5. Research design

In the remainder of this thesis the three research questions will be answered by studying the dynamics and performance of CCS Innovation Systems in five different countries. For each Innovation System, the drivers and barriers for its evolution will be identified. The results from the case studies will then be compared with each other. Based on these evaluative and comparative insights into the performance of the various TISs, strategies will be presented that may improve the functioning of the system and accelerate the development and deployment of CCS. In the country specific case studies different methods for evaluating the dynamics and performance of a TIS will be applied and discussed. Also directions for improving of the Innovation System Functions approach will be given. An overview of the research design is presented below.

1.5.1. Case study selection

This thesis aims to provide insight into what brings about progress during the formative stage of TIS development for present-day CCS technologies and to present strategies that could accelerate the progress of CCS. For meeting such objectives connected to ‘real life’ situations, a case study approach is most sensible [85]. A disadvantage of case study research is that it is time consuming. Within the duration of the research presented in this thesis, five cases are covered. This limitation implies that a generalization across cases cannot be done on the basis of statistics [47]. Instead generalization should be done by comparing and arguing from the content of the cases [86], and by relating these results to theory.

This thesis consists of five case studies that each focus on the historical development and the current performance of a TIS around CCS technologies for a particular country. The countries selected, include Canada, The United States, The Netherlands, Norway and Australia. As discussed in Section 1.2., these countries form the forefront of CCS development in the world and are therefore a logical choice for an in depth TIS analysis. Moreover, these cases should cover a long enough time-span and include enough variety of activity, i.e. build-up processes. This is of particular importance, as one of the main aims of this thesis is to synthesize these insights into strategies that could accelerate the deployment of CCS technologies on a global scale. A short introduction to the various case studies, including a rational for the development of CCS in these countries, is given below:

- *Norway* is the largest petroleum exporting country of Europe and Norway's increase in GHG emissions with 8% over the past two decades is mainly caused by a steep emission growth of the oil and gas industry. The Norwegian GHG emissions may rise even further, if the considered diversification strategy towards gas-fired power plants is pursued to meet a growing electricity demand. CCS offers a solution to Norway’s twin challenge of reducing GHG emissions while supporting the growth of its most important industries. The Norwegian industry already gained valuable experience in this area from its CO_2 storage operations at the subsurface Utsira reservoir, where 1 Mt CO_2 is injected into a sub-surface reservoir each year, since 1996. Meanwhile, CCS activities—particularly those concerning natural gas-based power production—have increased significantly over the past ten years in Norway, as the deployment of CCS plays an important role in the Norwegian climate and energy policy.
- *The Netherlands* has taken a leading role in the international CCS research community for over 20 years now. The Netherlands also has decades of industrial experience with the transmission, distribution and processing of natural gasses. Moreover, it is having substantial CO_2 storage capacity, which could be a valuable asset in developing a CCS infrastructure. CCS has been identified in Dutch climate policy as one of the key routes towards a low emissions energy future. At present there are 4 new coal fired stations planned to be build in the Netherlands. Without integrating CCS into these new power stations, it will be hard for the Netherlands to meet its emission reduction targets.
- In *The United States* CO_2 emissions from fossil fuel based power generation contributes close to 40% of the total CO_2 emissions. This number is expected to increase by 2% in the next decade. To balance the demand of both reducing GHG emissions and assuring a reliable energy supply, political leaders in the US have introduced CCS as a viable technological option to address both issues. The US Department of Energy (DOE) is taking a leading role in the advancement of CCS technologies. Through its Carbon Sequestration Program – managed by the office of fossil energy and implemented by the

National Energy Technology Laboratory (NETL) – DOE has been supporting the development of a large variety of CCS technologies since 2003. There are three main components to the US CCS activities: core R&D related to CCS; deployment through the Regional Carbon Sequestration Partnerships (RCSPs); and major demonstration projects through the Clean Coal Power Initiative and FutureGen efforts.

- *Canada*'s oil, natural gas and coal resources place the country firmly on the map of world-class energy locations. At 180 billion barrels of recoverable reserves, Canada is second to Saudi Arabia in national oil reserves. The country's low cost of energy resources provide important export opportunities and makes domestic heavy industries internationally competitive. Led by the growth of Canada's energy sector, notably the development of oil sands in Alberta, GHG emissions increased tremendously over the past 20 years. Already in 2006, Canada's GHG emissions amounted to 28% above its commitments under the Kyoto Protocol Kyoto target. The provinces that are responsible for most of the increase in GHG emissions are situated on the Western Canadian Sedimentary Basin, a location with a potential to store Canada's CO_2 emissions for decennia's. The co-location of Canada's major emission sources and potential storage reservoirs provides an important opportunity for Canada to implement CCS in order to limit its GHG emissions.
- *Australia* has a strong vested interest in reducing its GHG emissions, as the nation seems to be very vulnerable to the broad economic, social and environmental impacts of climate change. At the same time Australia derives substantial economic benefits from its abundant energy resources and from the competitiveness and reliability of its stationary energy system. It has attracted major energy intensive industries such as minerals extraction and metals processing. Energy commodity exports itself –i.e. coal, oil and (liquefied) natural gas- are also vital to the economy. In fact, black coal is the country's largest export product; generating more than $25 billion in exports in 2007, making Australia the world's largest exporter of coal. The importance of coal in the economy, the growing electricity demand, limitations on the potential for fuel switching and harnessing renewable energy sources, are the reason that CCS is an integral part of the Australia's greenhouse response.

In order to facilitate comparison across the cases, all studies apply the Innovation System Functions framework to create insight into the wide range of processes that drive or hamper the development of CCS technologies. The practical relevance of the analytical framework applied to all case studies is based on the assumption that policy interventions directed at stimulating sustainable changes in the energy system should focus on improving Innovation System Functions that operate weakly in order to increase the chances of positive system dynamics. To specify these interventions in the Innovation System it is necessary to analyze the relationship between the historical dynamics and the current performance of the Innovation System. However, the methods used to gain insight about the relationships between Innovation System dynamics, performance and intervention, are varied across the case studies.

1.5.2. Methods for analyzing Innovation System dynamics and performance

So far, the methods that have been used to analyze the build-up and performance of a TIS are literature reviews, interviews with key stakeholders [83], history event analysis [47, 71], or a combination. All these methods will be applied in the various case studies presented in this thesis. Furthermore, this thesis aims to complement these existing methods by applying quantitative methods that stem from other fields of innovation research: social network analysis; bibliometric analysis, media analysis and project analysis.

Social network analysis will be applied in this thesis to detect network formation, and gain more insight in the function of "knowledge diffusion". The bibliometric- and project analyses will be used to assess the fulfilment of the functions "knowledge development" and "entrepreneurial activities". Moreover, media analysis is expected to provide additional insights in the function: "Creation of Legitimacy". Although the possible benefits of these methods for TIS research has been mentioned several times in literature [see e.g. 64, 84], they have not yet been applied in empirical work to study the build-up of a particular TIS.

The methods that were used in this study and the particular case studies in which they have been applied, are described below (see also Table 1-2).

Table 1-2: Overview of case studies and methods applied in the chapters of this thesis.

Case Study / Method	Interviews and Literature Review	Event History Analysis	Group Decision Support System	Media Analysis	Project Analysis	Social Network Analysis	Bibliometric Analysis	Comparative Analysis	Chapter
Norway	X							X	2, 6
Australia	X							X	6
Netherlands	X	X	X	X				X	3, 6 & 7
United States	X				X	X		X	4, 6
Canada	X				X	X	X	X	5, 6

Interviews and Literature review

In order to map out the historical dynamics of the Innovation Systems in terms of (interactions between) functions and ascertaining to what extent the Innovation System Functions have been fulfilled, semi-structured interviews have been conducted with the main actors involved in the development and deployment of CCS in all five countries under study. In order to improve the comparability and reliability of the case studies, a number of indicative questions that provide insight in the fulfilment of the functions have been applied (see Table 1-3). The results of the interviews have then been verified and complemented by additional 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; representatives from natural resource companies as well as electric utilities; policy makers at various government levels). With cross-referencing as well as external justification, the validity of the group of interviewees has been guaranteed.

To minimize the personal bias of the researcher and to further assess the system's performance, the interviewees also reflected 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 [87] where 1 = very weak, 2 = weak, 3 sufficient, 4 = good and 5 = very good. The respondents also have given their view on what should be done to improve the fulfilment of system functions that are impeding a higher performance of the system. This provides the basis for advice on policy strategies to enhance the development and deployment of CCS.

Event History Analysis

Recently several authors have taken a more systematic approach to the historical analysis of TIS dynamics by adopting (and adapting) the event history analysis [see e.g. 71, 72, 88, 89]. This method was originally developed by Poole [90] and Van de Ven [91, 92] and has been proven to be a useful way to systematically analyze complex longitudinal data. The process approach conceptualizes development and change processes as sequences of events. By gathering data that indicates how the process unfolds over time, a timeline and narrative of events can be constructed that provides significant insights into the development and change processes [47].

The data collection is not so much about following all of the individual actors or innovation projects in the system, it contains the events that are reported at system level relevant to the development of CCS. The sources of data for the event analysis comprehend the Lexis Nexis TM academic news archive [93], specialized journals, and scientific literature. Then each event related to the development, diffusion, or implementation of CCS technologies has been listed chronologically in a database, for example workshops on the technology, the start-up of R&D projects, expressions of expectations about the technology, or announcements of resources made available. The database has then been structured according to year of the event, reference articles, event description, and system function involved. Each event is allocated to one system function using the classification scheme, presented in Table 1-4.

The event database is then used to construct a narrative that describes the appearance and evolution of the national CCS Innovation System. It explains the growth of the system in terms of changes in the fulfilment of Innovation System Functions by its components. This narrative has been used to point out how system functions reinforce or antagonize each other through time; thereby creating insight in the historical dynamics (growth or decline) of the TIS.

Table 1-3: Indicative questions that reflect the extent to which each function in the Innovation System is fulfilled by the components of the system [see also 68, 83].

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: Creation of Legitimacy
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)?

Table 1-4: Event types as indicators of functions [47].

System function	Event types
F1. Entrepreneurial Activities	Projects with a commercial aim, demonstrations, portfolio expansions
F2. Knowledge Development	Studies, laboratory trials, pilots, prototypes developed
F3. Knowledge Diffusion	Conferences, workshops, alliances, joint ventures, platforms, branch organizations
F4. Guidance of the Search	Expectations, promises, policy targets, standards, research outcomes
F5. Market creation	Regulations supporting niche markets, generic tax exemptions, 'obligatory use'
F6. Resource Mobilisation	Subsidies, investments, infrastructure developments
F7. Creation of Legitimacy	Lobbies, advice

Group Decision Support Systems

Based on the current performance of the system, in relation to what is reasonable to expect taking the historical development of the TIS into account and according to the judgment of key actors in the system, it is possible to specify strategic actions in terms of what should be done to improve the fulfilment of those system functions that were seen as obstructing positive system dynamics and thereby impeding a higher performance of the entire CCS Innovation System.

In the analysis for the Netherlands, the strategy development process has been facilitated by an additional workshop with CCS experts. They were brought together in an Electronic Board Room (hardware) with a Group Decision Support System (software) [94]. Again a broad representation from Industry, Government and Research has been sought in the composition of the participating CCS stakeholders. This interactive, computer-based system facilitates participants to communicate simultaneously and anonymously on unstructured and semi-structured problems by brainstorming, giving comments, and voting on statements [95]. In the Dutch case study the characteristics of a Group Decision Support System have been used to encourage open discussions between the stakeholders on the strengths and weaknesses of the Dutch CCS Innovation System and to construct strategies that would accelerate the built up of CCS Innovation System in the Netherlands.

Generally speaking, a Group Decision Support System may positively affect the following aspects of problem analysis [94, 96]:

4. The system increases insight into the complexity of a problem: the involvement of different stakeholders can lead to a clustering of information and insights that, together, have a surplus value;
5. It enables testing and evaluating: compared with individuals, a group of stakeholders can better assess the reality of results or solutions for a problem;
6. It increases acceptance: involvement of a variety of interests may broaden the insight into the needs and points of view of different participants, which may contribute to the acceptance of solutions;
7. It stimulates synergy and creativity: the involvement of different interests in the analysis of a problem can stimulate creativity when participants build on others' ideas, using insights and knowledge from different angles.

Media Analysis

In order to gain more insight in the fulfilment of Function 7: “Creation of Legitimacy”, the role of the print media in framing CCS technology in their communication to the public has been further investigated in the analysis of the Dutch CCS Innovation System. Therefore all documents related to CCS in the main Dutch daily newspapers were retrieved from the LexisNexis® Academic database [93]. The irrelevant articles have then been removed from the database and the remaining set comprised over 800 articles, covering a time period from 1991 – when the first article appeared – until 2009.

In the content analysis of the Dutch news articles on CCS, first of all, the events that triggered the publication of these articles have been recorded in the database; e.g. such as policy announcements, or the release of scientific reports. The extent to which external events stimulate media coverage has been explored and influence the way the press perceives and portrays CCS. For example, an increase in these ‘trigger events’ could change the way the media interpret and, subsequently, presents CCS to the public. Furthermore, it gives an indication of the recognition of CCS in the media (as more CCS related issues are being published) and it presents the background for the media portrayals of CCS technology. This helps to understand the legitimacy of CCS as portrayed in the media.

The legitimacy for CCS can be depicted by the distribution of positive, negative, and neutral articles over time. Articles have been classified ‘positive’ if the majority of statements used in the article were in favour of CCS, ‘neutral’ if the number of negative and positive statements was balanced, and ‘negative’ if the majority of statements and the overall impression of the article were negative towards CCS. A fourth category has been introduced, indicating whether CCS is mentioned in an article but not discussed as such. A second researcher has checked this classification, after which differences have been discussed to harmonize the classification procedure. In cases of doubt, more attention has been paid to the title and the first few lines of the article. Finally, the main arguments in favour or against CCS have been distilled from each article, as well as the type of actors linked to these arguments if they have been cited in the article.

Project Analysis

In order to assess the variety and advancement in the CCS knowledge base (Function 2) and the level of Entrepreneurial Activity (Function 1), two comprehensive project databases have been constructed for the cases of Canada and the United States. The databases contain around 150 CCS projects each that have been carried out in North America between 2000-2009, involving more than 400 actors in total. The most important source of information for the construction of the databases are the NETL ‘Carbon Sequestration Project Portfolio’s’ and the Canadian CCS Compendium [97]. The data has been complemented and verified using the CCS database of the IEA GHG R&D program [98]. Additional information has been gathered using various reports, project fact sheets and interviews with project managers. The following data has been recorded for each project in the database:

1. The name and organisational background (e.g. oil and gas industry, universities) of the actors involved in a project.
2. The technological focus of the project, distinguishing between three categories: CO_2 capture, CO_2 storage, and other CCS areas, including CO_2 transportation, public acceptance and policy analysis. The capture projects have then been subdivided into post-, pre-, and oxyfuel combustion; and in storage there have been three main types of geological reservoirs distinguished, i.e. saline aquifers, oil & gas fields (depleted and producing) and coal seams.

3. Each project has been classified in terms of 'distance to market'. A project is considered: a) basic and applied R&D; b) demonstration (early prototypes up to full-scale working devices) and c) pre-commercial (commercial scale- and integrated demonstration projects).
4. Finally, the start and end date, as well as the costs of the project have been recorded in order to gain insight in distribution of costs among the CCS component technologies over time.

Social network analysis

Social network analysis has been applied to identify the actor networks involved in the American and Canadian CCS Innovation Systems between 2000 and 2009. The social network approach assumes that the linkages among actors can favour or impede the development of innovations in the system [99]. The analysis identifies size and connectivity of the network structure as a major factor to help the system evolve [100]. The size of the network is characterized by three measures: number of actors, the size of the largest component –i.e. connected parts of the network- and average distance between actors in the network. The connectivity of the network is determined based on the average number of linkages per actor (mean degree) and the clustering coefficient, a measure to determine the existence of relative dense clusters in the network [101]. Social network analysis can also be performed on actor level. The number of linkages of an actor (node degree) and its betweenness are centrality measures indicating the position of an actor in the network. The betweenness of an actor is determined by the number of times that it is positioned on the shortest path between other actors.

In this study, two actors have been considered to be related when they are involved in the same CCS project. Involvement could take the form of a cooperative R&D effort, a policy network, but also a commercial joint venture. In order to specify the relations between actors in the Innovation System, the CCS project database as described above has been used. To create a network, an adjacency matrix A has been created. In this matrix, actors have been placed on top of the columns and rows. If a link exists between actors, this is represented by a positive value in the cell. The Adjacency matrices have then been used in specialized network software to visualize the networks, i.e. Visone [102] and UCINET 6 [103].

Bibliometric analysis

Bibliometric analysis has been applied to gain further insight in the CCS knowledge base (Function 2) develope din the Canadian CCS Innovation System. The scientific output of Canadian research institutes documented in the Scopus abstract and indexing database has been systematically analyzed for the period 2000-2009. The Scopus database covers over 15,000 peer-reviewed journal titles and is thereby the largest of the currently available databases for scientific searches [104]. The analysis included 138 selected articles for "CCS" or a combination of "Carbon/CO_2, Capture/Separation, and Storage/Sequestration" in the title, abstract, or key words. Analyzed parameters included affiliation and the technological focus of the study.

Comparative Analysis

Each case study will yield insights that hold for a particular TIS. In order to provide general insights, on how the dynamics come about, it is necessary to combine results from multiple cases, thereby strengthening the results through a logic of replication [85]. It is argued that a comparative analysis between different TISs across nations is a powerful way of improving the understanding of decision makers, as it provides an opportunity to learn from a broad range experiences regarding the development of CCS technologies in other countries (see e.g. [76] for biomaterials in Sweden, Massachusetts and Ohio and [105] for wind turbines in the Netherlands and Denmark). Most importantly, the question of how these systems are performing could be answered on the basis of comparison.

In this thesis the strengths and weaknesses of the different Innovation Systems will identified and compared, which is vital for the development of coherent long-term policy strategies that may enhance the successful deployment of CCS technologies in North America, North Western Europe and Australia. The comparative analysis also allows for a cross-national comparison on a function level; e.g. differences in focus of R&D programs and variation in regulatory frameworks.

1.6. Thesis outline

The remainder of this thesis is structured as follows:

Chapter 2 presents the results of the analysis of the Norwegian CCS TIS. Particular attention is paid to the pioneering role that Norway played in the development of CCS, which led to a remarkable build of the Innovation System. Furthermore, the Innovation System Functions approach is used to identify key issues that need to be addressed in order to prolong Norway's international leadership position in the development of CCS.

Chapter 3 presents the results of the case study on the Dutch CCS TIS. The core of this analysis is the construction of a narrative around the build up of the TIS, which is based on the recognition of patterns in event data. These insights are used to evaluate the current status of the “transition pathway CCS” in order to formulate new strategic policies to accelerate the energy transition process.

Chapters 4 presents the results of the evaluative analysis of the development and deployment of CCS technologies in the United States. In this case study the analysis of Innovation System Functions is refined by applying quantitative methods, like social network analysis. This study provides a clear understanding of the current barriers to the technology's future deployment and outlines a policy strategy that may relief these barriers.

Chapter 5 presents the results of the fourth case study, i.e. the Canadian CCS Innovation System. This study applies a range of quantitative and qualitative measures to gain insight in the fulfilment of Innovation System Functions. Furthermore, this chapter demonstrates how these insights can be useful to technology managers and policy makers in Canada that wish to strengthen their CCS programs.

Chapter 6 broadens the perspective on TIS performance by comparing the developments in the Dutch, Norwegian, American, Canadian, and Australian[10] TISs around CCS technologies. The cross-national comparison provides an opportunity for technology managers to learn from a broad range of experiences regarding the development of CCS technologies in other countries.

Chapter 7 zooms in on the fulfilment of one particular system function in the Dutch CCS TIS, namely “Creation of Legitimacy”. This Chapter describes an extensive study on the acceptance of CCS by stakeholders in the Netherlands and explores one of the determining factors in the creation of legitimacy for CCS by the lay public, i.e. the way the Dutch press perceives and portrays CCS.

Chapter 8 reiterates the background, objectives and scope of this thesis. Then the answers to the research questions of this thesis are provided and the main outcomes from the analyses presented in the previous chapters are highlighted. Finally, future research avenues are indicated.

[10] The performance assessment of the Australian CCS TIS will only be presented as part of this comparative analysis and is not presented in a separate Chapter.

References

1. IPCC (2007). *Summary for Policy makers. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change*, ed. B. Metz, et al. Cambridge University Press. Cambridge (UK), New York (USA).
2. IPCC (2007). *Climate Change 2007: Mitigation of climate change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. B. Metz, et al. Cambridge University Press. Cambridge (UK), New York (USA).
3. Oreskes, N. (2004). *Beyond the ivory tower: The scientific consensus on climate change.* Science. 306(5702): p. 1686.
4. UN (1992). *United Nations Framework Convention on Climate Change (UNFCCC).* United Nations.
5. Climate Congress (2009). *Synthesis Report, Climate change, Global Risks, Challenges and Decisions*: Copenhagen (Denmark).
6. IPCC (2001). *Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, ed. R.T. Watson and the Core Writing Team. Cambridge University Press. Cambridge (UK), New York (USA): p. 398.
7. Smith, J.B., S.H. Schneider, M. Oppenheimer, G.W. Yohe, W. Hare, M.D. Mastrandrea, A. Patwardhan, I. Burton, J. Corfee-Morlot, C.H.D. Magadza, H.-M. Fussel, A.B. Pittock, A. Rahman, A. Suarez, and J.-P. van Ypersele (2009). *Assessing dangerous climate change trough an update of the intergovernmental Panel on Climate Change (IPCC) "reasons for concern"*. Proceedings of the National Academy of Sciences 106(11): p. 4133-4137.
8. Meinshausen, M., N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M.R. Allen (2009). *Greenhouse-gas emission targets for limiting global warming to 2 °C.* Nature 458(7242): p. 1158-1162.
9. COP15 (2009). *Copenhagen accord, Decision -/CP.15*, Conference of the parties: Copenhagen (Denmark).
10. IEA (2009). *CO2 emissions from fuel combustion. Highlights (2009 edition)*, IEA/OECD: Paris (France).
11. IEA (2010). *World Energy Outlook 2010*, IEA/OECD: Paris (France).
12. WEA (2004). *World Energy Assessment: overview 2004 Update*, Prepared by UNDP, UN-DESA and the World Energy Council, United Nations Development Programme: New York (USA).
13. EIA-DOE (2010). *Annual Energy Outlook 2010*, Energy Information Administration, United States Department of Energy (DOE): Washington D.C. (USA).
14. IPCC (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*, ed. B. Metz, et al. Cambridge (UK).
15. IEA (2008). *CO2 Capture and Storage: A Key Carbon Abatement Option*. IEA/OECD. Paris (France).
16. Azar, C., K. Lindgren, M. Obersteiner, K. Riahi, D.P. van Vuuren, K. Michel, G. J. den Elzen, K. Möllersten, and E.D. Larson (2010). *The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS).* Climatic Change. 100: p. 195–202.
17. IIASA (2010). *CO2 could sink without trace by 2100*, International Institute for Applied Systems Analysis: Laxenburg (Austria).
18. IEA (2008). *World Energy Outlook 2008*, IEA/OECD: Paris (France).
19. IEA (2008). *Energy Technology Perspectives 2008- Scenarios & Strategies to 2050*, IEA/OECD: Paris (France).
20. IEA (2010). *Energy Technology Perspectives 2008- Scenarios & Strategies to 2050*, IEA/OECD: Paris (France).

21. Stern, N. (2007). *The Economics of Climate Change: The Stern Review.* Cambridge University Press. Cambridge (UK), New York (USA).
22. IEA (2009). *Technology roadmap: Carbon Capture and Storage*, IEA/OECD: Paris (France).
23. GCCSI (2010). *Status of CCS Overview 2010*, Global Carbon Capture and Storage Institute: Canberra (Australia).
24. Henderson, C. and S.J. Mills (2009). *Clean Coal Roadmaps to 2030*, IEA Clean Coal Centre: London (UK). p. 105.
25. IEA GHG (2006). *Near zero emission technology for CO2 capture from power plant, 2006/13*, IEA Greenhouse Gas R&D programme: Cheltanhan (UK).
26. GCCSI (2009). *Strategic Analysis of the Global Status of Carbon Capture & Storage*, Global Carbon Capture and Storage Institute: Canberra (Australia).
27. Dooley, J.J., C. L. Davidson, and R.T. Dahowski (2009). *An Assessment of the Commercial Availability of Carbon Dioxide Capture and Storage Technologies as of June 2009*, United States Department of Energy (DOE): Richland (USA).
28. Bradshaw, J., S. Bachu, D. Bonijoly, R. Burruss, S. Holloway, N.P. Christensen, and O.M. Mathiassen (2007). *CO_2 storage capacity estimation: Issues and development of standards.* . International Journal of Greenhouse Gas Control. 1(1): p. 62-68.
29. Buhre, B.J.P., L.K. Elliott, C.D. Sheng, R.P. Gupta, and T.F. Wall (2005). *Oxy-fuel combustion technology for coal-fired power generation.* Progress in Energy and Combustion Science. 31(4): p. 283-307.
30. GCCSI (2010). *The Status of CCS Projects Interim Report 2010*, Global Carbon Capture and Storage Institute: Canberra (Australia).
31. IEA/CSLF/GCCSI (2010). *Carbon Capture and Storage: Progress and Next Steps. IEA/CSLF Report to the Muskoka, Canada G8 Summit 2010.*, IEA/OECD: Paris (France)
32. Hawkins, D., G. Peridas, and J. Steelman (2009). *Twelve years after Sleipner: Moving CCS from hype to pipe.* Energy Procedia. 1(1): p. 4403-4410.
33. Murphy, L.M. and P.L. Edwards (2003). *Bridging the Valley of Death: Transitioning from Public to Private Finance*, National Renewable Energy Laboratory (NREL): Colorado (USA).
34. NETL (2009). *Best Practices for: Public Outreach and Education for Carbon Storage Projects*, National Energy Technology Laboratories, United States Department of Energy (DOE): Pittsburgh (USA).
35. Klein Woolthuis, R., M. Lankhuizen, and V. Gilsing (2005). *A system failure framework for innovation policy design.* Technovation. 25(6): p. 609-619.
36. Kline, S.J. and N.R. Rosenberg (1986). *An overview of innovation*, in *The Positive Sum Strategy Harnessing Technology for Economic Growth*, R. Landau and N. Rosenberg, ed. National Academy Press: Washington D.C. (USA). p. 275-306.
37. Albert, M. and S. Laberge (2007). *The Legitimation and dissemination processes of the innovation system approach: the case of the Canadian and Quebec science and technology policy.* Science Technology Human Values 32(2): p. 221-249
38. European Commission (1996). *First Action Plan for Innovation in Europe*, European Commission,: Brussels (Belgium).
39. European Commission (2002). *Innovation Policy in Europe*, European Commission: Brussels (Belgium).
40. OECD (1997). *National Innovation Systems*, Organisation for Economic Co-operation and Development: Paris (France).
41. OECD (1999). *Managing National Innovation Systems*, Organisation for Economic Co-operation and Development: Paris (France).
42. OECD (1999). *Boosting Innovation: The Cluster Approach*, Organisation for Economic Co-operation and Development: Paris (France).
43. Hoogwijk, M. (2004). *Thesis: On the global and regional potential of renewable energy sources*, Utrecht University: Utrecht (The Netherlands). p. 256.
44. Rogner, H. (2000). *Energy Resources*, in *World Energy Assessment*, J. Goldemberg, ed. UNDP: Washington D.C. (USA). p. 136-171.

45. Turkenburg, W.C. (2000). *Renewable Energy Technologies*, in *World Energy Assessment*, J. Goldemberg, ed. UNDP: Washington D.C. (USA). p. 220-272.
46. IEA (2007). *Key World Energy Statistics*, IEA/OECD: Paris (France).
47. Suurs, R.A.A. (2009). *Thesis: Motors of Sustainable Innovation. Towards a theory on the dynamics of technological innovation systems*, Innovation Studies Group, Copernicus Institute Utrecht University: Utrecht (The Netherlands).
48. Unruh, G.C. (2000). *Understanding carbon lock-in.* Energy Policy. 28: p. 817-830.
49. Fagerberg, J. and B. Verspagen (2006). *Innovation studies - an emerging discipline (or what)? A study of the global network of innovation scholars*, Presented at The Future of Science, Technology and Innovation Policy, Linking Research and Practice: University of Sussex, Brighton (UK).
50. Jacobsson, S. and A. Bergek (2004). *Transforming the energy sector: the evolution of technological systems in renewable energy technology.* Industrial and Corporate Change 13(5): p. 815–849.
51. Carlsson, B. and R. Stankiewicz (1991). *On the nature, function and composition of technological systems.* Journal of Evolutionary Economics. 1(2): p. 1432-1386.
52. Bergek, A. (2002). *Thesis: Shaping and Exploiting Technological Opportunities: The Case of Renewable Energy Technology in Sweden*, Department of Industrial Dynamics Chalmers University of Technology: Göteborg (Sweden).
53. Nelson, R.R. and S.G. Winter (1977). *In search of useful theory of innovation.* Research Policy. 6(1): p. 36-76.
54. Freeman, C. (1995). *The 'National System of Innovation' in historical perspective.* Cambridge Journal of Economics. 19(1): p. 524.
55. Lundvall, B.Å. (1992). *National Systems of innovation: Towards a theory of innovation and interactive learning* Pinter Publishers. London (UK).
56. Godin, B. (2006). *The Linear model of Innovation: The Historical Construction of an Analytical Framework.* Science Technology Human Values 31(6): p. 639-667.
57. Smits, R.E.H.M. (2002). *Innovation studies in the 21st century;: Questions from a user's perspective.* Technological Forecasting and Social Change. 69(9): p. 861-883.
58. Freeman, C. (1987). *Technology Policy and Economic Performance; lessons from Japan*. Pinter Publishers. London (UK): p. 155.
59. Nelson, R.R. (1992). *National Innovation Systems: comparative analysis.* Industrial and Corporate Change 1(2): p. 347-374
60. Cook, P., M.G. Uranga, and G. Etxebarria (1997). *Regional innovation systems: Institutional and organisational dimensions.* Research Policy. 26(4-5): p. 475-491.
61. Saxenian, A. (1994). *Regional Advantage: Culture and Competition in Silicon Valley and Route 128*. Harvard University Press. Cambridge (UK).
62. Breshi, S. and F. Malerba (1997). *Sectoral Innovation Systems: Technical Regimes, Schumpeterian Dynamics and Spatial Boundaries*, in *Systems of Innovation: Technologies, Institutions and Organizations*, C. Edquist, ed. Pinter Publishers: London (UK).
63. Carlsson, B. and S. Jacobsson (2004). *Dynamics of Innovation Systems. Policy making in a complex and non-deterministic world*, Presented at the International Workshop on Functions of Innovation Systems: Utrecht (The Netherlands).
64. Carlsson, B., S. Jacobsson, M. Holmén, and A. Rickne (2002). *Innovation systems: analytical and methodological issues.* Research Policy. 31(2): p. 233-245.
65. Jacobsson, S. and A. Johnson (2000). *The diffusion of renewable energy technology: an analytical framework and key issues for research.* Energy Policy. 28(9): p. 625-640.
66. Edquist, C. (1997). *Systems of innovation - Technologies, institutions and organizations*. Pinter Publishers. London (UK).
67. Galli, R. and M. Teubal (1997). *Paradigmatic shifts in national innovation systems*, in *Systems of Innovation: technologies, institutions and Organizations*, C. Edquist, ed. Pinter Publishers: London (UK). p. 342-371.
68. Hekkert, M.P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann, and R.E.H.M. Smits (2007). *Functions of innovation systems: A new approach for analysing technological change.* Technological Forecasting and Social Change. 74(4): p. 413-432.

69. Johnson, A. (2001). *Functions in Innovation System Approaches*, Presented at the DRUID's Nelson - Winter conference: Aalborg (Denmark).
70. Liu, X. and S. White (2001). *Comparing Innovation Systems: a framework and application to China's transitional context.* Research Policy. 30(7): p. 1091-1114.
71. Negro, S.O. (2007). *Thesis: Dynamics of technological innovation systems — the case of biomass energy,* Innovation Studies Utrecht University: Utrecht (The Netherlands).
72. Negro, S.O., M.P. Hekkert, and R.E.H.M. Smits (2007). *Explaining the failure of the Dutch innovation system for biomass digestion--A functional analysis.* Energy Policy. 35(2): p. 925-938.
73. Negro, S.O., R.A.A. Suurs, and M.P. Hekkert (2008). *The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system.* Technological Forecasting and Social Change. 75(1): p. 57-77.
74. Rickne, A. (2001). *Assessing the Functionality of an Innovation System*, Presented at the Nelson and Winter Conference: Aalborg (Denmark).
75. Carlsson, B. and S. Jacobsson (1997). *Diversity Creation and Technological Systems: A Technology Policy Perspective,* in *Systems of Innovation: Technologies, Institutions and Organizations,* C. Edquist, ed. Pinter Publishers: London (UK). p. 266-294.
76. Rickne, A. (2000). *Thesis: New Technology-based firms and industrial dynamics,* Chalmers University of Technology: Göteborg (Sweden).
77. Jacobsson, S., B.A. Sanden, and L. Bangens (2004). *Transforming the energy system—The evolution of the German technological system for solar cells.* Technology Analysis Strategic Management 16(1): p. 3–30.
78. Hekkert, M.P. and S.O. Negro (2009). *Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims.* Technological Forecasting and Social Change. 76(4): p. 584-594.
79. Suurs, R.A.A. and M.P. Hekkert (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): p. 1003-1020.
80. Hoogma, R. (2000). *Thesis: Exploiting Technological Niches,* Twente University: Enschede (The Netherlands).
81. Raven, R. (2005). *Thesis: Strategic Niche Management for Biomass: A comparative case study on the experimental introduction of bioenergy technologies in the Netherlands and Denmark*, Eindhoven University of Technology: Eindhoven (The Netherlands).
82. Kamp, L.M., R.E.H.M. Smits, and C.D. Andriesse (2004). *Notions on learning applied to wind turbine development in the Netherlands and Denmark.* Energy Policy. 32(14): p. 1625-1637.
83. Bergek, A., S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne (2008). *Analyzing the functional dynamics of technological innovation systems: A scheme of analysis.* Research Policy. 37(3): p. 407-429.
84. Markard, J. and B. Truffer (2008). *Technological innovation systems and the multi-level perspective: Towards an integrated framework.* Research Policy. 37: p. 596–615.
85. Yin, R.K. (2003). *Case study research, design and methods*. Newbury Park: Sage Publications. California (USA).
86. Abell, P. (1987). *The Theory and Method of Comparative Narratives*. Clarendon Press. Oxford (UK).
87. Likert, R. (1932). *A Technique for the Measurement of Attitudes.* Archives of Psychology 140: p. 1-55.
88. Boon, W. (2008). *Thesis: Demanding Dynamics. Demand articulation of intermediary organisations in emerging pharmaceutical innovations,* Innovation Studies Utrecht University: Utrecht (The Netherlands).
89. Chappin, M. (2008). *Thesis: Opening the black box of environmental innovation. Govermental policy and learning in the Dutch paper and Board Industry,* Innovation Studies Utrecht University: Utrecht (The Netherlands).

90. Poole, M.S., A.H. van de Ven, K. Dooley, and M.E. Holmes (2000). *Organizational Change and Innovation Processes: Theory and methods for research.* Oxford University Press. New York (USA).
91. Van de Ven, A.H. (1990). *Methods for studying innovation development in the Minnesota Innovation Research Program.* Organization Science. 1(3): p. 313-335.
92. Van de Ven, A.H., D.E. Polley, R. Garud, and S. Venkataraman (1999). *The Innovation Journey*. Oxford University press. New York (USA).
93. LexisNexis (2010). *LexisNexis Nederland*. Available from: http://www.lexisnexis.nl/dutch/.
94. Bongers, F.J. (2000). *Thesis: Participatory Policy Analysis and Group Support Systems*, Katholieke Universiteit Brabant: Tilburg (The Netherlands).
95. Agterbosch, S. (2006). *Thesis: Empowering wind power. On social and institutional conditions affecting the performance of entrepeneurs in the wind power supply market in the Netherlands*, University Utrecht: Utrecht (The Netherlands).
96. van de Herik, C.W. (1998). *Groups Support for Policy Making*, Delft University of Technology Delft University of Technology: Delft (The Netherlands).
97. Legg, J.F. and F.R. Campbell (2006). *Carbon Dioxide Capture and Storage: A Compendium of Canada's Participation*, Prepared under NRCan Office of Energy Research and Development Ottawa: Ontario (Canada).
98. IEA GHG (2009). *CO2 Capture and Storage RD&D Projects Database*, IEA Greenhouse Gas R&D Programme: Cheltanhan (UK).
99. Deroïan, F. (2002). *Formation of social networks and diffusion of innovations.* Research Policy. 31(5): p. 835-846.
100. Kim, H. and Y. Park (2009). *Structural effects of R&D collaboration network on knowledge diffusion performance.* Expert Systems with Applications. 36(5): p. 8986-8992.
101. Cantner, U. and H. Graf (2006). *The network of innovators in Jena: An application of social network analysis.* Research Policy. 35(4): p. 463-480.
102. Baur, M. (2009). *Thesis: Visone: software for the analysis and visualization of social networks*, University of Karlsruhe: Karlsruhe (Germany).
103. Borgatti, S.P., M.G. Everett, and L.C. Freeman (2009). *Ucinet for Windows: software for social network analysis*, Analytic Technologies: Lexington (USA).
104. Bornmann, L., W. Marx, H. Schier, E. Rahm, A. Thor, and H.D. Daniel (2009). *Convergent validity of bibliometric Google Scholar data in the field of chemistry--Citation counts for papers that were accepted by Angewandte Chemie International Edition or rejected but published elsewhere, using Google Scholar, Science Citation Index, Scopus, and Chemical Abstracts.* Journal of Informetrics. 3(1): p. 27-35.
105. Kamp, L.M. (2002). *Thesis: Learning in wind turbine development : a comparison between the Netherlands and Denmark*, Faculty of Geosciences Utrecht University: Utrecht (The Netherlands).

Interlude A

The following chapter contains the results of a case study of the Norwegian CCS Innovation System. This study involved the first real test of the three step research design. Hereby the analysis of the historical dynamics of the Innovation System is linked to the evaluative performance assessment and used to specify key policy interventions to accelerate the further growth of the Technological Innovation System. Particular attention is paid in this article to the pioneering role that Norway has played in the development of CCS, which has led to a remarkable build-up of the Innovation System.

The research presented in this chapter was executed in the period 2007 – June 2008 and was originally published as [1]: van Alphen, K., van Ruijven, J., Kasa, S., Hekkert, M., Turkenburg, W (2009). The performance of the Norwegian carbon dioxide, capture and storage Innovation System. *Energy Policy* 37 (1), 43-55.

2. The performance of the Norwegian Carbon dioxide, Capture and Storage Innovation System

Abstract

In order to take up Norway's twin challenge of reducing CO_2 emissions, while meeting its growing energy demand with domestic resources, the deployment of carbon capture and storage (CCS) plays an important role in Norwegian energy policies. This study uses the Innovation System Functions approach to identify key policy issues that need to be addressed in order to prolong Norway's international leadership position in the development of CCS. The analysis shows that Norway has been successful in building an Innovation System around CCS technology. The key determinants for this achievement are pinpointed in this article. However, the evolution of the Innovation System seems to have entered a critical phase that is decisive for a further thriving development of CCS in Norway. The results provide a clear understanding of the current impediments in the CCS Innovation System and stress the need to direct policy initiatives at the identified weak system functions—i.e. entrepreneurial activity and market formation—to improve the performance of the system. We discuss how policymakers can use these insights to develop a coherent set of policy instruments that would foster the deployment of CCS concepts related to power production and enhanced oil recovery in Norway.

2.1. Introduction

Norway is the largest petroleum exporting country of Europe, as only a small fraction of the produced 233 Mtoe a year is used domestically [2]. In fact, half of the national primary energy demand of approximately 21 Mtoe a year is met by CO_2 emission-free hydropower, providing 99% of the generated electricity in Norway [3]. This makes Norway's CO_2 emissions, in relation to its total energy use and GDP, relatively low compared with other OECD countries. Therefore, Norway is allowed in the Kyoto Protocol to increase its greenhouse gas (GHG) emissions with 1% in the period 2008–2012 compared with the level of 1990 [4]. However, Statistics Norway [5] showed that Norway's GHG emissions already increased with 8.5%. This is mainly caused by a 78% emission growth of the oil and gas industry since 1990; this industry is responsible for more than a quarter of all GHG emissions in Norway.

The Norwegian GHG emissions may rise even further, if the considered diversification strategy towards gas-fired power plants is pursued to meet the growing electricity demand of 1–1.5% per year [6]. Even though the deployment of gas power has been on the political agenda for over a decade, its implementation has continuously been delayed due to environmental concerns related to CO_2 emissions [7]. However, the increasing viability of carbon capture and storage (CCS) provides a possible solution to Norway's twin challenge of reducing GHG emissions, while meeting a growing energy demand with domestic resources.[1]

CCS technology comprises the separation of CO_2 from industrial and energy-related sources, transport to a storage location (e.g. saline aquifers and depleted hydrocarbon fields), and long-term isolation from the atmosphere [8]. The Norwegian industry already gained valuable experience in this area from its CO_2 storage operations at the Sleipner West gas field, where 1 Mt CO_2 is injected into a sub-surface reservoir each year, since 1996 [9]. Meanwhile, new CCS activities—particularly those concerning natural gas-based power production—have increased significantly over the past several years in Norway [10]. Most of the current CCS programs by companies and research institutions are established in cooperation with the Norwegian authorities [11], as the deployment of CCS plays an important role in the Norwegian climate and energy policy [2, 12].

The emergence of new technological trajectories, like CCS, is a complex and uncertain process, which is difficult to steer. Thus, for governmental bodies that intend to promote and shape the development of CCS technology, this is a phenomenal challenge. The question of how a process of socio-technical change, also labelled as a technological transition, can be understood and influenced is receiving increasing attention in scientific literature [see e.g. 13, 14, 15]. One of the frameworks that has been successfully applied to several emergent trajectories of energy technologies is that of Technological Innovation Systems (TIS) [see e.g. 16, 17-19]. This framework is rooted in the field of innovation studies and is used to analyse the "network of actors interacting in a technological area under a particular institutional infrastructure and involved in the generation, diffusion and utilisation of technology" [20].

[1] Environmental concerns have halted both the development of new hydropower and nuclear energy.

The central link between a TIS and socio-technical change is that emerging technologies are developed and applied within the context of a specific TIS. The maturation of technology and the growth of a TIS is a typical example of co-evolution; they mutually influence each other. When the technology matures, the TIS also grows due to an increasing knowledge base, new entrants, growing networks in terms of size and density, and due to specific institutional arrangements that come into place. On the other hand, when a TIS grows the rate of technological progress generally increases, which in turn enlarges the chances of success for the technology [21].

Over the past years, progress is made in determining functions that contribute to the growth and performance of an emerging TIS [17, 22-24]. These system functions are decisive processes, or key activities, that foster the shaping and development of a technology [25]. In earlier empirical work these functions have been used effectively to deliver explanations for the success or failure of technological trajectories of sustainable energy technologies in various countries [26-31].

This study applies the framework of Innovation System Functions to describe the evolution of the Norwegian CCS Innovation System and evaluate its current performance. We aim to provide insights into the relations between the historical dynamics of the system and the system's current performance. Furthermore, we will demonstrate how these insights can be useful to policy makers that wish to enhance the development and deployment of CCS.[2]

The article is structured as follows: first an overview is given of how Innovation System functions may optimally contribute to the development of emerging energy technologies in Section 2. Based on this, an analytical framework is constructed, which is applied in the subsequent sections to analyse the historical dynamics and the current performance of the Norwegian CCS Innovation System. Finally, the results are used to advice on how the performance this TIS can be improved and malfunctions can be remedied.

2.2. Theoretical framework: Innovation System Functions

A number of different Innovation System concepts have been put forward in the literature, including national systems of innovation [32-34], regional innovation systems [35, 36], sectoral systems of innovation and production [37] and technological systems [20]. In this paper, we apply this TIS framework, i.e. socio-technical systems focused on the development, diffusion and use of a particular technology (in this case CCS technology).

A TIS typically crosses geographic—as well as sectoral boundaries [23]. For example, the capture of CO_2 in the CCS process is mainly embedded in the power sector and other heavy industries, while CO_2-storage is partly the domain of the gas—and oil industry. Although, a TIS is often international in nature, system delineation usually encompasses a further specification in spatial terms, depending on the purpose of the analysis [38]. Therefore, we

[2] Note that the insights related to the performance of the system are also interesting for other organization —e.g. industrial parties and NGOs— that aim to strategically influence the development of CCS [40].

define[3] the Norwegian CCS Innovation System as: ‘a network of actors interacting under a particular institutional infrastructure and involved in the development, diffusion, and utilisation of CCS technology in Norway.’

According to this definition a TIS can be described by its three main components: actors, institutions and their relationships (networks). Actors or organisations are the operating parts of a system and can be of a variety of types, such as individuals, firms, banks, universities, research institutes, and public policy agencies. Institutions can be in the form of legislative artefacts such as laws, policy targets and social norms, which in turn regulate (network) interactions between actors.

In this paper, we present a framework outlining seven key processes—here labelled ‘functions’—, which have a direct impact on the development, diffusion and use of new technologies, i.e. the overall function of the TIS as defined above. These functions—e.g. the formation of markets and the mobilisation of resources—are the emergent properties of the interplay between actors and institutions. This framework has been applied effectively to describe and explain the (historical) dynamics of Innovation Systems at different levels of aggregation [for an overview, see 21]. Furthermore, the fulfilment of these functions can be assessed in order to derive policy recommendations for supporting the development of a specific technology [39].

A series of empirical as well as conceptual articles have proposed different sets of sub-functions for the analysis of Innovation Systems [for an overview, see 23, 39]. The seven functions that are applied in this study to describe the dynamics of Norwegian CCS Innovation System, assess its performance and arrive at policy recommendations, includes the functions on which there is quite large agreement between different functions approaches [21].

Function 1. Entrepreneurial activity: The existence of entrepreneurs in Innovation Systems is of prime importance. The role of the entrepreneur is to turn the potential of new knowledge into concrete actions to take advantage of business opportunities and stimulate learning by doing. Entrepreneurs can be new entrants that have the vision of business opportunities in new markets, or incumbent companies who diversify their business strategy to take advantage of new developments. Entrepreneurs are very important in overcoming the uncertainties that are present in the early stage of development of a new technology.

Function 2. Knowledge creation: Research and development (R&D) is a prerequisite for innovation. Mechanisms of learning are at the heart of any innovation process. For instance, according to Lundvall [33]: “the most fundamental resource in the modern economy is knowledge and, accordingly, the most important process is learning”. This function encompasses learning by searching and is associated with R&D and patenting activities that create a variety in the knowledge base.

[3] This definition is based on the description of a technology-specific Innovation System by Carlsson and Stankiewicz [20], which is presented in Section 2.1.

Function 3. Knowledge diffusion through networks: The diffusion of knowledge through networks of actors contributes to learning by interacting and facilitates the exchange of information, e.g. by workshops, conferences and research collaborations. This is important in a strict R&D setting, but especially in a heterogeneous context where R&D meets government, competitors and market. When the development of knowledge (Function 2) is diffused throughout the network, learning at system level takes place, which enhances technology development and diffusion.

Function 4. Guidance: This system function represents the selection process necessary for the convergence in technology development. Therefore, the activities within the Innovation System that can positively affect the visibility and clarity of specific wants among technology users fall under this system function. Guidance can take the institutional form of policy targets, but is often realised through expectations regarding the technology as expressed by various actors. This grants a certain degree of legitimacy to the development of the technologies and stimulates the mobilisation of resources for this development.

Function 5. Market formation: Emerging (sustainable energy) technologies often have difficulty with competing in existing markets. Therefore it is important to create protected spaces for new technologies. One possibility is the formation of niche markets for specific applications of the technology. This can be done by governments but also by other actors in the Innovation System. Another possibility is to create a temporary competitive advantage by favourable tax regimes, minimal consumption quotas, or other activities in the sphere of public policy.

Function 6. Resources mobilisation: The allocation of resources, both human and financial, is a necessary and basic input to all the activities in the innovation process. Both R&D and the construction of production facilities require financial resources, either from internal or external funds, e.g. government subsidies and venture capital. In terms of human capital, one could think of well-educated professionals in all parts of the Innovation System.

Function 7. Creation of legitimacy/counteract resistance to change: The new technology and its proponents need to be considered as desirable by the other actors in the system to acquire political strength. Parties with vested interests often oppose to the new technology. This function describes activities that influence the acceptance of technology with respect to policy and society, as the new technology should comply with legislation and relevant institutions. Advocacy coalitions are of great importance in this process, as they can put a new technology on the (political) agenda, lobby for resources or favourable tax regimes and by doing so create legitimacy for the new technological trajectory.

It is possible that the fulfilment of a certain function has effects on other functions [23]. For instance, a certain amount of knowledge creation is necessary to build expectations for the new technology, which may lead to an increasing availability of financial resources [30]. This implies that function fulfilment can lead to positive (virtuous) cycles of processes that strengthen each other and lead to the growth of the TIS. However, if particular system functions are inadequately addressed by the components of the system, a negative (vicious) cycle may be set off [40]. Therefore, positive ‘system dynamics’ can be considered as a prerequisite for the successful development and deployment of emerging technologies, like CCS [41]. The analytical framework that is outlined below elucidates this.

2.2.1. Framework of analysis: dynamics, performance and policy intervention

The practical relevance of this analytical framework is based on the assumption that policy interventions directed at stimulating sustainable changes in the energy system should focus on improving Innovation System Functions that operate weakly in order to increase the chances of positive system dynamics. To specify these policy interventions it is necessary to analyse the relationship between the historical dynamics and the current performance of the Innovation System. The relationships between system dynamics, performance and policy, are further clarified by the three different analytical parts that are discerned in this study.

Part 1: The first part consists of mapping the historical dynamics of the Innovation System in terms of (interactions between) functions. This includes the identification of the structural components that compose the TIS (actors, institutions and networks) and their contribution to the fulfilment of the seven Innovation System Functions through time.[4] The data for this sub-analysis is collected by reviewing scientific as well as 'grey literature' (newspaper articles, professional journals and policy documents), and by interviewing the main actors involved in the development of CCS in Norway. In total, 20 interviews have been conducted. With the selection of interviewees a balanced representation of the different actor groups in the Innovation System was pursued. Thereby a distinction is made between the following groups of actors: technology-developers, industry, research organisations, governmental parties and environmental NGOs. All of the interviewees have been involved in the development of CCS in Norway for a longer period of time, but are not necessarily proponents of the technology.

This part of the analysis results in a narrative that describes the appearance and evolution of the Norwegian CCS Innovation System. It explains the growth of the system in terms of changes in the fulfilment of Innovation System Functions by its components. This narrative is used to point out how system functions reinforce or antagonise each other through time; thereby creating insight in the historical dynamics (growth) of the TIS.

Part 2: The second part of the analysis assesses the performance of the Innovation System, as insights in the dynamics of the TIS do not tell us directly whether the Innovation System is well functioning or not. In order to further assess the system's performance—i.e. not how, but how well the system is functioning—the relative 'goodness' of its dynamics needs to be evaluated [39]. Since by definition diffusion is low for emerging technologies, it is problematic to test whether a good fulfilment of these functions of Innovation Systems indeed leads to successful diffusion. Therefore, we propose several indicators or 'evaluation questions' that provide insight in the performance of the functions separately (see Table 2-1). In order to determine possible improvements in function fulfilment we assessed the performance of functions for different time periods and compared these. To specify the current performance of the TIS even further, the main actors in the system are asked to reflect

[4] Note that these structural components can also be international actors, or institutions that influence the development of CCS in Norway.

upon the historical, as well as ongoing activities in the TIS and rate their level of satisfaction with the fulfilment of a particular system function. In this way the identification of functions that either induce (drive) or block positive system dynamics is verified by critical evaluations from experts who take part in shaping the technological trajectory for CCS.[5]

Table 2-1: Indicative questions that reflect the extent to which each function in the Innovation System is fulfilled by the system components [see also 23, 39].

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 R&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 and 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)?

Part 3: The third and last part of this analytical framework consists of the identification of key policy issues. Based on the current performance of the system, in relation to what is reasonable to expect taking the historical development of the TIS into account and according to the judgment of key actors in the system, it is possible to specify policy issues in terms of how the Innovation System Functions should develop in order to reach a higher performance. Furthermore, the respondents not only evaluated the current functioning of the TIS, but they also gave their view on what should be done to improve functions that are impeding positive system dynamics. This provides the basis for advice on policy strategies to enhance the development of deployment of CCS in Norway.

[5] The majority of the interviews with CCS experts were carried out in the first half of 2007.

2.3. Dynamics of the Norwegian CCS Innovation System

This section discusses the dynamics of the Norwegian CCS Innovation System by reconstructing its appearance and evolution (growth) over the past two decades. The narrative is chronologically organised into two periods. Each period covers two episodes characterised by a specific interaction pattern between functions. These dynamic patterns are discussed briefly at the end of every episode and depicted schematically in Figure 2-2, Figure 2-3, Figure 2-5 and Figure 2-6. This implies that the end of each episode is chosen on the basis of change in activities (function fulfilment); consequently the four episodes are not equal in length. All the major events that have influenced the development of the Norwegian CCS Innovation System will be discussed below and refer to the various system functions as F1, F2, F3, etc., following Table 2-1.

2.3.1. Period 1988–1999

The concept of CCS in Norway is originated between 1986 and 1988, when researchers from the Norwegian research institution SINTEF suggested the capture and storage of CO_2 in a study conducted for Norway's largest oil company Statoil. During that period, the report 'our common future' of the Brundtland Commission about the growing tension between economic growth and ecological deterioration was published [42]. After chairing the commission, Brundtland was re-elected as Norway's prime minister in 1990 and 1 year later she introduced a carbon tax for different fuels and sectors. This marks the start of an era wherein Norway fulfils a pioneering role in the field of CCS.

2.3.1.1. Episode 1: pioneering activities

The introduction of a carbon tax for offshore petroleum activities (approximately €40 per emitted tonne of CO_2) triggered Statoil to investigate options for cost-effective CO_2 handling at their offshore Sleipner West gas field (F2), including the underground storage of CO_2 in geological formations [43]. This natural gas field contains around 9% CO_2 that needs to be removed to use the gas for commercial purposes. If vented, the CO_2 would not only have increased Norway's CO_2 emissions with 3%, but also imposed a financial burden on the project due to the carbon tax [44].

In 1992, Statoil opted to inject the CO_2 in the Utsira formation, a large aquifer southwest of Norway with a capacity of probably more than hundred times the European annual CO_2 emissions[45].[6] In order to realise its plans, Statoil made available a research budget of €1.25–2.5 million per year (F6) to simulate the distribution of CO_2 in the Utsira formation [46]. Hereby, Statoil cooperated with SINTEF and the Trondheim-based technical university NTNU (F3). Additionally, Statoil initiated commercial R&D efforts (F2) to apply a CO_2 separation unit offshore [47]. In this R&D process they aligned with Kværner; one of Norway's largest technology vendors (F3). Following these R&D programs (F2), Statoil

[6] SINTEF and Statoil participated in a research project funded by the EU program Joule II from 1993 to 1996 (*F2*), which assessed the storage capacity in the North Sea, including the Utsira formation [45].

invested €94 million in the separation unit (F6) and started operations in 1996 (F1); sequestering 1 Mt CO_2 each year [48].

In the same year that Statoil announced its plans to sequester CO_2 in the Utsira formation (1992); the company started initial discussions with Kværner to find a cost-effective solution for the CO_2 emissions from offshore gas turbines. These emissions represent more than 80% of the CO_2 discharge by Norway's oil and gas industry and are therefore subjected to high carbon taxes [49]. Due to this carbon tax, Kværner knew the commercial value of CO_2 capture technology and started R&D of a post-combustion technique based on amine absorption using membrane contactors (F2) [50]. This R&D was partly done in cooperation, but also in competition with similar developments abroad[51].[7] During the project Kværner established a partnership with Gore Industries and involved six other oil international companies besides Statoil.

During Kværner's R&D efforts, the Norwegian Oil Industry Association criticized CO_2 capture at offshore gas turbines by pointing at the energy losses in the capture process and unfeasibly high costs [52]. Furthermore, some environmental groups, including Greenpeace, placed a critical note by the storage of CO_2 in the Utsira formation (F7), as they claimed that Statoil was in violation with the London Convention when 'dumping' CO_2 under the seabed [53].

Figure 2-1 depicts the relation between the introduction of the carbon tax (F5) and the applied R&D that has led to the world's first offshore CO_2 capture plant, together with a still unique CO_2 storage project (F1). Furthermore, it shows the research collaborations that were set up to share knowledge (F3) and to mobilise financial resources (F6) into this and other (typically expensive) CCS projects. This increased attention for CCS as possible mitigation option also led to opposition by several environmental and industrial interest groups (F7). However, this would rapidly change in the following episode, as a fierce debate on the deployment of onshore gas-fired power plants commenced.

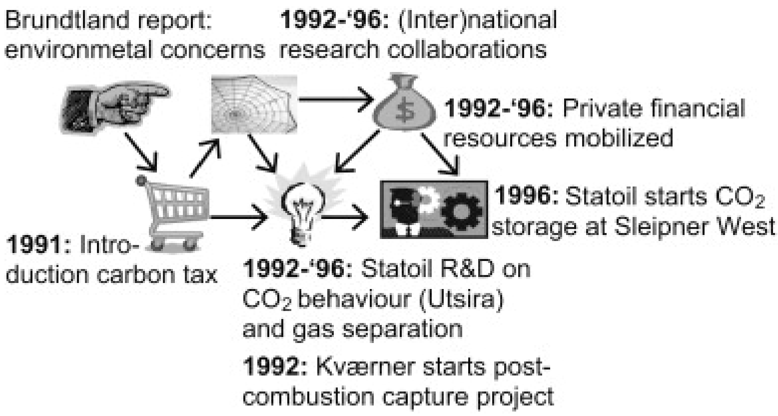


Figure 2-1: Function interactions episode I: 1991–1996.

[7] Norwegian research and industrial organisations were well represented in the emerging international CCS networks. This is for example manifested by their early membership of the IEA-GHG programme in 1991 and the Norwegian contributions to the first international conference on carbon dioxide removal [51].
.

2.3.1.2. Episode 2: CCS, a fiercely debated technology

In 1997, Norway adopted—but not yet ratified—the Kyoto Protocol (F4). In order to reach its Kyoto targets—i.e. an increase of GHG emissions limited to 1% between 2008 and 2012 compared with the level in 1990 [54]—the KLIMATEK funding program was established (F6). This program was administered by the Research Council of Norway and promoted R&D of various low emission technologies. In the first 4 years of the program, nearly half of KLIMATEK's budget of €3 million per year went to CCS-related projects (F6) [55]. This funding typically led to an accumulated turnover by private parties of 3–4 times the funded value.

Among others, Kværner's post-combustion capture technology received funding through KLIMATEK to establish a laboratory research unit at SINTEF and a larger pilot unit at Statoil's ‘K-lab’ facility at the gas terminal in Kårstø (F2). This first pilot project in Norway for CO_2 capture from exhaust gases ended in 1999 and resulted in several patents (F2). In that same period, Norway's other major technology company ‘Aker Technology’ started an oxyfuel capture R&D project based on a combined cycle gas turbine (F2). In this R&D project, Aker established a partnership with the French turbine developer Alstom and they (financially) aligned with several energy companies (F3) [56]. This consortium patented its “High Oxygen” technology in 1999 (F2).

The first substantial public–private research effort regarding CO_2 storage is the Saline Aquifer CO_2 Storage project [57], which ran between 1998–1999 (F2). This EU co-funded €5 million project (F6) was coordinated by Statoil and involved a long list of international oil, gas and energy companies, as well as research institutes (F3)[8] [57, 58]. The main objective of this program was to monitor the CO_2 behaviour at Statoil's storage site in the Utsira formation, which led to the world's first 3D seismic survey of CO_2 in an aquifer [9].

In 1998, Norway's second largest oil company, Norsk Hydro, launched its Hydrokraft project (F1). This comprehended the development of a pre-combustion capture technology with an integrated reformer combined cycle for a proposed 1200 MW power plant.[9] Larsen and Ruud [59] explain that the Hydrokraft project fitted rightly in the fierce political discussion about the two concessions received by power company Naturkraft—a consortium of Statoil, Norsk Hydro and Statkraft—to build gas-fired power plants. This debate was originally about whether or not to build these combined cycle plants, but after several influential environmental NGOs—including Bellona and Nature and Youth—introduced the concept of CCS in the public domain, it changed rapidly into whether to build these plants with or without CCS [52]. Particularly after Norsk Hydro started its ‘cost-effective’ Hydrokraft project, which made any other option look like ‘stone age technology’ (F4).

This elucidates that the ongoing R&D activities had a vast impact on the political and public legitimacy for CCS technology (see Figure 2-2). Influenced by the ‘Joint action against gas-

[8] Important Norwegian actors besides Statoil included Industrikraft Midt-Norge, Norsk Hydro, SINTEF and the Norwegian Geological Survey [57].
[9] The plant size was determined to use 60 Mt CO_2 for pressure support at the Grane oil field over a 15-year period.

fired power plants', which is considered as the broadest environmental movement campaign of the decade (F7), the Norwegian pollution control authority (SFT) refused to issue the full emission permits required by Naturkraft to develop gas power in Norway [60]. This implied that the only way to comply was to build a CCS facility as an integral part of the power plant (F4). However, this implication caused a strong parliamentary opposition. Especially after Norsk Hydro's decision in 1999 to put the Hydrokraft project temporarily on hold, because of technical and financial difficulties. This political crisis resulted in the resignation of the minority government led by Bondevik in March 2000.

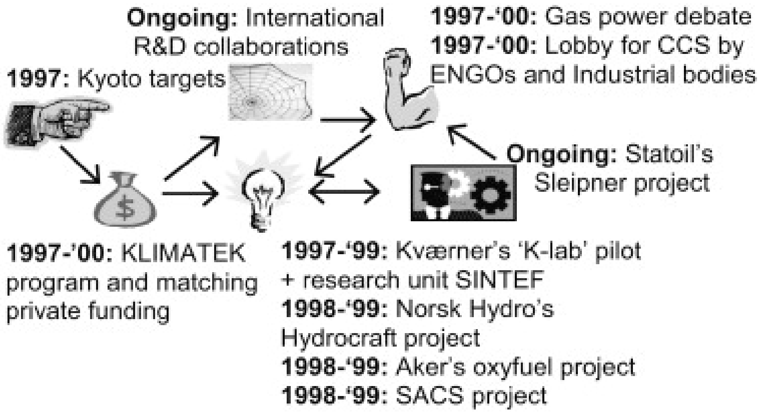


Figure 2-2: Function interactions episode II: 1997–2000.

2.3.2. Period 2000–2007

The situation regarding the deployment of gas power in Norway changed instantly after the Bondevik administration resigned in 2000. The interim government, led by Stoltenberg, favoured gas power and decided to issue full emission permits for Naturkraft's two power plants and another one for Industrikraft Midt-Norge. However, elections in 2001 brought Bondevik back in office, whose new administration was even more dedicated towards the deployment of CCS. This marks the start of the second period in this analysis, which lasts till 2008.

2.3.2.1. Episode 3: dedication towards CCS

Even though Bondevik could not reverse the decisions made by the Stoltenberg administration, energy policies changed quickly when he returned to power in 2001. After the policy negotiations following the election, it was announced that "no further concessions would be granted for fossil-fuelled plants without CCS" [52]. This was not only a clear statement to any organisation with plans to develop gas power, but also implied that the Norwegian government had to support the development of CCS to make its deployment viable (F4). Consequently, the budget for the development of environmental sound technologies in the KLIMATEK funding program was raised significantly (F6) and largely allocated to CCS R&D (see Figure 2-3).

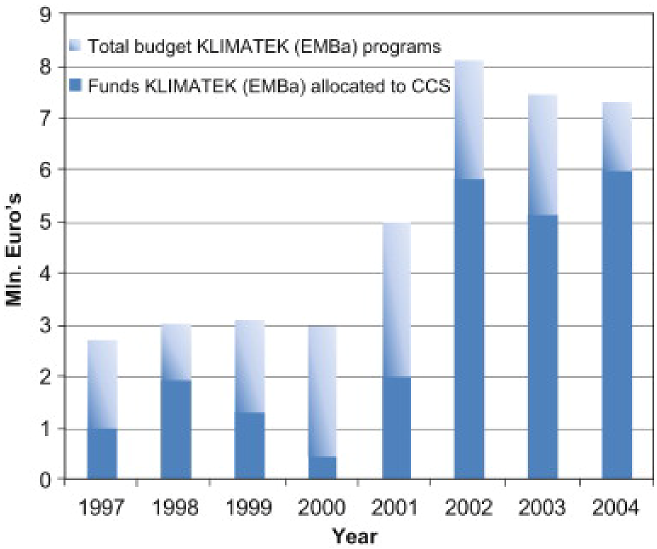


Figure 2-3: Total budget KLIMATEK and EMBa funding programs, including the share for CCS R& (Sorheim, 2004). Note that in 2002, KLIMATEK became part of the EMBa funding program.

In 2002, the KMB CO_2 project was launched (F2). The first phase (2002–2006) of this national competence-building project received €13 million funding and focused mainly on underground CO_2 storage and enhanced oil recovery (EOR). In that same year, the SACS-II project (F2) was succeeded by the 3 year CO_2Store program (F2). This program, which centred on CO_2 storage in aquifers, was co-funded by the EU (F6) and involved 19 international organisations from industry and research institutes (F3). Apart from these developments in CO_2 storage research, the newly available funding program also supported the expansion of studies regarding CO_2 capture.

After Norsk Hydro shelved its Hydrokraft technology, it started the Advanced Zero Emission Power (AZEP) project, which comprehended the development of a high-temperature oxyfuel gas turbine with membrane separation technology [61]. This project (F2) was part of the Carbon Capture Program (CCP), an international program run by 8–10 oil companies, with public support from the 5th Framework Program of the European Commission (F2), USA Department of Energy and the Research Council of Norway [62]. Another smaller Norwegian contribution to CCP was the NORCAP program, which tested several promising CO_2 capture technologies (F2) [63]. The development of capture technologies continued when relatively small technology-based companies entered the market (F1), which resulted in the Zero Emission Gas (ZEG) project[10] and the Zero Emission Norwegian Gas (ZENG) program (F2).[11] Furthermore, Norwegian technology company Sargas, another newcomer in 2003, started the design of a post-combustion capture technology, based on patents from Siemens (F2).

Next to these ongoing R&D efforts, Statoil announced its second commercial CCS project related to natural gas handling in 2001 (F1). The development of this project called Snøhvit

[10] ZEG is a joint venture between the IFE, CMR and Prototech that develops an integrated power production system, based on a high-temperature fuel cell, with CO_2 removal and hydrogen production.
[11] The ZENG program is being co-developed by Lyse Energi, Nebb Engineering, Procom Venture and CO_2-Norway and addresses the development of an oxyfuel combustion system.

(‘Snow white’) was motivated by Statoil's Sleipner project and the still existing carbon tax (see Figure 2-4). The project comprises the transport of natural gas from the Snøhvit gas field to an onshore LNG refinery located in Hammerfest. There, the CO_2 is separated from the gas and compressed. Instead of venting the CO_2 to the atmosphere, which would increase Norway's GHG emissions by 2%, 700 kt CO_2/year is transported back to the sub-sea installation by pipeline and injected in an offshore geological formation below the gas reservoir [64].

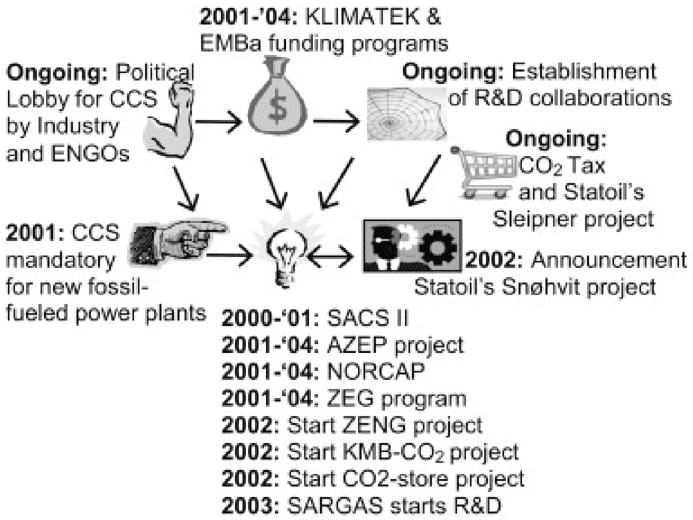


Figure 2-4: Function interactions episode III: 2001–2004.

Figure 2- 4 depicts the increasing interaction between system functions in this period. The ongoing lobbying activities by industrial and environmental interest groups led to changes in legislation (CCS compulsory for new fossil-fuelled power plants) and an increase in the available funds for CCS R&D. This subsequently led to establishment of more research collaborations and R&D projects. The existing carbon tax and successful Sleipner project also triggered the development of a second large-scale CCS project called Snøhvit.

The Norwegian government had no specific legal framework for CO_2 storage when Statoil initiated its Sleipner and Snøhvit projects. Therefore, existing mining regulations applied to them. This implies that Statoil is responsible for the stored CO_2 as long as the field is in operation; after that, it will prepare the field to hand it over to the Norwegian government, which is then liable for the sequestered CO_2. In the following and most recent episode, the transfer of liability for the stored CO_2 was further refined when this issue was taken up in European directives [65]. Moreover, important international legal issues related to the environment became clear under The London Convention and OSPAR treaties [66].

2.3.2.2. Episode 4: visions for the future

The interim government led by Stoltenberg gave permission for the construction of three gas-fired power plants without CCS in the year 2000. When he returned to power in 2005, his second administration set very ambitious emission reduction goals, i.e. to reduce GHG emissions 30% by 2020 and to be carbon neutral in 2050[12] (F4) [4, 67]. This gave reason for a lot of dispute about the need to implement CCS in the new power plants, during the policy negotiations in September 2005. In the end, the 'Soria Moria policy declaration' stated that new concessions for gas-fired power should be based on CCS. It also suggested that the government should retrofit the Naturfkraft power plant at Kårstø (420 MW) on own expenses and financially support the capture units of the other two power plants if they would be built (F1). Additionally, the declaration assured that the government would reinforce various policy measures and public financing to advance the realisation of infrastructure and test facilities for CCS [52].

Following up on this declaration, the government financially supported a land-based laboratory for CO_2 storage research on CO_2 leakage pathways and monitoring techniques (F2). This research centre is led by SINTEF and involves seven other Norwegian research groups (F3). Furthermore, the government and Statoil agreed in October 2006 to establish a capture technology test centre at Mongstad (F2); Norway's major industrial refinery and CO_2 emission source. This was part of the government's approval of a new combined heat and power (CHP) gas turbine (630 MW) at Mongstad. The first step in the agreement is the realisation of test facilities in 2010; with the capacity to capture 100 kt CO_2/year. The subsequent stage, which commences in 2014, involves the construction of a full-scale CO_2 post-combustion capture installation in connection with the CHP plant, capturing more than 1.5 Mt CO_2 annually.

Besides the establishment of these test centres and the further enrolment of Norwegian organisations in major international R&D programs[13] (F3), many of the R&D projects that were initiated in the beginning of the millennium were reinforced in this episode (F2). Important in this respect is the second phase of the prestigious KMB CO_2. This €29 million program named 'BIG CO_2' runs from 2007 to 2011[68]. Furthermore, the consortium led by Norsk Hydro started in 2005 with the construction of a 100 kW demonstration plant of the oxyfuel technology developed in the AZEP project (F2). However, the project stopped 2 years later because of unsatisfying results. The more successful ZENG program is working towards the demonstration of an oxyfuel combustion system in a 50–70 MW gas-fired power plant; and the development of a hydrogen production system with integrated CO_2 capture continues within the ZEG consortium.

The CLIMIT funding program financially supports most of this RD&D. CLIMIT focuses on CCS technologies only, and its budget is roughly €17.5 million a year (F6). The budget is administered by the Research Council of Norway and Gassnova [11]. The latter is an intermediary organisation that acts on behalf of the government regarding the implementation

[12] In an effort to reach the more stringent emission goals the Norwegian government implemented the first phase of a domestic ETS, under the Greenhouse Gas Emission Trading Act. The scheme covers 10–15 % of all Norwegian GHG emissions, as industries covered by the carbon tax are not (yet) included NME [4].

[13] Norwegian organisations joined various international research initiatives, such as: CCP (Statoil & Norsk Hydro); CASTOR (Statoil, SINTEF & NTNU); ENCAP (Statoil, SINTEF & NTNU); INCACO_2 (SINTEF & Statoil); CO_2RemMoVe (Statoil, SINTEF & DNV); CO_2Sink (Statoil & DNV); Dynamis (Statoil, SINTEF, Store Norske Spitsbergen Kullkompani & NTNU); CACHET (Norsk Hydro & SINTEF); and CO_2GeoNet (SINTEF & NTNU).

of CCS demonstration projects (F3).[14] Accordingly, Gassnova is an important funding partner in the development of AkerKværner's 'Just Catch' technology, which comprehends an amine-based post-combustion technology for combined cycle gas turbines (F2). AkerKværner and its consortium partners invested €4 million in this technology, which has to be demonstrated in Naturfkraft's 420 MW gas turbine at Kårstø in 2009, capturing 100 kt CO_2 annually. If successful, the technology will be scaled up to a capacity of 1 Mt CO_2/year in 2012. The offshore Utsira and Johansen formations are being evaluated for storage of CO_2 from Kårstø (and Mongstad).

AkerKværner was also involved—together with Statoil, Shell Norway, Norsk Hydro and climate change research institution CICERO—in a study called 'CO_2 value chain' in 2005, focusing on CO_2 capture and EOR (F2). The promising results of this study led to the announcement of the 'Halten CO_2 project' by Statoil and Shell Norway in March 2006. The project involved an 860 MW gas-fired power plant with CCS at Tjeldbergodden to power a methanol factory and offshore activities. The captured CO_2 would be used for EOR at the Draugen and Heidrun oil fields. Although Shell and Statoil already invested €50 million in the project, it was put on hold in June 2007, as studies showed that in this case EOR would not be commercially viable.

Next to the interest of the oil and gas industry in developing new commercial CCS projects, several Norwegian utility companies, as well as power-intensive industries, applied for construction permits for fossil-fuelled power plants with CCS. The first application came from Hammerfest Energi in January 2005, which planned to build a 100 MW gas-fired power plant based on the Sargas post-combustion technology (F1). However, in June 2007, the Norwegian Water Resources and Energy Directorate (NVE) decided not to grant a concession due to poor energy efficiency of the power plant. As depicted in Table 2-2, six other applications have been filed for CCS-based power plants to the Norwegian authorities. Although it is argued that if one of these projects gets approved, a power plant with full-scale CO_2 capture could be ready in 2015, all applicants are still awaiting the decision of the NVE.[15] Therefore, none of the organisations depicted in Table 2-2 has made an investment decision yet.

This leads to the odd case where the Norwegian government is at present the only party investing in full-scale deployment of CCS related to power generation (in Mongstad and Kårstø). This is partly the result of a broad political consensus that CCS will play a key role in Norway's low-emissions future (F7). A European survey showed that of all European countries, CCS plays by far the greatest—and still increasing—role in the national climate change debate in Norway [69]. The latter is nicely illustrated by Prime Minister Stoltenberg in his New Years speech on the 1st of January 2007, in which he compared CCS developments in Norway with the moon landing of the US in 1969 (F4); "It is our vision that within seven years we will have put in place capture and storage technology. This will be an important

[14] Gassnova is also responsible for the increasing number of gatherings on CCS (*F3*). For example, Gassnova co-organised the world's largest international CCS conference in Trondheim GHGT-8 (2006).
[15] Standards and qualification guidelines for CCS technologies are being developed by the Norwegian verification foundation (DNV) in cooperation with the authorities and industry.

breakthrough in the efforts to reduce GHG emissions in Norway, and once we succeed, I am convinced that the rest of the world will follow our example. This is a major project for our country. It is our moon landing."

Table 2-2: Proposed CCS projects in 2008 related to power generation in Norway [70]

Applicant(s)	Plant size (MW)	Fuel	Location
BKK	450	Gas	Mongstad
Skagerak Kraft	1000	Gas	Grenland
Industrikraft Møre	450	Gas	Elnesvågen
Haugaland Kraft	400–800	Coal	Haugalandet
Skagerak Kraft, Fortum Power, Østfold Energi	400–1100	Gas	Slagentangen
Eramet, Sargas, Sør Norge Aluminum, Tinfos	380	Coal	Hordaland

Figure 2-5 depicts the increasing—and more complex—positive feedback between system functions in the most recent episode of Norway's pioneering history in the field of CCS. It shows that the more stringent CO_2 emission reduction targets, the development of standards for CCS and supportive legislation led to increased funding for CCS RD&D and created legitimacy for CCS. Both processes were important for the development of additional large-scale CCS RD&D projects.

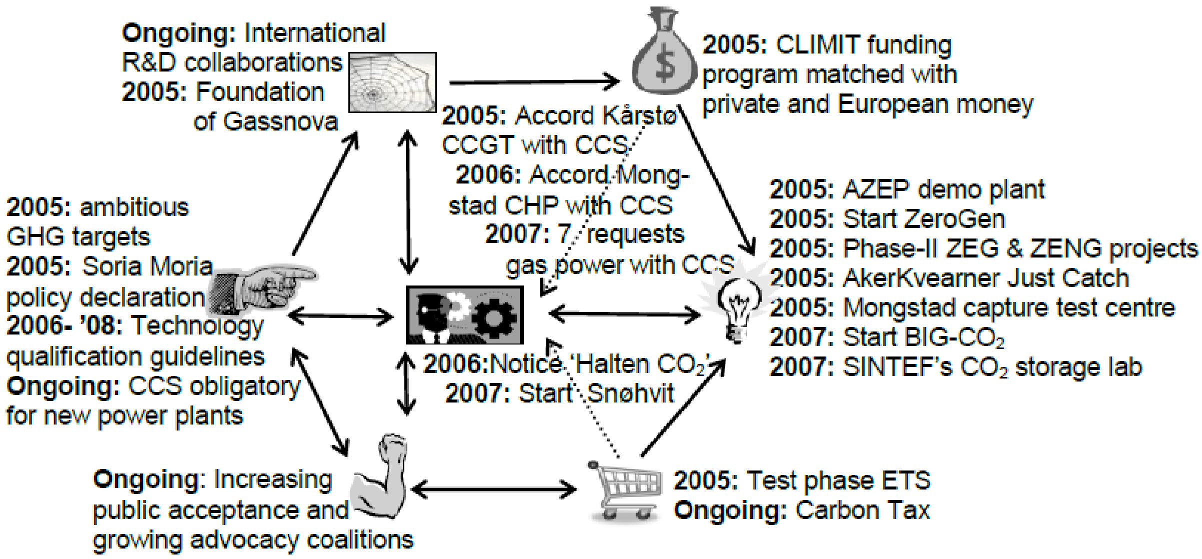


Figure 2-5: Function interactions episode IV: 2005–2008.

Despite the growing complexity due to an increased amount of activity regarding all system functions, the four distinguished episodes in the evolution of the CCS Innovation System show a similar kind of positive interaction pattern between the system functions. As a consequence of guiding emission reduction targets (F4) and an increasing legitimacy to support CCS technologies (F7), the government provided either financial resources (F6) or market incentives (F5). This resulted in a rising number of R&D programs (F2) and triggered entrepreneurial activities (F1). These research and commercial projects were done in strong partnerships (F3), which in turn created more legitimacy for CCS (F7). Thereby reinforcing this virtuous cycle.

2.4. Current Innovation System performance

The dynamic patterns in the growth of the Norwegian CCS Innovation System show that the early dedication of the national government to reduce Norway's CO_2 emissions has led to a remarkable consistent build-up of a CCS Innovation System in Norway. However, this functional pattern does not guarantee a thriving development of CCS in the future. The Norwegian CCS Innovation System may face recent challenges that obstruct a further expansion of the system.

In order to identify these possible impediments, the main actors composing the Innovation System have been asked to reflect upon the ongoing activities regarding CCS and rate their level of satisfaction with the fulfilment of a particular system function.[16] All ratings are on a scale of 1–5, whereby 5 equals high level of satisfaction. Based on these expert judgements, mechanisms that are currently inducing, or blocking the further development of CCS in Norway can be identified. In order to put the present strengths and weaknesses of the Innovation System into perspective, the progress in function fulfilment is detailed for each function. Thereby making use of the two distinctive time periods in the development of CCS in Norway.

2.4.1. Entrepreneurial activity

The entrepreneurs in the first period consisted of Norway's largest oil companies—i.e. Statoil and Norsk Hydro—and technology vendors Aker and Kværner. Although, its mergers and Statoil Hydro preserved their dominant position in the Norwegian Innovation System in the second period, the amount of foreign companies entering the system increased significantly during that time. Moreover, the analysis shows that in more recent years the field of CCS also became interesting for small to medium enterprises—resulting in projects like ZEG and ZENG—and that the power sector is now better represented in the Innovation System, than in the early days.

The entrepreneurial activities in the first period were centred around gas separation and CO_2 storage in aquifers as a result Statoil's Sleipner project. The success of this project has led to Statoil's second CCS project—i.e. Snøhvit—related to (liquid) natural gas handling, which started in 2007. The third and even more ambitious Halten CO_2 project, however, has been put on hold due to financial difficulties. The same holds for CCS projects related to power generation that have been proposed by several power companies. At present, only the Norwegian government announced its plans to invest in the full-scale deployment of CCS linked to gas power production (at Kårstø and Mongstad).

This implies that, despite the growing amount of entrepreneurs, the number as well as the diversity of demonstration and commercial projects is small. Consequently, the 'entrepreneurial activity' in Norway is with an average score of 2.7 the lowest rated function

[16] For a more thorough description of our method, we refer to our analytical framework.

by the 20 key stakeholders that participated in this study. The low standard deviation (SD) of 0.7 underlines the consensus that the lack of large-scale CCS projects in relation to power generation and EOR is the most important impediment for a higher rating.

2.4.2. Knowledge development

While advocating the demonstration of several promising technologies, the respondents stress the importance to continue laboratory research. The current research programs and technology test centres cover a wide variety of techniques for capture, transportation and storage of CO_2. The number and size of R&D projects increased considerably in the past decade, but the focus has been mainly on aquifer storage, gas separation and CO_2 capture related to gas power production. Many Norwegian organisations—e.g. SINTEF and NTNU—accumulated strong competences in these research areas, which can be seen as Norway's competitive advantage in relation to other nations.

Although some experts stress the need of diversifying Norwegian research efforts towards capture technologies for coal-fired plants—as they have a larger world market potential—, the knowledge created in Norway is considered as being of very high standard. Field experts generally praise the quality Norwegian CCS research and therefore this function received a relatively high rating of 3.9 with a SD of 0.8. It is hard to identify impediments in the fulfilment of this function other than the need to move several preferred technologies further up the innovation chain and enhance learning by doing.

2.4.3. Knowledge diffusion

In both periods, organisations had two main reasons to establish partnerships. First, to share the relatively high costs (and investment risks) related to CCS development. Second, the technological challenges involved in the development of particularly capture technology, as well as the integration of different fields of expertise (capture, transport and storage of CO_2), entail to share knowledge and competences. Therefore, project networks typically comprise a high number of diverse organisations. Furthermore, the Norwegian CCS Innovation System is strongly embedded in global CCS networks. Not only by Norwegian organisations participating in international programs, but also because of the large number of international parties involved in CCS projects on (and under) Norwegian soil. In comparison to the first period, these (inter)national CCS networks became larger and ‘denser’ in more recent years.

Despite their growing complexity, the Norwegian CCS networks are characterized as particularly open and trustworthy. With the foundation of Gassnova halfway the second period, industry could rely on an effective government body for support when entering, or acting in the CCS Innovation System. Gassnova stimulated knowledge exchange by creating network-building arenas, which resulted in an increasing number of CCS platforms and gatherings. Even so, it was noted that commercial interest and the protection of intellectual property hinder an optimal flow of knowledge between the actors attending these conferences, the performance of this function receives a score of 4.0 (SD of 0.8), which is the second highest rating of all functions.

2.4.4. Guidance

In 1987, the report ‘our common future’ of the Brundtland Commission addressed the growing tension between economic growth and ecological deterioration. After chairing the commission, Brundtland became Norway's prime minister from 1990–1996 and she agreed that ‘Norway's CO_2 emissions were to be limited so that they would not exceed the 1989 level in the year 2000’ [71]. However, clear statements on how to achieve these GHG emission reduction targets—let alone the role of CCS—were practically absent in the first half of the nineties. Moreover, Naturkraft received two concessions to build gas-fired power plants in 1996, without mentioning the option for CCS.

In 1997, Norway adopted the Kyoto Protocol (F4). However, the construction of two gas-fired plants would put Norway further away from reaching its Kyoto targets, i.e. an increase of GHG emissions limited to 1% between 2008 and 2012 compared with the level in 1990 [54]. The following ‘gas power debate’ resulted eventually in the resignation of the minority government led by Bondevik, when faced with parliamentary opposition to its strict gas power emission terms. In contrast, the succeeding interim Stoltenberg government issued full emission permits for the construction of three gas-fired power plants in 2000.

Elections in 2001 brought Bondevik back in office, whose new administration was even more dedicated towards the deployment of CCS and he announced that no additional concessions would be granted for fossil-fuelled power plants without CCS. This fitted rightly in the ambitious mid- and long-term emission targets, which have been reformulated several times in the second period, resulting in the goal to reduce CO_2 emissions with 30% in 2020 and to be carbon neutral in 2050. Following his predecessor, the second Stoltenberg administration emphasised the importance of CCS in realizing these emission reductions. The latter is nicely illustrated by his new year’s speech in 2007, where he calls the development of CCS technology for the Mongstad plant “Norway's lunar landing project”.

Nevertheless, it is unknown to what extent the Norwegian government can live-up to these high expectations, as it remains uncertain how many power plants with CCS will be built and in what way the Norwegian government is going to support this. Therefore, the guidance in the development of CCS is rated with a 3.0. However, the relatively high SD of 1.1 indicates that there is little consensus on this rating. This is mainly caused by the duality in strong generic guidance—i.e. CCS has an important role to play Norway's low-emissions future—and the lack of specific guidance—i.e. supportive policy instruments and short-term goals—, as CCS is not (yet) being adopted as a result of normal market forces.

2.4.5. Market creation

The introduction of a carbon tax proved to be a very 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- based power production. Despite these developments, the present high costs of CO_2 capture, is one of the main barriers to its application. So far, it appeared that the carbon tax of approximately €40/tonne CO_2 is not sufficient to initiate commercial CCS projects related to power generation. Also, the introduction of a domestic GHG Emissions Trading Scheme (ETS), which could be linked to the EU ETS in later stage, is not likely to create enough incentive for private actors to engage in such projects on a short term.

Although the Norwegian government agreed to finance the capture unit of the combined cycle gas turbines at Kårstø and Mongstad, its willingness to financially support other initiatives is uncertain. The amount of public money that will be allocated to realise relevant infrastructure is also debated. Therefore, the strong government statement, at the beginning of the millennium, not to issue emission permits for gas-based power plants, does not yet seem to create a commercial market for gas power production with CCS. Therefore, the 'formation of markets' is rated with a 2.9. However the SD is 1.3, meaning that there is no clear consensus. The latter can be explained by the successful execution of CCS projects related to natural gas handling due to the fixed carbon tax on the one hand, and the financial difficulties that are encountered by the large-scale application of CCS linked to power production on the other hand.

2.4.6. Resource mobilisation

In 1997, the Research Council of Norway established the KLIMATEK funding program with a budget of approximately €4.5 million for R&D of CCS technologies in the first 4 years. In the second period, similar types of subsidiary schemes succeeded this program and the financial support for CCS increased up to €6 million per annum. In 2005 that the first funding mechanism solely allocated to CCS was established. This CLIMIT program with a budget of €17.5 million a year meant a substantial increase in the total funds available for CCS RD&D, as these finances were matched with private investments and European funding. In fact, Norway has got by far the highest level of funding for CCS relative to GDP, compared with other high-income countries [72]. However, considering the need to shift from to learning by doing, many actors—especially the technology developing industries—would like to see more funding for demonstration projects.

The availability of financial resources was rated as 3.5 with a SD of 0.9. Insufficient funds for large-scale projects were mentioned as the most important barrier for a higher rating. Field experts rated the availability of human resources separately. In contrast to financial capital, the accessibility to human capital received a low rating; 2.7 with a SD of 0.8. The respondents are in agreement on the increasing scarcity of skilled (technical) personnel in CCS research.

2.4.7. Creation of legitimacy

During the development of Statoil's ground-breaking Sleipner project, some environmental groups, including Greenpeace, placed a critical note by the 'dumping' of CO_2 in the Utsira formation. This was not beneficial for the already limited political and public awareness of CCS as a potential CO_2 mitigation option. However, this would rapidly change in 1997, as a fierce debate on the deployment of onshore gas-fired power plants commenced. Important in this debate was the contribution of environmental groups, which held different views on CCS.

Norway's largest environmental NGO: 'Friends of the Earth (FoE)' followed Greenpeace in its opposition towards CCS. They reason that continued production of electricity from fossil fuels with CCS lengthens the dependence on non-renewable resources. Although these organisations have been critical, they haven't been very vocal in Norway. On the other hand, CCS was supported vigorously by 'Nature and Youth', formally the youth branch of FoE Norway. Also the environmental NGO Bellona has pushed CSS very actively since the late 1990s. They followed a pragmatic approach towards the oil and gas industry and emphasised the economic potential of CCS in combination with EOR; thereby contributing to the acceptance of CCS by society.[17]

Equally important and characterizing both periods, is that CCS is favoured by a powerful coalition of Norwegian industrial peak organisations (Norwegian Confederation of Trade Unions) and Norsk Industri (Federation of Norwegian Industries). These partners 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 and the Norwegian Innovation System [73]. These industrial organisations could benefit from CCS as one outlet for their substantial CO_2 emissions and therefore they perform a powerful lobby for its deployment in political arenas.

Besides lobbying activities of various environmental and industrial interest organisations, the increased public awareness of climate change and the more stringent GHG emission reduction targets formulated by governments have created more legitimacy to financially support the development of CCS with public money. Furthermore, the government's work on a supportive legal framework, including the development of qualification guidelines for CCS technologies (approximating similar EU directives), as well as the settlement of international legal issues under the London Convention and OSPAR treaty, created more legitimacy for the transfer of liability of the stored CO_2 to the Norwegian authorities. As a result, field experts give the creation of legitimacy for CCS a rating of 4.1 (SD of 0.8), which is the highest rating of all functions.

2.5. Identification of key policy issues

The performance assessment of the Norwegian CCS Innovation System shows that the extensive knowledge base, which has been accumulated over the past two decades, has not yet been valorised by entrepreneurs to explore the market for CCS concepts linked to power generation and EOR. 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 Norway. In order to move the Norwegian CCS Innovation System through this present difficult episode and deploy more advanced CCS concepts; it is necessary to direct policy initiatives at the identified weak system functions, i.e. entrepreneurial activity, market formation and guidance (see Figure 2-6).

[17] Also the fact that the CO_2 is stored in offshore reservoirs contributed to a more positive stand towards CCS by the general public. As there are no communities directly exposed to the possible risks of CO_2 leakage from the reservoirs. In other words, there is no reason for 'Not In My Back Yard' opposition to the current CCS projects.

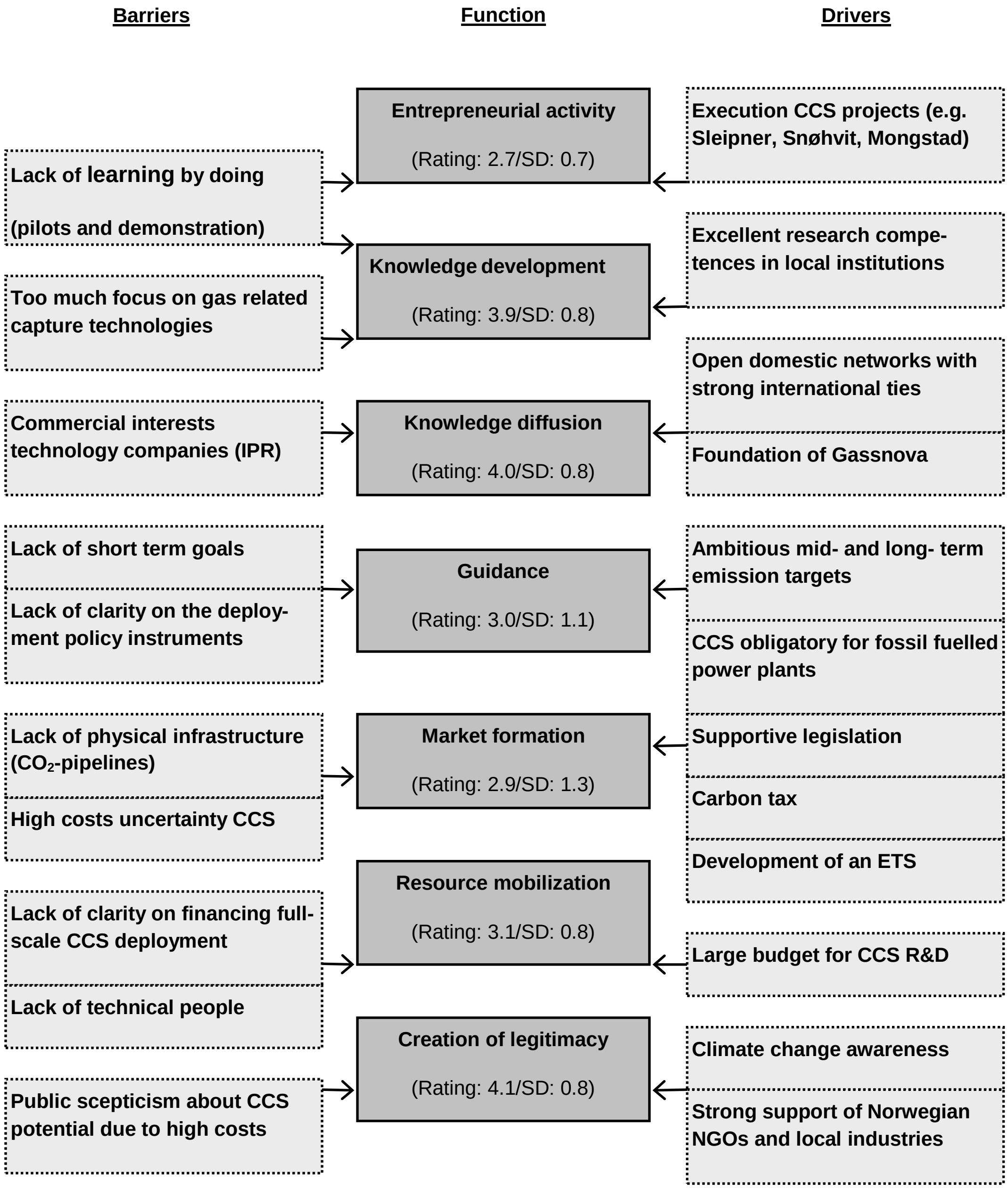


Figure 2-6: Drivers and barriers for CCS development in Norway as of 2008.

In order to improve its guiding role, the Norwegian government can foster the implementation of CCS technologies by stating short-term objectives in addition to the mid-term GHG emission reduction targets and long-term visions. Furthermore, it seems desirable to provide clarity on the set of policy instruments that will be used to reach these goals. The latter is important for the involvement of private parties in the development of CCS linked to gas power. The industrial sectors that may apply CCS in their daily operations should be able to rely on a long-lasting change in the institutional structure of the Innovation System that creates a clear market for CCS. Temporal subsidies, or taxes that are applied at present, do not seem to be strong enough to deal with the relatively high costs of CCS.

Policies can foster market formation and entrepreneurial activity by financially supporting learning by doing, i.e. by establishing more demonstration projects. In this way the technology is brought down its learning curve. This is necessary to bring about the required cost reductions and performance improvements for the technology to enter the market. The current Norwegian (carbon) tax system and the proposed emissions trading scheme, provide opportunities to create such financial incentives. This can be done by reallocating the tax revenues of the oil and gas industry to the implementation of full-scale CCS projects and the construction of an pipeline infrastructure for CO_2 transportation.

2.6. Discussion and conclusions

The analysis of the Norwegian CCS Innovation System provides insights into the relations between the historical dynamics of the system and the system's current performance. The results show that the early dedication of the national government to reduce Norway's CO_2 emissions has led to a remarkable consistent build-up of a national CCS Innovation System. Throughout the evolution of the system, conditions have been supportive for this to happen. Converging perspectives on the importance of CCS in the Norwegian energy system by researchers, (industrial) entrepreneurs, the national government and somewhat later also environmental groups, has resulted in a steady growth of the Norwegian CCS Innovation System as a whole. This is visible through the entry of new actors; extension of the knowledge base; successful entrepreneurial projects; increasing availability of public money; changes in legislation; creation of strong advocacy coalitions; and a guiding government fostering the development of CCS.

The positive system dynamics point out that strong advocacy coalitions of industrial peak organisations (e.g. Statoil, Hydro, AkerKværner) and several environmental NGOs (e.g. Bellona and ZERO), as well as the national government (or its representative body Gassnova) have been successful in stimulating the creation of technological knowledge (e.g. by SINTEF and NTNU) in comprehensive national and international consortia (e.g. SACS and BIG CO_2); and in triggering entrepreneurs to apply this knowledge in the market (e.g. Statoil's Sleipner & Snøhvit projects and AkerKværner's ‘Just Catch’ technology). The latter is done by providing market incentives (e.g. carbon tax and performance standards) and financial stimuli (e.g. KLIMATEK and CLIMIT), but also by creating a supportive legal framework (e.g. resolving liability issues for the sequestered CO_2) and the realisation of relevant infrastructure. These actions are legitimised by the country's strong climate policies (e.g. the reduction of CO_2 emissions of 30% by 2020 compared with 1990), which in turn guide the search for sustainable solutions.

The build-up of a well-performing CCS Innovation System has given Norway an international leadership position in the field of CCS. However, it is realised by the key stakeholders participating in the study that Norway's leading role in the development of CCS should not be taken for granted. Their evaluation of the current Innovation System performance identified several barriers that may block continuing positive system dynamics. The results provide a clear understanding of the current impediments in the CCS Innovation System and stress the need to direct policy initiatives at the identified weak system functions—i.e. guidance, entrepreneurial activity and market formation—to enhance the performance of the system.

In order to improve its guiding role, the Norwegian government could provide more clarity on the set of policy instruments that will be used to involve private parties in the development of CCS linked to power production and EOR. These industrial sectors that may apply CCS in their daily operations should be able to rely on a long-lasting change in the institutional structure of the Innovation System that creates a clear market for CCS.

Policies can foster market formation and entrepreneurial activity by financially supporting learning by doing, i.e. by establishing more demonstration projects linked to power generation and EOR. This is necessary to bring about the required cost reductions and performance improvements for the technology to enter the market. Although the current subsidies and taxes do not seem to be strong enough to deal with the relatively high costs of CO_2 capture at power facilities, they do provide opportunities to create such financial incentives. For instance, the (carbon) tax revenues of the oil and gas industry can be re-allocated to the implementation of full-scale CCS projects.

However, the choice for a specific set of policy instruments should not only be assessed to the extent of how they manage to remedy poor functionality in the CCS Innovation System, but national CCS policy development should also take into account the possible negative effects on the development of other (competing) sustainable energy technologies. In that respect, this study has got a narrow perspective, as it only focuses on CCS technologies.

Another point of discussion is the geographical focus on Norway, as foreign activities in the field of CCS can be determinative for the choice of policy instruments that will be employed to enhance the application of CCS Norway. Whether to buy foreign technology, or rely on ‘home-grown’ solutions and expertise is at the heart of this policy decision. It might be possible that new and more influential Innovation System dynamics start off as part of international developments. Due to the extensive international relationships of the Norwegian CCS Innovation System, a policy maker at the national level should be aware of the increasing importance of these global innovation processes for local activities.

In order to analyse these global trends in the development of CCS technologies, it is desirable to apply the analytical framework presented in this study to other countries as well. These analyses would not only allow for cross-national comparison on a function level—e.g. differences between R&D expenditures, technological focus, or market incentives—, but would also provide an opportunity to learn from other countries in overcoming the obstacles encountered in the development of CCS technologies.

Despite the technological and geographical delineations applied in this study, the results contain important insights in the current performance of the Norwegian CCS Innovation System and identified several key policy issues that need to be addressed in order to enhance positive Innovation System dynamics. These insights are not only of specific use for policy decisions regarding the deployment of CCS in Norway, but can also be of value for decision makers in other countries that wish to foster the development of CCS technologies.

Acknowledgements

We would like to gratefully acknowledge AndreasTjernshaugen (CICERO), for his cooperation with and supervision of Jochem van Ruijven during his internship at the Center for International Climate and Environmental Research Oslo (CICERO). Furthermore, we thank Trygve Riis (The Norwegian Research Council) for his inspiring comments on earlier versions of this paper, as well as two anonymous reviewers of this journal who put in a lot of effort to improve the quality of this paper. This research is part of the CATO program, the Dutch national research program on CCS.

References

1. van Alphen, K., J. van Ruijven, S. Kasa, M. Hekkert, and W. Turkenburg (2009). *The performance of the Norwegian carbon dioxide, capture and storage innovation system.* Energy Policy. 37(1): p. 43-55.
2. IEA (2005). *Energy Policies of IEA Countries - Norway 2005 review*, IEA/OECD: Paris (France).
3. Kjærland, F. (2007). *A real option analysis of investments in hydropower--The case of Norway.* Energy Policy. 35(11): p. 5901-5908.
4. NME (2005). *Norway's fourth national communication under the Framework Convention on Climate Change*, Norwegian Ministry of the Environment: Oslo (Norway). p. 1 - 92.
5. Statistics Norway (2007). *Natural Resources and the Environment 2006*, Statistics Norway: Oslo–Kongsvinger (Norway).
6. Trømborg, E., T.F. Bolkesjø, and B. Solberga (2007). *Impacts of policy means for increased use of forest-based bioenergy in Norway--A spatial partial equilibrium analysis.* Energy Policy. 35(12): p. 5980-5990.
7. Godoe, H. and S. Nygaard (2006). *System failure, innovation policy and patents: Fuel cells and related hydrogen technology in Norway 1990-2002.* Energy Policy. 34(13): p. 1697-1708.
8. IPCC (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*, ed. B. Metz, et al. Cambridge (UK).
9. Torp, T.A. and J. Gale (2004). *Demonstrating storage of CO2 in geological reservoirs: The Sleipner and SACS projects.* Energy. 29(9-10): p. 1361-1369.
10. OED (2007). *Fact Sheet: Carbon Capture and Geological Storage*, The Royal Norwegian Ministry of Petroleum and Energy (OED): Oslo (Norway).
11. Gassnova (2006). *Norwegian Gas Power Technology RD&D Program CLIMIT: Work Programme 2006*, Gassnova and the Research Council Norway: Oslo (Norway).
12. Torvanger, A., K. Rypdal, and A. Tjernshaugen (2007). *Carbon capture and storage projects under the climate policy regime: The case of Halten CO2*, Centre for International Climate and Environmental Research - Oslo (CICERO): Oslo (Norway).
13. Geels, F.W. (2002). *Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study.* Research Policy. 31(8-9): p. 1257-1274.
14. Kemp, R., D. Loorbach, and J. Rotmans (2007). *Transition management as a model for managing processes of co-evolution towards sustainable development.* International Journal of Sustainable Development and World Ecology. 14(1): p. 78-91.
15. Smith, A., A. Stirling, and F. Berkhout (2005). *The governance of sustainable socio-technical transitions.* Research Policy. 34(10): p. 1491-1510.
16. Foxon, T.J., R. Gross, A. Chase, J. Howes, A. Arnall, and D. Anderson (2005). *UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures.* Energy Policy. 33(16): p. 2123-2137.
17. Jacobsson, S. and A. Bergek (2004). *Transforming the energy sector: the evolution of technological systems in renewable energy technology.* Industrial and Corporate Change 13(5): p. 815–849.
18. Jacobsson, S. and A. Johnson (2000). *The diffusion of renewable energy technology: an analytical framework and key issues for research.* Energy Policy. 28(9): p. 625-640.
19. Negro, S.O., M.P. Hekkert, and R.E.H.M. Smits (2007). *Explaining the failure of the Dutch innovation system for biomass digestion--A functional analysis.* Energy Policy. 35(2): p. 925-938.
20. Carlsson, B. and R. Stankiewicz (1991). *On the nature, function and composition of technological systems.* Journal of Evolutionary Economics. 1(2): p. 1432-1386.
21. Hekkert, M.P. and S.O. Negro (2009). *Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims.* Technological Forecasting and Social Change. 76(4): p. 584-594.

22. Edquist, C. (2004). *Reflections on the systems of innovation approach.* Science and Public Policy. 31(6): p. 485-489.
23. Hekkert, M.P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann, and R.E.H.M. Smits (2007). *Functions of innovation systems: A new approach for analysing technological change.* Technological Forecasting and Social Change. 74(4): p. 413-432.
24. Johnson, A. (2001). *Functions in Innovation System Approaches,* Presented at the DRUID's Nelson - Winter conference: Aalborg (Denmark).
25. Edquist, C. (2001). *The systems of innovation approach and innovation policy: an account of the state of the art. Lead paper under the theme 'National Systems of Innovation, Institutions and Public Policies'*, Presented at the DRUID conference: Aalborg (Denmark).
26. Alkemade, F., C. Kleinschmidt, and M.P. Hekkert (2007). *Analysing emerging innovation systems: a functions approach to foresight.* International Journal of Foresight and Innovation Policy. 3(2): p. 139-168.
27. Hekkert, M.P., R. Harmsen, and A. de Jong (2007). *Explaining the rapid diffusion of Dutch cogeneration by innovation system functioning.* Energy Policy. 35(9): p. 4677-4687.
28. Jacobsson, S., B.A. Andersson, and L. Bångens (2002). *Transforming the energy system - the evolution of the German technological system for solar cells,* Electronic Working Paper Series SPRU Science and Technology Policy Research: Brighton (UK).
29. Jacobsson, S. (2008). *The emergence and troubled growth of a 'biopower' innovation system in Sweden.* Energy Policy. 36: p. 1491–1508.
30. Negro, S.O., R.A.A. Suurs, and M.P. Hekkert (2008). *The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system.* Technological Forecasting and Social Change. 75(1): p. 57-77.
31. van Alphen, K., M.P. Hekkert, and W.G.J.H.M. van Sark (2008). *Renewable energy technologies in the Maldives--Realizing the potential.* Renewable and Sustainable Energy Reviews. 12(1): p. 162-180.
32. Freeman, C. (1987). *Technology Policy and Economic Performance; lessons from Japan*. Pinter Publishers. London (UK): p. 155.
33. Lundvall, B.Å. (1992). *National Systems of innovation: Towards a theory of innovation and interactive learning* Pinter Publishers. London (UK).
34. Nelson, R.R. (1992). *National Innovation Systems: comparative analysis.* Industrial and Corporate Change 1(2): p. 347-374
35. Asheim, B.T. and A. Isaksen (1997). *Localisation agglomeration and innovation: towards regional innovation systems in Norway?* European Planning Studies. 5: p. 299–330.
36. Doloreux, D. and S. Parto (2004). *Regional Innovation Systems : A critical review. UNU-MERIT Discussion Paper*. United Nations University-Maastricht Economic Research Institute on Innovation and Technology (UNU-MERIT). Maastricht (The Netherlands).
37. Malerba, F. (2002). *Sectoral systems of innovation and production.* Research Policy. 31: p. 247–264.
38. Markard, J. and B. Truffer (2008). *Technological innovation systems and the multi-level perspective: Towards an integrated framework.* Research Policy. 37: p. 596–615.
39. Bergek, A., S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne (2008). *Analyzing the functional dynamics of technological innovation systems: A scheme of analysis.* Research Policy. 37(3): p. 407-429.
40. Bergek, A., M.P. Hekkert, and S. Jacobsson (2006). *Functions in innovation systems: A framework for analysing energy system dynamics and identifying goals for system-building activities by entrepreneurs and policy makers,* Presented at Innovations in energy systems: Oxford (UK).
41. Suurs, R.A.A. and M.P. Hekkert (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): p. 1003-1020.
42. Burton, I. (1987). *Our Common Future.* Environment. 29(5): p. 25.
43. Karstad, O. (1992). *Emission-free fossil energy from Norway.* Energy Conversion and Management. 33(5-8): p. 781-786.

44. Kongsjorden, H., O. Karstad, and T.A. Torp (1998). *Saline aquifer storage of carbon dioxide in the Sleipner project.* Waste Management. 17(5-6): p. 303-308.
45. Holloway, S. (1996). *An overview of the Joule II project: The underground disposal of carbon dioxide.* Energy Conversion and Management. 37(6-8): p. 1149-1154.
46. Korbol, R. and A. Kaddour (1995). *Sleipner vest CO2 disposal - injection of removed CO2 into the utsira formation.* Energy Conversion and Management. 36(6-9): p. 509-512.
47. Karstad, O. (2002). *The Sleipner and Snohvit CO2 Projects and Possible Future Roles of Underground Storage,* Statoil: Trondheim (Norway).
48. Berger, B., T. Sundset, and T. Torp (2003). *The Sleipner & SACS experience*. Presented at NorCap seminar. Trondheim (Norway).
49. Falk-Pedersen, O. and H. Dannstrom (1997). *Separation of carbon dioxide from offshore gas turbine exhaust.* Energy Conversion and Management. 38(Supplement 1): p. S81-S86.
50. Falk-Pedersen, O., Y. Bjerve, G. Glittum, and S. Ronning (1995). *Separation of carbon dioxide from offshore gas turbine exhaust.* Energy Conversion and Management. 36(6-9): p. 393-396.
51. Turkenburg, W.C. (1992). *CO_2 removal; Some conclusions.* Energy Conversion and Management 33(5-8): p. 819-823.
52. Tjernshaugen, A. (2007). *Gasskraft. Tjue års klimakamp*. Pax forlag Oslo.
53. Johnston, P. (1999). *Ocean Disposal/Sequestration of Carbon Dioxide from Fossil Fuel Production and Use: An Overview of Rationale, Techniques and Implications,* Greenpeace Research Laboratories: Amsterdam (The Netherlands).
54. NME (1997). *Norway's second National Communication under the Framework Convention on Climate Change - April 1997,* Norwegian Ministry of the Environment: Oslo (Norway).
55. Sorheim, H.-R. (2004). *Klimateks engasjement innen Gasskraft med CO2-håndtering,* Presentation for Norwegian Ministry of Petroleum and Energy (OED).
56. Ursin, T.P. and P.T. Halvorsen (2001). *HiOx - Emission Free Gas Power: A technology developed by Aker Maritime*. Second Nordic Minisymposium on Carbon Dioxide Capture and Storage. Göteborg (Sweden).
57. SACS (2000). *SACS - Saline Aquifer CO_2 Storage - final technical report*. Available from: http://www.co2captureandstorage.info
58. Karstad, O. (2002). *Geological storage, including costs and risks, in saline aquifers,* Presented at the IPCC workshop on carbon dioxide capture and storage: Geneva (Switzerland).
59. Larsen, O.M. and A. Ruud (2005). *HydroKraft: Mapping the innovation journey in accordance with the research protocol of CondEcol,* Program for Research and Documentation for a Sustainable Society (ProSus) Centre for Development and the Environment, University of Oslo: Oslo (Norway). p. 1 - 49.
60. Tjernshaugen, A. and H. Lee (2004). *Shaming and Framing: Norwegian Nongovernmental Organizations in the Climate Change Negotiations,* Center for International Climate and Environmental Research - Oslo (CICERO): Oslo (Norway).
61. Sundkvist, S.G. and H. Eklund (2005). *AZEP -an EC funded project for development of a CCGT power plant without CO2 emissions,* Presented at the 4th Nordic Minisymposium on CO2 Capture and Storage: Espoo (Finland).
62. Thomas, D.C. and S. Benson (2005). *Carbon Dioxide Capture for Storage in Deep Geologic Formations - Results from the CO2 Capture Project*. Vol. 1. Elsevier Science. London (UK).
63. Sundset, T. (2003). *CO2 - From problem to business opportunity,* Presented at the 3rd Nordic minisymposium on CO2 capture and storage: Trondheim (Norway).
64. Maldal, T. and I.M. Tappel (2004). *CO2 underground storage for Snohvit gas field development.* Energy. 29(9-10): p. 1403-1411.
65. European Commission (2008). *Proposal for a directive of the European Parliament and of the council on the geological storage of carbon dioxide and amending Council Directives,* European Commission: Brussels (Belgium).
66. Mace, M.J., C. Hendriks, and R. Coenraads (2007). *Regulatory challenges to the implementation of carbon capture and geological storage within the European Union under EU and international law.* International Journal of Greenhouse Gas Control. 1(2): p. 253-260.

67. NME (2007). *Norwegian climate policy*, Summary in English: Report No. 34 (2006–2007) to the Storting. Norwegian Ministry of the Environment: Oslo (Norway). p. 43.
68. Røkke, N. (2007). *Big CCS Plattformen - basis for videre vekstbasis*. Presented at the CO2 Seminar Teveltunet. Teveltunet (Norway).
69. Shackley, S., H. Waterman, P. Godfroij, D. Reiner, J. Anderson, K. Draxlbauer, and T. Flach (2007). *Stakeholder perceptions of CO2 capture and storage in Europe: Results from a survey*. Energy Policy. 35(10): p. 5091-5108.
70. NVE (2008). *Meldinger og søknader om varmekraft og gassrørledninger*, Norwegian Water Resources and Energy Directorate: Oslo (Norway).
71. NME (1994). *Norway's national communication under the Framework Convention on Climate Change - September 1994*, Norwegian Ministry of the Environment: Oslo (Norway). p. 1 - 66.
72. Tjernshaugen, A. (2006). *Political commitment to CO2 capture and storage: evidence from government RD&D budgets.* Mitigation and Adaptation Strategies for Global Change. 13(1): p. 1-21.
73. Narula, R. (2002). *Innovation systems and 'inertia' in R&D location: Norwegian firms and the role of systemic lock-in.* Research Policy. 31(5): p. 795-816

Interlude B

This Chapter presents the results of the second case study on the Dutch TIS around CCS technologies. The core of this analysis is the construction of a narrative around the build of the TIS, which is based on the recognition of patterns in event data. These insights are used to evaluate the current status of the "transition pathway CCS" in order to formulate new strategies to accelerate the energy transition process.

The research presented in this chapter was executed in the period 2007 – June 2010 and is partly based on [1, 2]:

- Van Alphen, K. (2009) *Effectief Innovatiebeleid ten aanzien van CO2 afvang en opslag (English: Effective innovation policy for CO2 capture and Storage).* Innovation Studies Group, Copernicus Institute, Utrecht University, Utrecht, The Netherlands.
- Hekkert, M.P., Alkemade, F.A., Negro, S.O., Suurs, R.A.A. and Van Alphen, K. (2007). *Het versnellen van transitiepaden door het versterken van innovatiesysteemdynamiek (English: Accelerating transition pathways for low emissions technologies by strengthening innovation system dynamics).* Innovation Studies Group, Copernicus Institute, Utrecht University, Utrecht, The Netherlands. Contract research for the Ministry of Economic Affairs.

3. An evaluation of the transition pathway for CCS technologies in the Netherlands and strategies to accelerate the build up of a CSS Innovation System

Abstract

In a broad strategic context, CCS has been recognized as one of the transition paths to reform the Dutch energy system. In this chapter the Innovation System Functions approach is used to evaluate the current status of the transition pathway for CCS in the Netherlands in order to formulate new strategic policies to accelerate the energy transition process. This approach posits that new technology is developed, demonstrated and deployed in the context of a Technological Innovation System. The dynamic patterns in the growth of the Dutch CCS Innovation System show that the early dedication towards CCS of a small community of Dutch researchers has led to a remarkable build-up of an Innovation System around CCS technologies. However, not all system functions have received equal attention in the built up the Innovation System so far. There seems to be a lack of incentives that create a market for CCS. This can be seen as one of the main reasons why the extensive knowledge base and CCS knowledge networks, accumulated over the past years, have not yet been valorised by entrepreneurs to a full extend. In order to advance the overall performance of the Innovation System and accelerate the deployment of 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, regulatory guidance and the creation of legitimacy by the general public also need to be addressed. Therefore, a policy strategy has been abstracted from the analysis that would enhance the performance of the innovation system by: 1) supporting learning by doing; 2) altering short-term financial stimuli and long-term market incentives; and 3) improving supportive regulation and sound communication on CCS.

3.1. Introduction

Carbon dioxide capture and storage (CCS) is expected to become an important CO_2 emission reduction technology in the Netherlands. The annual Dutch CO_2 emission is nearly 180 $MtCO_2$ at present, of which approximately 100 $MtCO_2$/year is emitted by the energy and manufacturing industry [3]. The estimated storage potential on Dutch territory (>11 $GtCO_2$) is sufficient to cover at least a few decades up to one century of the CO_2 emissions produced in the energy and manufacturing industry, depending on the availability of the Groningen gas field [4].[1] The Netherlands also has decades of industrial experience with the transmission, distribution and processing of natural gas, which could be valuable in developing a CCS infrastructure.

A recent scenario analysis that assessed the potential and costs of different measures to reduce Dutch GHG emissions in 2020 illustrated the importance of CCS [5]. The general conclusion was that energy saving, CCS and nuclear energy have a large potential at relatively low costs. It was found that a 25% reduction in 2020 with respect to the 1990 level could only be achieved when also CCS is applied. This can be explained by the fact that by 2010 roughly 3 GWe of new capacity is needed to cover the increase in electricity demand and replace old units that will be decommissioned [6]. The demand for new capacity in the coming years seems too early for nuclear and too large for renewables, and therefore an important role is foreseen for fossil fuel based power plants, especially coal-fired units. At present there are 4 new coal fired stations planned to be build in the Netherlands[2]. Without integrating CCS into these new power stations, it will be hard for the Netherlands to meet its emission reduction targets.

In recent years, the limitations in alternative low emissions technologies as well as the specific advantages of CCS have become more apparent. Together with recent international developments in energy and climate policy, over two decades of R&D and several successful pilot projects, this has caused a growing interest in CCS by Dutch policy makers. In a broad strategic context, CCS has been officially recognized as one of the transition paths to reform the Dutch energy system [7, 8]. The energy transition is an ambitious long-term dynamic process to realise a sustainable energy supply system by 2050.

Within this policy framework, 24 promising low carbon innovations (‘transition pathways’) have been identified which are supported in various ways by actors from government, industry and intermediary organisations. Researchers from the Innovation Studies Group of the Utrecht University (including the author of this thesis) were asked by the Interdepartmental Project bureau Energy transition (IPE) to apply a ‘Technological Innovations Systems’ approach to evaluate the current status of the transition pathways (low-carbon technologies) in order for them to formulate new strategic policies to accelerate the energy transition process.

[1] The storage capacity of the Slochteren gas field is estimated at 7350 Mt, which accounts for approximately two thirds of the total storage capacity in the Netherlands [4].

[2] The four power stations are: Electrabel’s 600/800 MWe PC plant at Maasvlakte (Rotterdam), Eon’s 1100 MWe PC plant also at Maasvlakte (Rotterdam), Nuon’s (Magnum) 1200 MWe IGCC plant at Eemshaven (Groningen), and RWE’s 1600-2200 MWe PC plant at Eemshaven (Groningen).

In the following section the approach taken to create insight in the main drivers and barriers for the development of low emission technologies is explained, then the research design is presented and subsequently the results for the evaluation of the ‘transition pathway CCS’ are discussed. Finally study aims to demonstrate how these analyses have provided handholds for the formulation of intervention strategies in order to accelerate the development and diffusion of CCS technologies in the Netherlands.

3.2. Technological Innovation Systems – An approach to evaluate low emission transition pathways

According to Carlsson and Stanckiewicz [9], a Technical Innovation System is defined as:

“A network or networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilise technology.”

This implies there is a technological Innovation System for each technology and that each system is unique in its ability to develop and diffuse a new technology [10]. In recent years the ‘technological Innovation System’ (TIS) framework is developed to give insight in the key factors that drive or block low carbon technologies, like CCS. The main idea of the TIS framework is that technological change is the result of the build up of a new TIS, and changes in the existing Innovation Systems [11, 12]. Therefore, in order to understand the development and diffusion of low carbon technologies, or in this case the progress made along a transition pathway for CCS, it is necessary to create more insight in the *dynamics* of Innovation Systems. To analyse the *dynamics* of Innovation Systems, a number of key processes that need to be fulfilled in a well-functioning TIS are identified [13]. These processes are labelled as ‘functions of Innovation Systems’ or system functions, namely: entrepreneurial activity, knowledge development, knowledge diffusion, guidance of the search, market creation, mobilization of resources and creation of legitimacy (see Table 3-1 for definitions).

A well functioning TIS is a requirement for the technology in question to be developed and widely diffused. In several previous studies historical analyses have been made of the emergence of low-carbon technologies; these studies showed that the presence or absence of these system functions induce to a great extent the build up of an Innovation System around low carbon technologies and thereby strongly influence the chances of success of these technologies to reach a stage of wide scale market deployment [11, 14-16].

Table 3-1: Functions of technological Innovation Systems [17].

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 favourable 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 lead to resistance from established actors, or society. Advocacy coalitions can counteract this inertia and lobby for compliance with legislation/institutions.

Both the individual fulfilment of each system function and the interaction dynamics between them are of importance. Positive interactions between system functions could lead to reinforcing dynamics within the TIS, setting off virtuous cycles or ‘motors of change’ that lead to the diffusion of a new technology [18]. An example of a virtuous cycle that has been observed regularly in the field of low-carbon technology development is the following [18]. The virtuous cycle starts with F4: Guidance of the Search. In this case, societal problems are identified and government goals are set to limit environmental damage. These goals legitimise the mobilisation of resources to finance R&D projects in search of solutions *(F6),* which in turn, is likely to lead to Knowledge Development *(F2)* and increased expectations about technological options *(F4)*. Thus, the fulfilment of the individual system function is strengthened through interaction with other system functions. On the other hand, vicious cycles are also possible. Here a negative system function fulfilment leads to reduced activities in relation to other system functions. The system functions interact and reinforce each other in a negative way, with the result of slowing down or even stopping the process of building up a TIS.

To summarise, if we want to evaluate the dynamics and performance of an emerging TIS, or a ‘transition pathway’ for that matter, we need to analyse the fulfilment of the system functions, identify the presence of ‘motors of change’ and determine the underlying drivers and blocking mechanisms.

3.2.1. Research design and method: dynamics, performance and intervention strategies

The practical relevance of this analytical framework is based on the assumption that policy interventions directed at stimulating sustainable changes in the energy system should focus on improving Innovation System functions that operate weakly in order to increase the chances of positive system dynamics. To specify these policy interventions it is necessary to analyse the relationship between the historical dynamics and the current performance of the Innovation System. The relationships between Innovation System dynamics, performance and policy, are further clarified by the three different analytical parts that are discerned in this study.

Part 1: The first part consists of mapping the historical dynamics of the Innovation System in terms of (interactions between) functions. Therefore a so-called process approach or sequence analysis is applied in this study [19-21]. The process approach conceptualizes development and change processes as sequences of events. By gathering data that indicates how the process unfolds over time, a timeline and narrative of events can be constructed that provides significant insights into the development and change process [18, 19, 22, 23].[3]

The data collection is not so much about following all of the individual agents or innovation projects in the system, it contains the events that are reported at system level relevant to CCS. The first source of data was the Lexis Nexis TM academic news archive, which contains all articles published in national, regional newspapers and specialized journals that have been published from 1990 onwards. In total around 800 relevant articles were found by means of a keyword search. Then each event related to the development, diffusion, or implementation of CCS technologies is listed chronologically in a database, as for example workshops on the technology, the start-up of R&D projects, expressions of expectations about the technology, or announcements of resources made available. The database, which contained a bit over a hundred events, is structured according to year of the event, reference articles, event description, and system function. Each event is allocated to one system function using the classification scheme, where specific event categories are allocated to specific system functions (see Table 3-2).

[3] In studies carried out by Van de Ven and colleagues, events around a specific innovation project are mapped. Due to the focus on the micro level of innovation, detailed information is gathered by means of observing organizational meetings and by studying minutes of meetings and reports [19]. Negro [23] and Suurs [18] have successfully applied to this approach to study the historical dynamics of TISs, reporting all events that took place on a system level.

Table 3-2: Event types as indicators of functions [18].

System function	Event types
F1. Entrepreneurial Activities	Projects with a commercial aim, demonstrations, portfolio expansions
F2. Knowledge Development	Studies, laboratory trials, pilots, prototypes developed
F3. Knowledge Diffusion	Conferences, workshops, alliances between actors, joint ventures, setting up of platforms/branch organizations
F4. Guidance of the Search	Expectations, promises, policy targets, standards, research outcomes
F5. Market creation	Regulations supporting niche markets, generic tax exemptions, ‘obligatory use’
F6. Resource Mobilisation	Subsidies, investments, infrastructure developments
F7. Support from Advocacy Coalitions	Lobbies, advice

This part of the analysis results in a narrative that describes the appearance and evolution of the Dutch CCS Innovation System. It explains the growth of the system in terms of changes in the fulfilment of Innovation System functions by its components. This narrative is used to point out how system functions have reinforced or antagonized each other through time; thereby creating insight in the historical dynamics (growth or decline) of the TIS.

Part 2: The second part of the analysis assesses the performance of the Innovation System, as insights in the dynamics of the TIS do not tell us directly whether the Innovation System is well functioning or not. In order to further assess the system's performance—i.e. not how, but how well the system is functioning—the relative ‘goodness’ of its dynamics needs to be evaluated [24]. Since by definition diffusion is low for emerging technologies, it is problematic to test whether a good fulfilment of these functions of Innovation Systems indeed leads to successful diffusion. Therefore, 20 interviews have been conducted with key stakeholders in the Dutch CCS Innovation System. See Table 3-3 for the list ‘evaluative questions’ that provide insight in the performance of each of the functions. With the selection of interviewees a balanced representation of the different actor groups in the Innovation System was pursued. Thereby a distinction is made between the following groups of actors: technology-developers, industry, research organisations, governmental parties and environmental NGOs. All of the interviewees have been involved in the development of CCS in Netherlands for a longer period of time, but are not necessarily proponents of the technology.

To minimise the personal bias of the researchers and to further assess the system's performance, interviewees have also reflected 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 [25] where 1 = very weak, 2 = weak, 3 sufficient, 4 = good and 5 = very good. In this way the identification of functions that either induce or block positive system dynamics is verified by critical evaluations from experts who take part in shaping the technological trajectory for CCS.

Table 3-3: Indicative questions that reflect the extent to which each function in the Innovation System is fulfilled by the components of the system [see also 17, 24].

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)?

Part 3: The third and last part of this analytical framework consists of the identification of 'system intervention strategies'. Based on the current performance of the system, in relation to what is reasonable to expect taking the historical development of the TIS into account and according to the judgment of key actors in the system, it is possible to specify strategic actions in terms of what should be done to improve the fulfilment of those system functions that were seen as obstructing positive system dynamics and thereby impeding a higher performance of the entire CCS Innovation System.

The strategy development process was facilitated by an additional workshop with 12 CCS experts that were brought together in an Electronic Board Room (hardware) with a Group

Decision Support System (software).[4] Again a broad representation from Industry, Government and Research was sought after in the composition of the participating CCS stakeholders. This interactive, computer-based system facilitates participants to communicate simultaneously and anonymously on unstructured and semi-structured problems by brainstorming, giving comments, and voting on statements [26]. We used the characteristics of a Group Decision Support System to encourage open discussions between the stakeholders on the strengths and weaknesses of the Dutch CCS Innovation System and to construct strategies that would accelerate the built up of CCS Innovation System in the Netherlands.

3.3. Results: Dynamics of the Dutch CCS Innovation System

This section discusses the dynamics of the Dutch CCS Innovation System by reconstructing its appearance and evolution (growth/decline) over the past two decades. The narrative is chronologically organized into four episodes characterized by a specific interaction pattern between functions. These dynamic patterns are discussed briefly at the end of every episode. This implies, that the end of each episode is chosen on the basis of change in activities (function fulfilment); consequently the four episodes are not equal in length. All the major events that have influenced the development of the Dutch CCS Innovation System will be discussed below and refer to the various system functions as *F1, F2,* etc., following Table 3-1.

3.3.1. Episode 1: 1988-1996: Amsterdam - the birthplace of an international CCS research community

In the Netherlands, CCS has been investigated since the late eighties (*F2*), starting with the Dutch Integrated Research Programme on Carbon Dioxide Recovery and Storage (SOP-CO_2).This research program was led by researchers of the Department of Science Technology and Society of the Utrecht University and funded (*F6*) by the Dutch Ministry of Housing, Physical Planning and Environment [27, 28]. Besides assessing the techno-economic potential of CCS in mitigating climate change, several studies under this program focussed on the possibility to remove CO_2 from future coal gasification based power facilities (*F2*) [29, 30]. This can be explained by the start of a coal gasification demonstration plant at Buggenum in the south of the Netherlands.

The results of these studies were presented at the First International Conference on Carbon Dioxide Removal held in Amsterdam [31], where more than 250 researches from various parts of the world gathered to exchange their knowledge (*F3*).[5] This was a major event in the history of CCS, as until the early 1990s, most researchers involved in CCS worked in isolation. Howard Herzog, a principal research engineer at the MIT Laboratory for Energy and the Environment and a leading expert on CCS, says that "*attendees arrived as individuals but left as a research community that now includes funding agencies, industries, and nongovernmental organizations throughout the world*" [32]. One year after the conference,

[4] This workshop expert workshop was held in March 2009.
[5] The second International Conference for Carbon Dioxide Removal (ICCDR-2) was held in Kyoto in 1994 and the Third in Boston in 1996. Two important changes were made for the future conferences. First, the IEA GHG R&D Programme has become the sanctioning organization. Secondly, the name has changed to the International Conference on Greenhouse Gas Control Technologies (GHGT).

the first EU funded (*F6*) collaborative research program was set up. This Joule II program consisted of various European research partners, including the Dutch Organization for Applied Scientific Research (TNO), and investigated amongst other things the storage capacity of CO_2 underneath the North Sea (*F3*) [33].

In the same year as the first international CCS conference, the potential role of CCS as a climate change mitigation option was discussed at the Earth Summit in Rio de Janeiro, and assessed nationally in the Dutch Energy Outlook 1990–2015 (*F4*) [34]. Although requested by the Dutch research community, these events did not lead to any pilot projects (*F1 & F2*), because of the disapproval of such projects by the Dutch Energy Council (*F4*) [35] and a reserved stance of the ministry of economic affairs with regard to financing these projects (*F6*). Despite this rather cautious approach towards CCS by the authorities in the mid-nineties, the promise of CCS was further strengthened (*F4*) by the publication of the IPCC [36] Special Report on Climate Change and subsequent Dutch reports on this matter by the Centre for Energy Conservation [37] and the Dutch Organization for Applied Scientific Research (*F4*) [38]. Moreover, in 1996, Norwegian oil company Statoil started its CO_2 storage operations at the Sleipner West gas field, where 1 $MtCO_2$ is injected into a sub-surface reservoir each year [39]. This project showed the world that the CCS concept can be a reality and triggered companies in the Netherlands to start developing CCS projects in the years to come (*F4*).

To recapitulate, positive results from various research activities has put CCS on the agenda and quickly results in the rise of expectations for CCS in the early 1990s. This, in turn, triggers a series of collaborative activities that can be classified as both Knowledge Development and Knowledge Diffusion. Triggered by guiding examples from abroad, the rise of a virtuous cycle is observed, since positive results from research lead to higher expectations of CCS and the mobilization of resources for further research *(F2, F4, F6)*.

3.3.2. Episode 2: 1997-2004: CO_2 Reuse

Following the example of Statoil, Shell announced its plans to store the CO_2 stream from the Shell Pernis refinery located close to the city of Rotterdam (*F4, F1*). This announcement triggered fair media attention in 1997 [40], especially after the Conference of Parties (CoP)-3 in Kyoto, where the Netherlands has accepted a 6% reduction in emissions between 2008-12, compared to 1990 levels (*F4*). At that time the Dutch Government envisaged that it would meet its reduction targets partially by Kyoto mechanisms as Joint Implementation and Clean Development Mechanism, and partially by domestic reductions, mainly through energy conservation and renewable energy. Two years later, a policy document on climate change issued by the Ministry of Housing, Spatial planning, and Environment [41], referred to CCS as the most important back-up option for the Netherlands to reach its emission reduction targets as formulated in the Kyoto protocol (*F4*). A similar message was conveyed at the CoP-6 in The Hague (*F4*).

The official policy note on CCS composed by the Dutch Ministry of Economic Affairs in 2003 acknowledged the role of CCS for the medium and long term (*F4*) [42]. In that same year the Dutch Government decided to fund (*F6*) the €13.6 million CO_2 Re-use through

Underground Storage (CRUST) program [43]. The first Dutch project to demonstrate storage was realized within the CRUST programme (*F1, F2)*). The injection started in 2004 and entails the capture of CO_2 from produced natural gas and injection of 20 kt CO_2 per year in an offshore gas field (K-12 B). The project is carried out by Gaz de France (owner of the K-12 B field) and monitored by the Dutch Organization for Applied Scientific Research (TNO).

Related to this project, a feasibility study has been carried out for underground buffer storage of CO_2 in a nearby gas field (the De Lier field) [44]. After a more detailed assessment of this field, which was one of the options to store part of the CO_2 from Shell's refinery in Pernis, it was however cancelled as candidate field for storage demonstration (*F1*). Eventually, the CO_2 from Shell Pernis was not stored underground, but transported to greenhouse horticulture in order to meet the CO_2 requirement. This plan was already approved in 1999 and realized by OCAP in 2004 (*F1*) (Organic Carbon dioxide for Assimilation of Plants, 2004).

Besides the involvement of the TNO in the national CRUST program, this Dutch organization for applied science has also been partnering (*F3*) in various CCS R&D projects co-funded by the European Union (*F6*) at the beginning of the new millennium (see Table 3-4). Examples are the SACS project, which is linked to Statoils' CO_2 storage operations on the Norwegian continental shelf and the RECOPOL project in Poland, where CO_2 is used for enhanced coal bed methane production (ECBM). The University of Twente is involved in two of Europe's major CO_2 capture R&D programs, i.e. ENCAP and CASTOR (*F2, F3*). Research cooperation within the EU was further enhanced by the creation of 'CO_2Net', which functions as a European knowledge sharing network (*F3*). At the start of the next episode a large number of Dutch organisations start to work together under a national research program for CCS, which clearly changed the system dynamics.

The event sequence is characterised by contributions to Entrepreneurial Activities, Knowledge Development and Knowledge Diffusion (in international research networks). The role of Guidance (climate policy statements and emissions reduction targets) and, directly linked to it, the allocation of financial resources (*F6*) has become more important as well.

3.3.3. Episode 3: 2005-2008: Building momentum

In 2005, the CATO program (CO_2 Capture, Transport and Storage) was launched. This national R&D program has a budget of nearly €25 million (*F6*) and consists of 17 industrial, (non)governmental, and research organisations collaboratively working together on CCS (*F3*) [45]. CATO is co-ordinated by the Utrecht Centre for Energy Research[6] and covers CO_2 capture, CO_2 storage, systems analysis and public outreach (*F2*). One year later the Dutch CAPTECH R&D program (2006–2009) started. This program, 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% [46, 47] . In order to achieve this, a wide portfolio of future capture technologies is being investigated under this program (*F2*).

[6] In 1998 the Utrecht University Centre for Energy Research was founded, with a program based on what they called the 'trias energetica': energy conservation, renewable energy, and 'clean fossil'. But as late as in 2003 money became available (from a competitive bid for 'research infrastructure funds' from Dutch natural gas remits) to finance CCS research, which later became the CATO program.

Table 3-4: EU co-funded CCS research programs that involve Dutch scientific research organizations.

Name	Description	Budget (Million)	Duration
Saline Aquifer CO_2 Storage (SACS)	Large-scale demonstration of CO_2 injection and storage in an undersea deep saline aquifer	8	1998-2002
Assessing European Potential for Geological Storage of CO_2 From Fossil fuel Combustion (GESTCO)	Assessed whether geological storage of CO_2 provides a viable method for wide scale application.	3,76	1999-2002
CO_2Store	Utilising the knowledge gained from other projects to study new CO_2 storage opportunities in Europe.	2.5	2003-2006
CO_2GeoNet	Development of excellence in research and demonstration projects for efficient and safe geological storage of CO_2	9	2004-2009
CO_2Sink	Research project concerned with the geological storage of CO_2 as a viable option for reducing greenhouse gas emissions.	15.2	2004-2010
Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian coal basin of Poland (RECOPOL) (Management of GHG emissions)	Research and pilot field tests to assess applicability of ECBM method under European conditions.	3.5	2001-2004
CASTOR, "CO_2 from Capture to Storage"	European initiative to develop and validate the innovative technologies needed to capture and store CO_2 in a reliable way.	5.8	2004-2008
Enhanced Capture of CO_2 (ENCAP)	Research project for the development of pre-combustion technologies for enhanced capture of CO_2	22	2004-2009
CO_2 Capture Project (CCP)	The storage, measurement and verification (SMV) components of the CCP Project.	28	2001-2004
CO_2NET	A European CO_2 Knowledge Sharing Network, facilitating co-operation between various organisations/projects.	2.1	2000-ongoing
Weyburn-Midale CO2 Project	Enhanced understanding of the application of CO_2 in EOR operations and modelled regional gas concentrations and the extent of CO_2/rock reactions taking place.	5.1 (EU funding)	2001-2004

In the beginning of 2005, possible locations for zero emission power plants (ZEPPs) are proposed, i.e. the North of the Netherland (an area known as ‘Energy Valley’), Maasvlakte (City Rotterdam) and the Sloegebied (Province of Zeeland). The locations of these projects are closely linked to the 4 new coal fired power plants that received permits to meet increasing electricity demand and replace old capacity. In the public debate the possibility to equip these new power plants with CCS was often portrayed as an alternative to expand the nuclear energy capacity as a GHG mitigation strategy [40]. This discussion on the possible role of CCS in the future energy supply system of the Netherlands was not only triggered by the realization of national research program on CCS (CATO), but also due to events like the release of the IPCC Special Report on CCS [48], the CoP 11 in Montreal, and the first National Conference on CCS in the Netherlands; both held in 2005 (*F4*).

One of the outcomes of this nuclear versus 'clean coal' debate was that the current nuclear plant (Borssele) in the Netherlands will be kept open for a longer period of time, i.e. until 2033, instead of 2013, and that part of the revenues (80 million Euros) are reserved for CCS demonstration projects (*F6*). This corresponded with an influential report presented by the Energy Research Centre of the Netherlands (ECN) and the Dutch Environmental Planning Bureau [49], proclaiming that prolonging the life of the existing nuclear energy facility and new build coal fired power plants with CCS are the most affordable options when it comes to achieving the emission reduction targets on the short term (*F4*). In that same year CCS also has been officially recognised as one of the main transition paths to reform the Dutch energy system (*F4*) [8].

In March 2007, European ministers agreed to reduce CO_2 emissions by 20% in 2020 during their climate summit in Brussels. At this summit the Dutch Prime Minister Jan Peter Balkenende stated he supports the development of CCS projects in the Netherlands and sees it as an important technology for the Netherlands to combat climate change (*F4*). A message that was also given by the Task Force Energy Transition (*F4*) [7]. Later, in that same year the Dutch government's 'Clean and Efficient' programme calls for a 30 percent reduction in Dutch greenhouse gas emissions by 2020 and recognizes CCS as a key component to meet these targets (*F4*) [50]. A vision that is shared in the report published by the Energy Centre of the Netherlands [51], called EnergyVision 2050 (*F4*).

The city of Rotterdam (responsible for 20% of all emissions in the Netherlands) goes even further in its climate ambitions and aims to reduce the city's emissions by 50% in 2025 (*F4*). CCS has the potential to fulfil more than half of Rotterdam's CO_2 reduction targets, with an effect of approximately 20 Mt captured and stored or reused by 2025 (*F4*). This Rotterdam Climate Initiative (RCI) is a collaboration between the City of Rotterdam, the Port of Rotterdam, the Environmental Protection Agency Rijnmond (DCMR), and the industry organization Deltalinqs. The initiative is chaired by the Dutch former Prime Minister Ruud Lubbers and has been kick-started by a visit of former US president Bill Clinton; hence the ongoing involvement of the Clinton Foundation in the RCI. In 2007, the RCI presented its strategy for CCS by developing a CO_2 cluster approach for the Port of Rotterdam area. Various sources will be connected to multiple storage sites, depleted gas fields in the North Sea in particular. RCI sees a lot of business opportunities for CCS and envisages being the "CO_2 Hub" of North Western Europe [52, 53].

In March 2008, the national government announced its aim to create two large-scale CCS demonstration projects in the Rijnmond region (which includes Rotterdam) and in the Northern part of the Netherlands (*F4, F7*). The 4 Northern provinces and the central government have signed an agreement in which they agreed to reduce CO_2 emissions in the region by 4.5 Mt CO_2 in 2011. In order to achieve its goals regarding the large-scale deployment of CCS a public private Task Force was created, which main task is to create conditions for application of large-scale CCS. In this it follows the recommendations of the new “Regieorgaan Energietransitie”, a new independent advisory body that advises about long-term strategies and transitions in the energy field.[7] Furthermore, a government CCS-team was established, including the Ministries of Economic Affairs and the Ministry of Environment, to work on a supportive legal framework (*F4*). This includes amendments to the existing Mining Act and by transposing recent EU directives addressing CCS into national legislation.

Furthermore, at European level, as a member of the Zero Emissions Platform (ZEP) advisory council (established in 2005), the Netherlands contribute to the broad portfolio of CCS initiatives in Europe (*F4, F7*). In 2008, the Dutch government also joined the North Sea Basin Task Force, which aims to develop broad, common principles that could form a basis for regulating the storage of CO_2 under the North Sea (*F3, F4*). On a global level the Netherlands is a member of the Carbon Sequestration Leadership Forum. This international ministerial-level panel is amongst other things tasked with the planning of joint projects (*F3, F4*) [54].

In 2008, the Dutch government also allocated €30 million in funding (*F6*) to 3 capture pilot projects, i.e. SEQ 50 MWe Oxy fuel plant, Nuon's IGCC pre-combustion CO_2 capture project at Buggenum, and EnecoGen's Cryogenic capture project (*F1*, *F2*). Furthermore, power company E.ON and the Dutch Organisation for Applied Scientific Research (TNO) have installed a post-combustion pilot capture plant as part of the CATO programme (CATO CO_2 Catcher) to test different solvents and membranes at the site of E.ON's coal-fired power plant near Rotterdam (*F1, F2*) [55]. Finally the national government awarded two CO_2 storage projects with €30 million each (*F6*). The first project encompasses the injection of CO_2 from ammonia production in a lime/sandstone formation at 1.8 km depth near Geleen, in the south of the Netherlands *(F1, F2)*. The second project is planned to start in 2011 near the village of Barendrecht and encompasses the annual injection of ~0.4 Mt from the Shell refinery in Pernis in a depleted gas field at 1.7 km depth *(F1, F2).*[8] This project, however, caused major opposition by the local community and became headline news in the beginning of 2009 *(F7).* This event changed the dynamics in the final episode.

The main source of dynamics in this episode is the CATO programme. The programme served as a catalyst, bundling and connecting activities. The interaction patterns indicate the

[7] The “Energy Report’ appeared in mid-2008. It addresses the question how to provide for a reliable, affordable, and clean energy provision for the short and the long term. It calls for a ‘fundamental systemic change’ in order to achieve a sustainable energy system. It sketches three future visions without choosing one: The Netherlands as European power house, with a lot of coal and CCS; The Netherlands as ‘energy flex working’ with a lot of off-shore wind and natural gas; and The Netherlands as smart energy city, with a lot of local decentralized power, and a very smart grid. Interestingly, a direct coupling is made between the deployment of new coal power plants and the necessity for CCS.

[8] The Barendrecht depleted gas field is only 18 km from a source of pure CO2: Shell's hydrogen production plant in Pernis. The location is attractive because existing natural gas infrastructure can be re-used and the small reservoir can be filled rapidly so that the entire transport and storage cycle down to the permanent sealing of the injection wells can be demonstrated within a timeframe of several years.

dominant system functions are now mainly Knowledge Development, Knowledge Diffusion, Guidance of the Search and Resource Mobilisation, resulting in a boost to ‘scientific’ activities in the form of feasibility studies (*F2*), some entrepreneurial experiments (*F1*) and also conferences, workshops and other meetings (*F3*). The other pivot is a recurring lobby (to the government) for resources by regional entrepreneurs (*F1-F7-F6-F1*). If successful, the companies in the Rotterdam area and the North of the Netherlands manage to realise their pilot projects, thereby providing a basis for positive expectations and more projects (*F1-F2/F3-F4-F1*). Given the predominance of scientists and technology developers in this dynamic patter, and acknowledging that projects are mainly initiated through a government programme, Suurs [18] labels this type of interactions between functions a causation a ‘Science and Technology Push Innovation Motor’. Note that the dynamics that characterise this motor are driven by promises of technology developers combined with the visibility, networks, and funding delivered by the policy programme.

3.3.4. Episode 4: 2009: Ready to take off or a false start!?

Since February 2009, the siting of the first onshore CO_2-storage pilot project in the Netherlands met tremendous public resistance. 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 (*F7*). 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 (*F7*) [56].

In the first quarter of 2009, national newspapers reported vigorously about the Barendrecht project and the tone of these articles was rather negative about CCS. In the period before the report of the Dutch Commission of Environmental Impact Assessment (‘Commissie MER’[57]) on the Barendrecht project – due in April 2009– nearly 100 articles were published in national newspapers about CCS and the Barendrecht project [58]. Most of these articles emphasized the lack of support of the project by the local community of Barendrecht and the possible local health and safety risk associated with the project (F4, F7). Some environmental NGOs, e.g. Greenpeace and the Dutch branch of Friends of the Earth (‘Mileudefensie’), contributed to this negative portrayal of CCS in the media by stating that it is an ‘end of pipe solution’ that enhances the use of coal and distracts resources from other preferred solutions to the climate change, like renewable energy and greater energy efficiency (*F4, F7*) [see e.g. 59].

Despite the fact that the Environmental Impact Assessment resulted in a positive advice about the project in April 2009 and that the Ministers for Environment and Economic Affairs gave a green light for the project later in the year, the project was cancelled in September 2010 (*F1*). On top of the ‘local problems’ for CCS in the Netherlands, in 2009 the global landscape for CCS had changed as well. The Copenhagen accord that came out of the UNFCCC’s CoP-15 was not as comprehensive as many people would have hoped. Even though all parties recognized the climate change problem, a binding agreement with firm emission reduction targets for the period after 2012 was lacking (*F4*). Furthermore, the global financial crisis made it much harder to generate private equity in the development of CCS projects (*F6*). So when reading the local and international newspapers, one could be pessimistic about the future of CCS in the Netherlands (and abroad). However, when looking at the other events that occurred in 2009, there is room for optimism as well.

Most of the activities that were initiated after 2005 were continued or intensified in 2009. For example, the national CCS R&D programme entered its second phase (2009-2014). The budget of this CATO-2 program more than doubled to €60 million (*F6*) and the R&D consortium now consists of 40 partners from Industry, research institutes and NGOs (*F3*). Major funding partners of the program are the Dutch Government as well as leading industrial partners E.ON, Shell and RWE-Essent (*F6*). Participants in the CATO-2 program continued to be involved in many international projects and networks regarding CCS (*F2, F3*), like those funded by the EU Sixth and Seventh Framework Programs. Furthermore, members of the CATO-2 program are involved in international bodies such as International Energy Agency's GHG R&D programme, the CSLF, the Global CCS Institute and European Zero Emissions Platform (*F2, F3, F7*). The focus of these international bodies is not only on addressing technical issues, as they also try to create conducive regulatory and market environment for CCS technology deployment.

The CATO-2 program will focus a significant part of its applied research efforts to support the ongoing CCS pilot projects and fulfil the Dutch ambition to realize large scale demonstration sites in the port of Rotterdam area and the Northern Netherlands region (*F1, F2*). Part of the finance for the large-scale integrated demonstration project –capturing and storing 1 $MtCO_2$ per year or more– will come from the EU, which has made available €1.05 billion for six CCS projects as part of their European Economic Recovery Plan (*F6*) [60]. At the end of 2009 the EU allocated 180 million to the development of a 250 MW unit coal fired unit with CCS on the Maasvlakte in the Rotterdam. The project is owned by E.ON and Electrabel and involves post combustion capture technology with plans to store the captured CO_2 in a depleted natural gas field in the Dutch sector of the North Sea (*F1*).

Table 3-5 shows that there are currently 3 other large-scale integrated CCS projects under development in the Netherlands (*F1*). The realization of these projects will largely depend on their ability to obtain funding under the European New Entrants Reserve [61] funding scheme (*F6*). The EU has allocated the revenues from the auctioning of 300 million emissions allowances in the new round of the EU ETS to the construction of 10-12 large-scale CCS projects [62]. At a price of €20/tCO_2 this would total to €6 billion.[9] The competition and selection of CCS projects will take place in 2010 and a final funding decision is expected to be made in 2011 [63].

[9] Note that at this point in time a CO_2 price of €20/tCO_2 in itself is not high (and stable) enough to make CCS projects commercially viable.

Table 3-5: Planned large-scale integrated CCS projects linked to power production in the Netherlands [64]

Project Name	Location	Capture facility	Capture type	Transport type	Storage type	Size Mtpa	Operation year
1.Eemshaven (RWE)	Groningen	814 MW gross coal fired power plant (biomass in future)	Post-combustion	Not specified	Geological (depleted oil/gas reservoirs)	0.2/0.3 –1.2	2015
2.Rotterdam (CGEN)	Rotterdam	450 MW hydrogen power plant	Pre-combustion	Pipeline / Ship	Beneficial reuse or Geological	2.5	2014
3.Rotterdam Afvang en Opslag DEMO (E.ON/Electrabel)	Zuid – Holland	1100 MW gross coal-fired power plant	Post-combustion	25 km pipeline	Geological (depleted oil and gas reservoirs)	1	2015
4.Eemshaven (Nuon Magnum)	Groningen	1200 MW IGCC power plant	Pre-combustion	Pipeline	Geological (depleted oil and gas reservoirs)	1.3	2015

The combination of this significant financial stimulus for CCS demonstration in the Netherlands by the EU (*F6*); the strong ambitions from the Dutch national and regional governments regarding CCS (*F4*); as well as a prominent role of Dutch companies and research institutes in the international CCS arena (*F1, F2*); make Amsterdam a logic choice to host the 10th Greenhouse gas technology conference (*F3*) (GHGT-10). After 18 years since the first international conference on CCS (highlighted in the first episode), the conference series will return to its birthplace, only this time its number of delegates has increased up to 1600 and the focus has switched from “research to reality”.

This final episode is characterised by an increasing activity level for most system functions of actors that increasingly operate in networks. The increased availability of funding -offered through the National and European funding programs –plays a crucial role in this. The renewed pattern is characterised by Knowledge Development and Diffusion, Entrepreneurial Activities inducing Support from Advocacy Coalitions (mainly in CCS regions) and Resource Mobilisation. The entrepreneurs and their expectations about their CCS projects play a pivotal role in this episode. The positive event sequences observed may suffer from recent negative Guidance (*F4*) from politicians and anti CCS lobbies from local community groups and some environmental NGOs (*F7*) regarding the implementation of CCS projects (Barendrecht in particular). Furthermore, not all system functions have received attention in built up of the

Innovation System so far. There seems to be a lack of market creation policies (*F5*) by the Dutch government, as well as the European Union; an issue that will be further addressed in the performance evaluation of the system.

3.4. Innovation System Performance

The dynamic patterns in the growth of the Dutch CCS Innovation System show that the early dedication towards CCS of a small community of Dutch researchers has led to a remarkable build-up of an Innovation System around CCS technologies. However, this functional pattern does not guarantee a thriving development of CCS in the future. The Dutch CCS Innovation System may face challenges that obstruct a further expansion of the system. In order to identify these possible impediments, the main actors composing the Innovation System have been asked to reflect upon the recent activities in the TIS and rate their level of satisfaction with the fulfilment of a particular system function. All ratings are on a scale of 1 to 5, whereby 5 equals a high level of satisfaction. Based on these expert judgments, mechanisms that are currently driving, or blocking the future deployment of CCS in the Netherlands have been identified.

3.4.1. Entrepreneurial activity

In the Netherlands there are two main regions where industry and governments are working together to implement CCS projects: the Port of Rotterdam (also called Rijnmond) and the Northern provinces of the Netherlands: Groningen, Drenthe, and Friesland (also known as "Energy Valley"). The Northern part of the Netherlands has a large potential of on-shore storage capacity in smaller natural gas fields and eventually in the major Slochteren natural gas field; the stated long-term wish for economic development of this region; the presence of a harbour (Eemshaven) with industrial complexes, including 2 new coal fired power plants. In Eemshaven, RWE and Gasunie, are collaborating in building a CCS demo in RWE's new PC power plant of 1600 MW to be finished in 2015, initially capturing 0.2 Mt/CO_2 per year, but with the potential to scale up to 1.5 Mt/CO_2 per year. Also in Eemshaven, Nuon is planning to build a 1200 MW multi-fuel (coal, biomass, natural gas) power plant based on coal gasification technology. This plant, also known as Nuon Magnum, is expected to capture and store around 1.3 Mt/CO_2 per year by 2015. The pre-combustion technology to be used in this Magnum project will be tested by Nuon in the Buggenum gasification plant.

The other CCS cluster in the Netherlands is the Rotterdam area, including the "Maasvlakte". Rotterdam is the largest harbour in Europe and hosts a fast amount of petrochemical and chemical industries, as well as power plants. The area is highly dependent on fossil fuels (coal fired power plants and refineries) and wants to keep its leading position during the energy transition to sustainable energy by implementing CCS technologies. The geographical position of Rotterdam with a large concentration of CO_2 emitters and nearby storage capacity, as well as the availability of residual heat, makes CCS less expensive as compared to other high-CO_2 emission areas like Antwerp and the German Ruhr region and thus more attractive for business. Most experts interviewed for this study agree that the amount of businesses involved in the development of CCS technologies has increased substantially over the past years. Under the banner of the RCI alone, more than 20 major companies are involved in the development of CCS projects (See Table 3-6).

Table 3-6: Companies contributing to the development of a CCS network in the Rotterdam Rijnmond area.

Emitters	CO_2 transport	CO_2 storage
E.ON	Gasunie	NAM
Electrabel / Gaz de France Suez	Port of Rotterdam	Gaz de France
Shell	OCAP	Wintershall
Air Products	Stedin	TAQA
Air Liquide	Vopak, Anthony Veder, Air Liquide, Gasunie (Consortium)	Maersk
AVR		
C.Gen	Maersk	
Corus	Gaz de France Suez E&P	

The Port of Rotterdam hosts one of the most advanced full-chain CCS demonstration projects planned in the world. E.ON Benelux and Electrabel group GDF Suez have formed a joint venture to build a post combustion carbon capture unit with a capture capacity equivalent to 250 MW generation at the new coal-fired power plant E.ON is building at the Maasvlakte. Both the pipeline and the intended storage location (i.e. TAQA's depleted natural gas field 20km offshore) have the capacity to serve other CO_2 emitters in the Rotterdam area as well. One of the other emitters is the C.GEN. This company intends to build a hydrogen electricity power plant in the port of Rotterdam. This plant consists of a gasification plant that converts solid fuels into hydrogen. The hydrogen is used in a combined cycle gas turbine to generate electricity. The C.GEN project is an important element in RCI's network approach, as it has the potential to capture and store 2.5 Mt CO_2 annually, the equivalent of almost 10% of RCI's reduction target.

Furthermore, Air Liquide and Air Products are both developing Hydrogen Plants that have the potential to deliver approximately 0.5 MtCO_2/year to the Rotterdam CCS cluster. Both projects are scheduled to come on stream early in 2011 and will supply hydrogen to the major refineries in the port. Following the investment decision, the CO_2 capture unit can be realized within 18-24 months. The companies developing CCS projects in Rotterdam are in a similar situation as the power producers in the North of the Netherlands, as the final investment decision regarding the construction of the capture units will largely depend on their success to obtain funding under the European NER300 CCS demonstration program [61].

Shell has several projects running in the greater Rotterdam area with the refinery and petrochemical plants of Pernis and Moerdijk. Since 2005, pure CO_2 has been captured from a hydrogen plant at the Pernis refinery, compressed by Linde Gas Benelux, and transported to the beverage industry to carbonate soft drinks. Another part of the pure CO_2 goes through the OCAP network (a joint venture of Linde Gas Benelux and Volker Wessels) and delivers over 0.3 MtCO_2/year to approximately 500 nearby greenhouses.[10] Besides the Shell refinery, OCAP plans to take CO_2 from bio-ethanol producer Abengoa as from 2011 and is actively looking into tapping more CO_2 sources. This would increase security of CO_2 supply and would create an opportunity to expand the CO_2 supply to other greenhouse areas. OCAP is

[10] The greenhouses use this CO2 instead of producing their own CO2 by burning natural gas.

also a partner in the development of Shell's project whereby 0.3-0.4 $MtCO_2$/year should be stored in the depleted Barendrecht gas field. Shell has been granted a subsidy under a 2007 CO_2 storage tender (€30 million). It has engaged in dialogue with the Barendrecht community and it has performed an environmental impact assessment.[11] The permits are anticipated to be approved by the end of 2011. Based on a project final investment decision by the end of 2011, the first CO_2 is expected to be injected in 2013. Shell has stated that it will continue to review opportunities to capture further volumes of CO_2 from its facilities as legislation and the European Emissions Trading System develop (see also Section 4.5. Market Creation).

In order to realize a CO_2 transportation network (connecting the various CO_2 sources and sinks) Vopak, Anthony Veder, Air Liquide and Gasunie are currently working together to create a solution to the logistical CCS challenge both emitters and CO_2 storage providers have to face. Captured CO_2 is envisaged to be gathered at a CO_2 hub either through (inland) shipping and/or pipelines. The scope of companies developing the hub is not limited to emitters in the Rotterdam area, as they also see a potential to collect CO_2 from other parts of the Netherlands, like the Corus' steel manufacturing plants close to Amsterdam (IJmond region)[12] and the industrial complex in the south of the Netherlands (Geleen-Sittard)[13], and even outside the National Borders, like the German Ruhr area. Given the envisaged flexibility of the concept, it also allows for small emitters and small storage locations to be connected to the network. At the hub, the CO_2 can be intermediately stored and treated (i.e., vaporized and/or liquefied) to be transported, again by ship or pipeline, to the various offshore storage locations on the Dutch, UK, Danish, and Norwegian continental shelves using pipelines or seagoing vessels. One of the fields that is most likely to be included in this network is the K12-B field on the Dutch continental shelf, wherein GDF Suez has been injecting CO_2 since 2004, storing over 80 $KtCO_2$ to date. It was noted by several experts participating in this study that the current lack of a 'backbone' CO_2 infrastructure in industrial areas hampers the implementation of more entrepreneurial experiments with the technology.

Most experts recognize the value of the CCS pilot and demonstration projects that are carried out or planned in the Netherlands. However, with an average score of 2.5, this function scores relatively low compared to the other functions. Most experts agree that Dutch businesses could do more to develop, commercialize and export CO_2 capture technologies (e.g. membranes). It is argued that Dutch research institutes have gained high quality knowledge over the past decade, which hasn't been utilized to its full potential by existing and start-up companies. Positive exceptions that were often mentioned in this respect by the experts

---

[11] The residents of Barendrecht are concerned as this is the first onshore CCS project in the Netherlands. The impact of the public resistance encountered on the development of this project will be further discussed in Section 4.7 Creation of Legitimacy.

[12] SEQ International is working on an integrated feasibility study for the development of a large scale CCS demonstration project, to be located in the IJmond region. The capture technology involved consists of the oxy-fueled Zero Emission Power Plant (ZEPP)-concept, based on combustion of low-calorific fuel (e.g. blast furnace gas) with pure oxygen. When successfully tested the ZEPP-process could be applied in the power sector as well in the world wide steel industry.

[13] At the Chemelot site in Geleen Orascom (former DSM Agro) operates two ammonia factories whereby relatively pure CO2 is released. This CO2 is used partly in other chemical production processes and partly delivered to the soft drink industry. The excess amount of pure CO2 can be can be injected in a chalk-sandstone layer below coal layers located under the site (see also Section 3.4.2. Knowledge Development).

participating in this study are Procede BV, which is a spin-off of the University of Twente working on gas treatment (CO_2 removal and desulphurisation) and SEQ International BV. The latter company was established in 2004 on the premise of developing CCS projects in combination with power production and has obtained 3 production license applications. Besides innovative capture technologies, high quality knowledge regarding CO_2 handling (compression and transportation), as well as the subsurface expertise that is hold by Dutch research organisations and industry, offers an opportunity for Dutch businesses to enter foreign markets. In sum, experts agree that the Netherlands could export technology and knowledge if it continues to develop itself as a frontrunner in deployment of CCS.

The relatively low score for the fulfilment of this function can also be explained by the relatively slow progress of CCS projects related to power production. In contrast to the current storage projects (e.g. K12-B and the planned projects in Barendrecht and Geleen), which make use of CO_2 from relatively pure industrial CO_2 streams, CO_2 capture from power plants is hardly tested at scale (also outside the Netherlands). 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 of CCS as well as the possible loss of availability of the power plant are important cost factors. The lack of clear market incentives and the observed uncertainty on the future availability of public funding for integrated CCS projects in the Netherlands are partly causing the hesitance in the development of large scale CCS projects. The actual implementation of large-scale projects will therefore largely depend on the success of the CCS regions to obtain money for its major demonstration projects under the National and European funding programs. We will further elaborate on the issues of market creation and finance for CCS projects in sections 3.5 and 3.6.

3.4.2. Knowledge development

In the Netherlands, CCS R&D is concentrated around one large heterogeneous national CCS consortium. The first phase of this CATO (CO_2 Capture, Transport and Storage) program had a budget of nearly €25 million, about half of which was financed by the government. CATO is led by a consortium which includes major Dutch Universities, Shell Netherlands, other energy and gas companies, the Dutch government, Energy Centre Netherlands, TNO, and NGOs like Netherlands Foundation for Nature and Environment, and WWF (Netherlands). The CATO program is novel in the sense that many different research groups from different fields of expertise are working together on a common objective. Several of the work packages are specifically aimed at integration. Some issues that emerged were: criteria for sustainability of CCS systems; which of the many technological options are most promising or desirable; questions about storage potential, safety, and ecological risks, as well as the accessibility of storage sites for injection. Furthermore, E.ON and TNO 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.[14]

[14] The Dutch CAPTECH R&D program (2006-2009) complements part of the capture research within CATO and aims to reduce the CO2 capture cost with 50%. In order to achieve this, a wide portfolio of future capture technologies is being investigated.

The bottom-up created CATO programme quickly became seen internationally as the "National research program" on CCS of the Netherlands and soon after the favourable mid-term evaluation of the program a plea for a follow-up 'CATO- 2' program was heard. This CATO-2 program started in 2009 and is led by the Dutch Organization for Applied Science (TNO). The program with over 40 research partners and a budget of €60 million concentrates mainly on enabling commercial CCS technology implementation and is much more "demand driven". Research priorities are now better aligned with requirements from Industry and issues related to the technology deployment, like public perception, financing and costs or monitoring techniques are of increasing importance in the CATO-2 program. Meanwhile, new technologies, processes and procedures with a focus on application within five to ten years continue to be important topics of fundamental research within CATO-2.

Applied research on capture, transport and storage is focussed on a number of pilot sites, including the two storage demonstration projects (see Section 3.4.1) and three CO_2 capture pilot projects; all co-funded by the National Government. The first capture pilot is a post-combustion cryogenic CO_2 capture project at an existing E.ON combined heat and power (CHP) plant at the Maasvlakte, where 50% of the 'cold' would be provided by a nearby LNG terminal (total costs €36.5). The second is a pre-combustion capture unit at the Nuon combined IGCC-coal and biomass gasifier at Buggenum (total costs €44.5 million). This technology is a pilot for the intended multi-fuel power plant to be built by Nuon in the Eemshaven (see also Section 4.1. for a description of this project). The third is an oxyfuel plant which uses pure oxygen for combustion (total costs €60 million), to be realized in the IJmond (close to Amsterdam). The first technology is key for adding CCS to existing power plants (retrofit); the second is considered important for CCS in combination with the next generation IGCC plants. The third project is another key technology with potential global significance, but still in the development stage with still many uncertainties.

The experts participating in this study consider the capture test facilities as crucial, as they need to be further developed in order to become more cost-effective. Although most of them stress that it is too early to pick winners and that all three capture options need to be further developed, some experts ply for more focus on pre-combustion technologies, as the R&D budget in the Netherlands is too small to be a front-runner in all three CO_2 capture areas. Therefore it is considered important that Dutch research organisations continue to participate in international R&D efforts related to CO_2 capture, like EU funded CO_2ReMoVe and ENCAP programs.

In general, the knowledge developed regarding CO_2 storage is considered by the experts as 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 the Netherlands. In order to advance the current knowledge regarding CO_2 storage, experts identified several research priorities for the future, including the development of advanced monitoring, measurement and verification (MMV) technologies. In addition, it is needed to improve and validate numerical models to determine the (long-term) integrity for a large variety of reservoir types. When applied to the North of the Netherlands or the North Sea, this would give a more reliable overview of the most suitable storage sites in a particular region. Thereby facilitating the siting of future CCS projects.

Furthermore, it is argued that even though CO_2 pipelines can be considered a proven technology, more research is needed into CO_2 pipelines when applied in a network context like Rotterdam whereby the quality of CO_2 (i.e. level of impurities) provided by the different emitters connected to pipeline might differ, which has implications for balancing the system. From an economic and commercial perspective more research is needed as the high upfront costs of oversized pipelines, creates a different investment risk profile. The participation of multiple stakeholders, both current and future, complicates commercial structures, terms and contracting, especially due to the need for early users and operators to bear disproportionate amounts of risk.

Despite the above, the experts consider the CCS knowledge base created in the Netherlands as of high quality and have scored this function with a 3.7, together with Knowledge Diffusion, the highest score of all functions. It is argued 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.

3.4.3. 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, entail to share knowledge and competences. Therefore, it is very much appreciated by the experts that comprehensive national and regional CCS consortia exist in the Netherlands with strong international ties. Together with the increasing amount and quality of conferences, this is reflected in the relatively high average evaluation score of 3.7.

First of all most experts point to the strong ties between industry, government and local research organisations in the CCS regions in the Netherlands and the importance of these collaborative networks for the realization of large-scale CCS projects in Rotterdam and the North of the Netherlands, which main task is to create conditions for application of large-scale CCS in Rotterdam and North Netherlands. Furthermore, it was recognized that there are strong, also personal, links between the CCS Regions, and the national CCS Task Force. The CCS Task Force consists of important persons from Industry and Government, including a former Prime Minister, a Provincial Governor, the chairman of Shell Netherlands, a Director of Gasunie, and many others, including the director of the Netherlands Foundation for Nature and Environment [65].

Most experts participating in this study also stressed the unique combination of organisations involved in the CATO program when the issue of knowledge diffusion was raised. The 40 organisations involved in this national R&D program have their backgrounds in industry, small to medium enterprises, government, research and the NGO community. In turn participants in the CATO program are involved in many international projects and networks regarding CCS, like those funded by the Sixth and Seventh Framework Programs of the EU.

This will help to ensure coordination with ongoing and envisaged research efforts in these programs. Members of the CATO-2 program are also involved in international Boards such as IEA-GHG and the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ETP ZEP).[15] On a European level Dutch project developers also share knowledge in the CCS projects network. Herein projects come together to share experiences that have received European funding; including the ROAD project in the Netherlands (see section 4.1.).

Although most experts appreciate this European initiative, some of them argued 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. It was noted that such a coordinating role could be taken up by the Carbon Sequestration Leadership Forum (CSLF) wherein the Netherlands is represented. This international ministerial-level panel is amongst other things tasked with the planning of joint projects. Some experts pointed to the role the Global CCS Institute, established in July 2009 by the Australian Government, could play in this field, as it has been set up for the purpose to build a ‘central base’ of CCS project based knowledge and expertise and several Dutch companies, as well as the National government have joined as a member.

The fast majority of the interviewees recognized that the increasing amount of (inter)national CCS platforms and conferences have contributed significantly to the optimization of CCS networks and the formation of a Dutch as well as international CCS communities. However, the experts argue that R&D of CCS technologies (and CO_2 capture in particular) often occurs behind ‘closed doors’, since this knowledge can create a competitive advantage for businesses. The protection of intellectual property is often considered by companies as the sole base of survival in a competitive market. However, the protection of IP hinders an optimal flow of information between the actors involved in CCS R&D and therefore the creation of that very same market for CCS technologies.

Knowledge sharing for companies can be considered as a difficult balancing act, whereby on the one hand companies are willing to share knowledge to benefit from the creation of a market from which they could profit. On the longer term and on the other hand they would like to keep IP for themselves, so they can position themselves as a market leader when CCS becomes a global industry. Some of the interviewees noted that more information could be shared by companies without compromising their competitive advantages in any future market for CCS and saw the current lack of knowledge sharing as the most important barrier for the performance of this function.

3.4.4. Guidance

On average, the experts rated their satisfaction of this function with a moderate to good score of 3.3. They are satisfied with the clarity of technological demands articulated by industry towards scientific organizations (especially in the CATO-2 program); the development of

---

[15] The European utilities, petroleum companies, equipment suppliers, scientists, academics and environmental NGOs that together form ZEP have three main goals: 1.) Enable CCS as a key technology for combating climate change; 2.) Make CCS technology commercially viable by 2020 via an EU-backed demonstration programme; and 3.) Accelerate R&D into next-generation CCS technology and its wide deployment post-2020.

targets regarding CCS by the National and regional authorities, as well as the role of political and industrial leaders in advocating the importance of CCS in low emissions future. In this respect the positive role of former Prime Minister Ruud Lubbers, current chair of the Rotterdam Climate Initiative, was mentioned several times by the interviewees.

Climate policy in the Netherlands became prominent after the ratification of the Kyoto Protocol of 1997, but it was not until 2007 before it was explicitly mentioned in policy documents. In 2007, the new cabinet aimed to reduce CO_2 emissions by 30% in 2020 as compared with 1990, from 215 $MtCO_2e$/year to 150 $MtCO_2$/year. As compared to 246 Mt with unchanged policy in 2020; this would be a reduction of 94 Mt. The main reduction should come from industry and electricity production, from 101 Mt now till 75 in 2020, a reduction of 26 $MtCO_2$. The 'working program' ("Clean and efficient") elaborates on the main pillars of reaching Kyoto objectives and beyond, i.e. energy conservation, renewable energy, and 'clean fossil'. The related policy document "New energy for Climate policy" [50] states: "The aim of the Netherlands is to locate two (Groningen and Rijnmond) of the major demos desired by the EU for an electricity power plant with CO_2 capture and storage in the Netherland." Another policy document that guided the development of CCS is the "Innovation Agenda Energy", which sums up which innovations are necessary and what government policies will help implement them. It is an elaboration of the innovation budget in "Clean and Efficient" and mentions CCS under the theme "new gas".

Besides national policies and targets, the most important regions for CCS, i.e. Rotterdam and the North of the Netherlands, adopted even more stringent targets. For example, the 4 Northern provinces and the central government have signed an agreement in which they agreed to reduce CO_2 emissions in the region by 4.5 Mt in 2011. And in 2007, the Rotterdam Climate Initiative (RCI) announced its plans to realize 50% CO_2 reduction in 2025 as compared to 1990, from 24 Mt tot 12 Mt, as compared to a projected 46 Mt in a trend extrapolation. This reduction will be realized by energy saving (7 Mt) and sustainable energy (7 Mt), but mainly through CCS in industry (20 Mt).

However, 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. It is argued by most experts that a new set of rules is needed for CCS in particular for underground injection and storage of CO_2.

In the Netherlands, the inter-ministerial project directorate CCS (consisting of representatives from the Minister of Housing, Spatial Planning and the Environment and for the Minister of Economic Affairs) has started to work on a supportive legal framework by transposing recent EU directives addressing CCS into Mining Law, in Environmental Management Law and in several General Governmental Decisions and Ministerial Rules. Amongst other things, the CCS Directive proposed by the European Commission [66] 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. Furthermore, representatives of the Dutch government participate in the North Sea Basin Task Force, which aims to develop broad, common principles that could form a basis for regulating the storage of CO_2 under the North Sea.

Although experts agree that that EU CCS directive is a good model to build from, they identified three main gaps in existing regulatory frameworks that need to be addressed, namely:

1. in order to establish an international CCS hub in Rotterdam cross boarder transportation still needs to be permitted under international treaties like the London Protocol (offshore transportation) and the Basel Convention (onshore);
2. the regulatory requirements to cover the operation of CO_2 storage projects, including guidelines to site selection and MMV need to be specified in more detail;
3. The timeframes and responsibility for the different liability types (operational, local, and global climate) in case of CO_2 leakage from the reservoir need to be clearly articulated and assigned.

Resolving the third issue is considered most important, primarily because the liability timeframes for CCS projects extend far beyond other typical liability timeframes that companies are held to today, which increases the risk profiles of project investors. Regulators therefore need to clarify if and when liability will transfer to relevant government bodies once a project moves to the post-abandonment phase.

3.4.5. Market creation

Within two decades 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 the OCAP project in the Rijnmond, but also in other (government funded) entrepreneurial experiments as described in section 3.1. However, it is unlikely that utilities will adopt CCS on a large scale until sound climate policies make CO_2 financially worth capturing. It is argued that one of the main barriers standing in the way for a broader uptake of integrated large-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 of 2.0; the lowest score of all functions.

The Netherlands relies heavily on the European Union’s ETS, when 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 €/t CO_2 [67], and the carbon price, varying between 6 and 30 €/t CO_2 in the period 2007-2009. In the assessment of the “Clean and Efficient” program by ECN (Energy Centre Netherlands) the Dutch goals regarding CCS are called ambitious and probably not achievable because too much is dependent on developments elsewhere in Europe and the developments of the CO_2 price in the market [68]. In the “low” EU scenario, with moderate EU policies and a modest CO_2 prices of 20€/ton CO_2, it is found that there will be hardly a contribution from CCS in the Netherlands by 2020. Therefore, it is likely that additional policies will be needed to ensure large-scale deployment of CCS in Europe within the 2020 timeframe. One of the experts noted that this scenario did not take into account the possibility that Enhanced Oil Recovery operations in combination with storage, whereby CO_2 is used to increase oil production, could be included in the ETS. The additional revenues from oil production could bring CCS closer to the market (as is the case in CCS projects in North America).

In response to a lack of market incentives for CCS in the near future the European Commission has outlined the possibility of a "CO_2 emissions fade out", implicating the obligation of CCS for all new coal based power stations from 2020 onwards [69]. Until that time additional financial support for demonstration of CCS is required to bring down the costs of these projects. For that reason, the European Council plans to co-finance 10-12 CCS demonstration projects in commercial electricity generation by 2015 [63]. The importance of financing the first large-scale CCS demonstration projects that have not yet benefited from scale economies and technological learning has been noted by large number of the interviewees. 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.

3.4.6. Mobilization of resources

Until 2009 the Dutch government has provided a €90 million impulse for three capture projects (€30 million) and two storage projects (€60 million) [70]. The subsidy funding comes from the "Borssele deal": an agreement between the government and the operators of the only Dutch nuclear power plant to prolong the lifetime of that plant, and in exchange to fund the development of amongst others CCS technologies. Over the past years a similar amount of money has been provided by government and industry for basic R&D programs, like CATO, CAPTECH and CRUST (see also Section 4.1: Knowledge Development).

In 2010, the Dutch Goverment allocated €150 million for the development of the ROAD project on the Maasvlakte, which was granted with €180 million by the EU. In the policy document "New energy for Climate policy" [50], the Dutch government already expressed its willingness to co-finance the desired European flagship projects, if sited in the Netherlands. In December 2009, the EU has made available €1.05 billion for 7 CCS projects as part of their European Economic Recovery Plan, of which the ROAD project was one. Furthermore, the European Investment Bank 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. At a price of €20/tCO_2 this would total to €6 billion. The competition and selection of CCS projects by national governments will take place in 2011 and a final funding decision is expected to be made somewhere in 2011.

Although investments in CCS RD&D have grown substantially over the past years, experts rate their satisfaction on the availability resources with a low score of 2.5. The most shared opinion is that the current availability of financial resources is not sufficient to realize large-scale integrated CCS demonstration projects in the near future. Interviewees (especially from private firms) argued that financial risks are too high to obtain private equity and 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 be needed to demonstrate the technology at commercial scale.

To provide investor certainty, it is believed that public private partnerships are the way to go, whereby government agencies fund a substantial part of the hundreds of millions of Euros necessary to deploy large-scale CCS projects that need to be realized in the Netherlands to meet the set emission targets. 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. The experts participating in this study therefore applaud the public private approach that is taken by National CCS Task Force.

Next to the current lack of financial resources, most of the interviewees recognize that 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. Experts see the solution for this potential problem by introducing educational programs at universities to get future engineers and project managers acquainted with specific CCS knowledge.

3.4.7. Creation of legitimacy

The current fulfilment of this function is scored 3.0. Although moderate, the creation of legitimacy is a somewhat difficult function in the Dutch CCS Innovation System. 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 for different stakeholder groups.

In the Netherlands CCS is favoured by a powerful coalition of industrial peak organizations. Major oil and gas companies, like Shell, Gasunie and the NAM are present in the two CCS regions, but also a large number of influential utilities, like E.ON Benelux, Nuon and RWE – all involved in the realization of new coal fired power plants– play an important role in pushing the CCS agenda. It appears that the regional initiatives, and especially the Rotterdam Climate Initiative, play a major role in stimulating the policy development on the national level. The regional initiatives are more ‘hands-on’, and the problems encountered there are fuelling the national scene. The large number of businesses active in the regions need national support for their projects by legislation and also through funding (see e.g. Table 3-6 in Section 4.1. Entrepreneurial Activities). The fact that these industrial lobby groups are led by former political heavy weights like ex Prime Minister Ruud Lubbers and Stan Dessens, a former Director-General Energy of the Ministry of Economic Affairs and now chair of the CCS Task Force, have contributed to the case for CCS.

On the other hand, 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. The big environmental NGOs in the Netherlands have different positions on CCS. The Foundation for Nature and Environment (SNM) is cautiously in favour (‘yes, if”); they are also part of the CCS Task Force. Greenpeace Netherlands and Greenpeace International however moved recently from “no, except” towards “no, because”. Their main argument is twofold: CCS promotes coal and coal is a dirty technology over the entire chain, from mining to combustion, and alternatives (conservation and renewables) are available. The second argument is specifically about climate change: coal combustion emits more CO_2 than any other fuel, and it seems to be counterproductive from a climate change perspective to switch towards coal. In the vision of Greenpeace CCS is used as the main argument to push for new coal power plants.

According to most experts participating in this study, one of the major bottlenecks in the fulfilment of this function lies in possible public resistance towards CCS because of similar reasons as currently given by some environmental interest groups, but also because of the opposition to large-scale infrastructural works like CO_2 pipelines, and potential health and safety risks.

Research within the CATO program by Leiden University indicated that the majority of the population (around 70%) had not heard about CCS; their opinion thus should be considered a pseudo-opinion because it could quickly change through new information. If people are informed on all aspects of the technology, there is a light endorsement of CCS [71]. The Rathenau Institute, an independent institute that advises the Dutch Parliament on technological innovations and potential controversies, conducted a study on public attitudes by means of four focus groups. First outcome was that the connection between CO_2 emissions and climate change was very blurred; some saw CCS as waste dumping while others considered it throwing away a valuable commodity. After providing information by an expert and by a protagonist and an opponent, three out of four groups were still divided; and only one group supported CCS. Participants were worried by the high energy penalty of CCS. They state that CCS could be a transitional technology but only for a very short time [72].

The problems with public acceptance surfaced around the CCS storage project in Barendrecht. 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. To prevent this from happening again, it is argued by experts participating in this study 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. Several Experts 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 (for example the work done by Leiden University in the CATO program).

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. Given the urgency of implementing large-scale demonstration plants in the next few years, it is crucial to take a strategic approach to (risk) communication of CCS.

3.5. Strengthening the Innovation Systems' performance: implications for policy

The analysis of the Dutch CCS Innovation System provides insights into the relations between the historical dynamics of the system and the system's current performance. 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, regulatory guidance and the creation of legitimacy may also be improved (see Figure 3-1). Below a general strategy that would relief the current barriers to the technology's future deployment will be discussed. The three interrelated elements target the fulfilment of different sets of system functions simultaneously: 1) Stimulate learning by doing; 2) create financial and market incentives; and 3) improve regulation and legitimization for CCS.

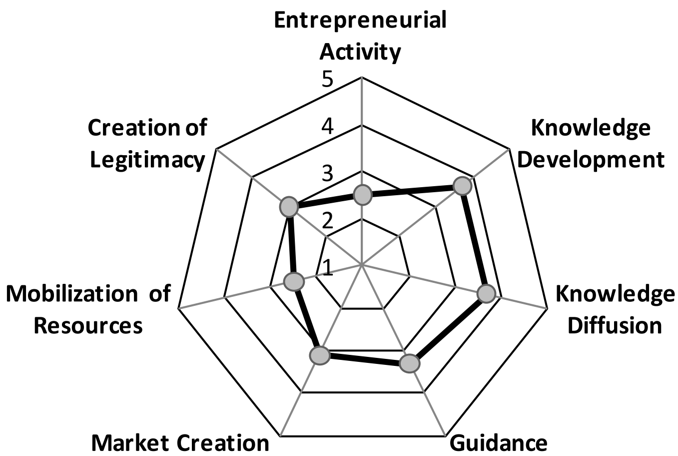


Figure 3-1: Radar diagram depicting the overall score on the functions of Innovation Systems by more than twenty experts in the Netherlands.[16]

[16] The majority of the interviews were held in the second half of 2007 and the beginning of 2008. For validation purposes a smaller number of interviews were held with the same interviews in the first half of 2009.

3.5.1 Stimulate learning by doing

The performance assessment of the Dutch CCS Innovation System shows that the extensive knowledge base and CCS knowledge networks, accumulated over the past years, have not yet been utilized to a full extend by entrepreneurs to explore markets for CO_2 capture concepts linked to power generation. Even though high quality knowledge regarding CO_2 capture exists in Dutch research institutes and universities not many companies have taken the risk to bring these technologies to the market.[17] Besides innovative capture technologies, high quality knowledge regarding CO_2 handling (compression and transportation), as well as the subsurface expertise that is hold by Dutch research organisations and industry, offers an opportunity for Dutch business to enter foreign markets. Subsidies or loans for science spin-off companies could generate more business activities around CO_2 capture technologies in the Netherlands.

In general capture technologies are still hardly tested at scale. Therefore, it is necessary that various promising technologies should be demonstrated at commercial scale to advance technological learning and bring down its costs. Furthermore, it is of prime importance that, besides demonstrating the different parts of the CCS chain separately, a number of integrated large-scale CCS projects are implemented in order to prove the concept. In order to reduce the current “first mover disadvantage” for early CCS project developers and induce more entrepreneurial activities the development of a common user CO_2 transportation and storage infrastructure needs to be facilitated. The latter could substantially lower the project lead times, upfront costs and thereby the financial risks for new entrepreneurs that wish to enter the CCS market.

It is recognized that more pre-competitive storage site characterization work is needed on the Dutch continental shelf of the North Sea to accommodate the large quantities of CO_2 that are envisaged to be captured in the CCS regions, i.e. the Rotterdam area and the Northern Netherlands. Furthermore, more work is needed to advance and commercialize CO_2 monitoring techniques on the basis of active CO_2 storage operations, like the K12-B project. This can be done by starting up more “low-cost” CCS projects that make use of CO_2 from relatively pure industrial CO_2 streams, e.g. refineries and natural gas processing. In short, it is time that entrepreneurs really start learning by doing, instead of ‘learning by planning’ and that business opportunities are taken now in order to secure a profitable market in the future.

3.5.2. Create financial and market incentives

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 on the longer term. Therefore, it is necessary that

[17] SEQ International and Procede BV can be seen as positive exceptions here.

governments change ‘the rules of the game’. It is believed that a high and stable ETS price of €40-50 per ton CO_2 in combination with Emissions Performance Standards for power plants could be a strong policy mechanism to create a market for CCS on the mid- and longer term. Furthermore, the possibility to include Enhanced Oil Recovery operations in combination with storage in the ETS should be further explored. The additional revenues from oil production could make CCS commercially viable on the short term (as is the case in CCS projects in North America).

However, taking into account that the carbon price in the 2020 timeframe 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. It is argued that public private partnerships are the way to go in establishing early commercial-scale CCS demonstration projects. The billions of Euros that will become available for CCS demonstration in the EU after auctioning 300 million emission allowances, would offer a high incentive to early projects in the Netherlands 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 the Netherlands.

3.5.3. Improve regulation and legitimization

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, timeframes and responsibility for the different liability types (operational, local, and climate) need to be articulated and assigned. Second, requirements to cover the operation of CO_2 storage projects, including guidelines to site selection and monitoring, measurement and versification (MMV) need to be further specified. Third, in order to establish an international CCS hub in Rotterdam cross boarder transportation still needs to be permitted under international treaties. The experience gained from early projects might be used in the development of these new guidelines and regulations. Regulatory agencies in the Netherlands could 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.

A strong regulatory framework could also minimize concerns of CCS being a ‘risky technology’, thereby building public trust in CCS applications. It is clear from the Barendrecht case 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.

3.6. Discussion of results and concluding remarks

This study applies the functions of Innovation Systems framework to provide insight into the wide range of processes that drive or block the development of CCS technologies in the Netherlands. The study also aims to demonstrate how insights in the build-up and performance of the Dutch CCS Innovation System can be useful to technology managers and policy makers that wish to accelerate the (commercial) deployment of CCS. Before conclusions from this analysis are drawn, first some important methodological issues are discussed and a reflection on the proposed system intervention strategy will be given.

3.6.1. Methodological issues and implications

The method used to provide insight in the build up of a CCS Innovation System in the Netherlands is the event history analysis. This method is based on the systematic collection of events in a database. The literature sources used were professional energy journals and a digital database called Lexis Nexis [73]. The Lexis Nexis database contained all Dutch national and regional newspapers from 1990 onwards. Especially the regional newspapers provided much information about local entrepreneurial activities. The professional journals were quite useful for gaining insight into the political debates, lobby activities, and R&D activities. The problem encountered in collecting the data is that the availability and the quality of event data varied over time. For the more recent periods it was easier to collect data from archives, especially those containing digitalised media. A solution to this problem was to complement the primary dataset of events with historical accounts from secondary literature. Also, additional information from interviews was used.

The overview provided by the database allowed for the allocation of events to the System Functions using a classification scheme taken from [18, 23]. The classification scheme is based on the definitions of the System Functions. By mapping events over time, it was possible to track the historical fulfilment of each of the system functions. Moreover, because events are related to each other in time, it was possible to reconstruct event sequences, and thereby the interactions between system functions. The historic analysis reduces both the author's bias in constructing a narrative and the retrospective bias of interviewees to a minimum.[18]

Despite the above it not a trivial task to construct a function interaction pattern based on the identification of event sequences. After all, events do not all follow up on each other in neat sequences. The narratives constructed as part of the case study should therefore be considered as stylised simplifications of reality (wherein a lot of noise data has been filtered out) and not be interpreted as literal accounts of what happened [18]. As suggested by Poole et al. [19], the narratives should be regarded as interpretation schemes which can be used to understand a variety of stories that are all related. Therefore, the narrative as presented in this study serves to show how the build up of the Dutch CCS Innovation System has generally worked. See Suurs [18] for a first attempt to identify generic interaction patterns between functions across various case studies of various emerging TISs in the field of renewable energy).

[18] See Negro [23] and Suurs [18] for a more elaborate justification of the event history analysis.

In order to further ascertain the fulfilment of Innovation System functions (and determine the systems current performance in terms of strong and weak system functions), we conducted semi-structured interviews with more than 20 CCS experts from industry, research, government and interest groups. The interviewees were asked to verify and complement our results and rate their level of satisfaction with the fulfilment of a particular System Function on a 5 point Likert scale (five being very satisfied with the fulfilment of a particular function). Furthermore, they gave their view on what should be done to improve System Functions that are impeding a higher performance of the system. Their evaluations were mostly in agreement with the results of our historical analysis. For example, we found a sharp increase in CCS RD&D activities, as well as high potential for knowledge diffusion in the fast growing RD&D networks and CCS regions in the Netherlands. These functions received the highest expert rating. In similar fashion the slow development of market incentives for CCS and the lack of regulatory guidance resulted in low scores on these functions. The main discrepancy related to the function ‘mobilization of resources’. Even though the results show a substantial increase in CCS investments, the majority of experts argue that current budgets are not sufficient to realize large-scale CCS deployment on the short term.

Despite the possible subjectivity of the forward-looking perspective of this study, our historical analysis of the Dutch CCS Innovation System has been corroborated by various data sources. Furthermore, the analysis focused on drivers and barriers of dynamics and withheld from normative statements with respect to the outcome of particular projects or desirability of various policy instruments. The stepwise approach and the combination of different qualitative research methods proved to be very useful for assessing the build-up and performance of the Dutch CCS Innovation System. Thereby providing an important contribution to innovation scholars that wish to extend the application of this approach. Moreover, it provides a solid basis for advice on policy strategies to enhance the development of deployment of CCS in the Netherlands and possibly also in other countries.

3.6.2. Reflection on CCS support strategies

Another key contribution of this study, especially compared to other Innovation System analyses, is the explicit focus on support strategies. There are not many studies that combine a full-fletched dynamic systems analysis with knowledge on technology support strategies for policy makers and technology managers. By pointing out how strategies of decision makers are likely to affect Innovation System’s performance, this study delivers insights of value to scholars as well as practitioners.

This study provides a clear understanding of the current barriers to the technology’s future deployment and outlines a policy strategy that 1) supports learning by doing; 2) provides sound alteration of short term financial stimuli and long-term market incentives; and 3) improves supportive regulation and public legitimacy for CCS. The proposed strategy targets a 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 et al. [74] on policies related to the creation of a market for CCS in Europe; the studies done by the IEA's regulators network on providing regulatory guidance for CCS [75]. See Damen et al. [76] regarding the creation of legitimacy and public acceptance of CCS; or de Coninck et al. [77] on knowledge diffusion and global technological learning. We would argue that these in depth studies could help to fill in the general CCS deployment strategy outlined in this study.

Furthermore, it might be possible that new and more influential Innovation System dynamics start off as part of developments in other countries. Due to the extensive international relationships in this technological field especially in the European context, a policy maker at the national level should be aware of the increasing importance of these international innovation processes for local activities. In order to analyse these global trends in the development of CCS technologies, it is desirable to apply the analytical framework presented in this study to other countries as well. These analyses would not only allow for cross-national comparison on a function level –e.g. differences between R&D expenditures, technological focus, and regulatory frameworks–, but would also provide an opportunity for technology managers to learn from a broad range of experiences regarding the development of CCS technologies in other countries [see e.g. 78].

3.6.3. Summary and conclusions

The dynamic patterns in the growth of the Dutch CCS Innovation System show that the early dedication towards CCS of a small community of Dutch researchers has led to a remarkable build-up of an Innovation System around CCS technologies. The interaction patterns in the most recent history of the Dutch CCS Innovation System indicate that Guidance *(F4)* in the form of climate policies and, directly linked to it, the Mobilization of Resources (*F6*) have resulted in a boost to Research activities (*F2*), an increasing amount of entrepreneurial experiments (*F1*) and also conferences and collaborative CCS efforts that are conducive to Knowledge Diffusion (*F3*). The other observation is a recurring lobby (to the government) for resources and regulations by (regional) entrepreneurs (*F7*). Thereby providing a basis for positive expectations *(F4)* and more projects *(F1).*

The positive event sequences observed may suffer from recent negative Guidance (*F4*) from politicians and anti CCS lobbies from local community groups and some environmental NGOs (*F7*) regarding the implementation of "controversial" CCS projects intending to store CO_2 in onshore depleted natural gas reservoirs (i.e. the Barendrecht project). Furthermore, not all system functions have received equal attention in the built up the Innovation System as investigated till 2010. There seems to be a lack of market creation policies (*F5*) by the Dutch national government, as well as the European Union. This can be seen as one of the main reasons why the extensive knowledge base *(F2)* and CCS knowledge networks *(F3)*, accumulated over the past years, have not yet been valorised by entrepreneurs to explore markets for CO_2 capture concepts linked to power generation *(F1)*. 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, regulatory guidance and the creation of legitimacy also need to be addressed.

In order to remedy malfunctioning in the Dutch CCS Innovation System the following general strategy has been abstracted from the analysis presented in this study that aims to accelerate the transition pathway for CCS in the Netherlands:

- Short-term investor certainty needs to be provided by establishing public private partnerships combined with direct subsidies for at least two large-scale integrated CCS projects. It is believed that the creation of partnerships could offer a high incentive to projects in an early phase that have not yet benefited from scale economies and technological improvement. In order to further reduce this "first mover disadvantage" such a coordinated effort should also target the development of a common user CO_2 transportation and storage infrastructure, which includes an oversized CO_2 backbone pipeline system and pre-competitive storage site characterization efforts. The latter could substantially lower the project lead times, upfront costs and thereby the financial risks for new entrepreneurs that wish to enter the CCS market.
- Clear legislation and regulation is needed regarding site selection, safety standards, monitoring requirements, and timeframes as well as responsibilities for the different liability types related to CCS projects. Clear guidance from regulators on these aspects is not only crucial in providing investment certainty 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 therefore be an integral part of every CCS project plan. The latter would provide businesses with a "social licence to operate".
- Finally, we would argue that abovementioned efforts would only be successful if overarching long-term climate policies are developed. The Dutch Governments (in close cooperation with the European Commission) need to change 'the rules of the game' by putting a price on carbon dioxide that is sufficient to drive commercial investments in CCS. If the current EU emissions trading scheme won't provide such an incentive in the near future, the introduction of performance standards for emitting facilities might be necessary to drive large-scale deployment of CCS. Another option worth exploring is to include Enhanced Oil Recovery operations in the ETS, as the additional revenues from oil production could make CCS commercially viable on the short term.

Summarizing the above, it can be concluded that sound alteration of 1) short-term financial incentives to stimulate learning by doing; 2) clear legislation and regulation to reduce non-technical risks; and 3) long-term market incentives, is key in the development and commercialization CCS technologies in the Netherlands.

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

1. van Alphen, K. (2009). *Effectief Innovatiebeleid ten aanzien van CO_2 afvang en opslag*, Innovation Studies Group, Copernicus Institute, Utrecht University: Utrecht (The Netherlands).
2. Hekkert, M.P., F.A. Alkemade, S.O. Negro, R.A.A. Suurs, and K. van Alphen (2007). *Het versnellen van transitiepaden door het versterken van innovatiesysteemdynamiek (English: Accelerating transition pathways for low emissions technologies by strengthening innovation system dynamics). Contract research for the Ministry of Economic Affairs,* Innovation Studies Group, Copernicus Institute, Utrecht University.
3. Klein Goldewijk, K., J.G.J. Olivier, J.A.H.W. Peters, P.W.G.H. Coenen, and H.H.J. Vreuls (2005). *Greenhouse emissions in the Netherlands 1990-2003. National Inventory report 2005*, National Institute for Public Health and the Environment (RIVM/MNP): Bilthoven (The Netherlands).
4. Simmelink, H.J., A. Lokhorst, V. Vandeweijer, R. Rijkers, T. Benedictus, and R. van Eijs (2007). *Options for CO_2 storage in the Netherlands - Time dependent storage capacity, hazard aspects and regulations*, TNO: Utrecht (The Netherlands).
5. Daniels, B.W. and J.C.M. Farla (2006). *Potentieelverkenning klimaatdoelstellingen en energiebesparing tot 2020. Analyses met het optiedocument energie en emissies 2010/2020*, Energy research Centre of the Netherlands (ECN) and National Institute for Public health and the Environment (RIVM): Petten (The Netherlands).
6. Vroonhof, J.T.W., H.C. Croezen, and S. Slingerland (2006). *Report on debate "Welke nieuwe electriciteiitscentrale(s) in Nederland"*, CE: Delft.
7. Task Force Energietransitie (2006). *Meer met energie. Kansen voor Nederland*.
8. Jepma, C., J. Gigler, P. Aubert, H. Cahen, M. van Groeningen, D. D'Hoore, J-K. Hordijk, D. Jansen, M. Kuijper, E. Lysen, S. Van Egmond, A. Mom, H. Spiegeler, P. Stollwerk, J. Vis, T. Wildenborg, and H. Pagnier (2006). *Advies van de werkgroep Schoon Fossiel van het Platform Nieuw Gas aan de Task Force Energietransitie, Platform Nieuw Gas*.
9. Carlsson, B. and R. Stankiewicz (1991). *On the nature, function and composition of technological systems.* Journal of Evolutionary Economics. 1(2): p. 1432-1386.
10. Jacobsson, S. and A. Johnson (2000). *The diffusion of renewable energy technology: an analytical framework and key issues for research.* Energy Policy. 28(9): p. 625-640.
11. Hekkert, M.P., R. Harmsen, and A. de Jong (2007). *Explaining the rapid diffusion of Dutch cogeneration by innovation system functioning.* Energy Policy. 35(9): p. 4677-4687.
12. Jacobsson, S. and A. Bergek (2004). *Transforming the energy sector: the evolution of technological systems in renewable energy technology.* Industrial and Corporate Change. 13(5): p. 815-849.
13. Hekkert, M.P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann, and R.E.H.M. Smits (2007). *Functions of innovation systems: a new approach for analysing technological change.* Technological Forcasting and Social Change. 74(4): p. 413-432.
14. Negro, S.O., R.A.A. Suurs, and M.P. Hekkert (2008). *The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system.* Technological Forecasting and Social Change. 75(1): p. 57-77.
15. Alkemade, F., C. Kleinschmidt, and M. Hekkert (2007). *Analysing emerging innovation systems: a functions approach to foresight.* International Journal of Foresight and Innovation Policy. 3(2): p. 139-168.
16. Negro, S.O., M.P. Hekkert, and R.E. Smits (2007). *Explaining the failure of the Dutch innovation system for biomass digestion-A functional analysis.* Energy Policy. 35(2): p. 925-938.
17. Hekkert, M.P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann, and R.E.H.M. Smits (2007). *Functions of innovation systems: A new approach for analysing technological change.* Technological Forecasting and Social Change. 74(4): p. 413-432.
18. Suurs, R.A.A. (2009). *Thesis: Motors of Sustainable Innovation. Towards a theory on the dynamics of technological innovation systems*, Innovation Studies Group, Copernicus Institute Utrecht University: Utrecht (The Netherlands).

19. Poole, M.S., A.H. van de Ven, K. Dooley, and M.E. Holmes (2000). *Organizational Change and Innovation Processes: Theory and methods for research.* Oxford University Press. New York (USA).
20. Van de Ven, A.H. and M.S. Poole (2002). *Field Research Methods*, in *Companion to Organizations*, J. Baum, ed. Basil Blackwell Publishers: London (UK). p. 867-888.
21. Abbot, A. (1995). *Sequence Analysis: New Methods for Old Ideas.* Sociology. 21: p. 93-113
22. Negro, S.O., M.P. Hekkert, and R.E.H.M. Smits (2007). *Explaining the failure of the Dutch innovation system for biomass digestion--A functional analysis.* Energy Policy. 35(2): p. 925-938.
23. Negro, S.O. (2007). *Thesis: Dynamics of technological innovation systems — the case of biomass energy*, Innovation Studies Utrecht University: Utrecht (The Netherlands).
24. Bergek, A., S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne (2008). *Analyzing the functional dynamics of technological innovation systems: A scheme of analysis.* Research Policy. 37(3): p. 407-429.
25. Likert, R. (1932). *A Technique for the Measurement of Attitudes.* Archives of Psychology 140: p. 1-55.
26. Agterbosch, S. (2006). *Thesis: Empowering wind power. On social and institutional conditions affecting the performance of entrepeneurs in the wind power supply market in the Netherlands*, University Utrecht: Utrecht (The Netherlands).
27. Hendiks, C.A., K. Blok, and W.C. Turkenburg (1989). *The recovery of carbon dioxide from power plants*, in *Climate and Energy*, P.A. Okken, R.J. Swart, and S. Zwerver, ed. Kluwer Academic Publishers: Dordrecht (The Netherlands).
28. Blok, K. (1993). *Final Report of the Research Program on Carbon Dioxide Recovery and Storage*, Department of Science, Technology and Society, Part of the Dutch Integrated Research Program on Carbon Dioxide Recovery and Storage (SOP-CG2).
29. Jansen, D., A.B.J. Oudhuis, and H.M. van Veen (1992). *CO2 reduction potential of future coal gasification based power generation technologies.* Energy Conversion and Management. 33(5-8): p. 365-372.
30. Hendriks, C.A. and K. Blok (1992). *Carbon dioxide recovery using a dual gas turbine IGCC plant* Energy Conversion and Management. 33(5-8): p. 387-396.
31. Turkenburg, W.C. (1992). *CO_2 removal; Some conclusions.* Energy Conversion and Management 33(5-8): p. 819-823.
32. Schmidt, C.W. (2007). *Carbon Capture & Storage: Blue-Sky Technology or Just Blowing Smoke?* Environmental Health Perspectives 115(11): p. 538-545.
33. Holloway, S. (1996). *An overview of the Joule II project: The underground disposal of carbon dioxide.* Energy Conversion and Management. 37(6-8): p. 1149-1154.
34. Boonekamp, P.G.M., O. van Hilten, R. Kroon, and M.N.E.V. Rouw (1992). *Nationale Energie Verkenningen (Dutch Energy Outlook) 1990-2015*, Netherlands Energy Research Foundation (ECN): Petten (The Netherlands).
35. AER (1994). *Advies AER over de Vervolgnota Energiebesparing*, Algemene Energieraad (AER): The Hague, The Netherlands.
36. IPCC (1995). *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific–Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, ed. R.T. Watson, M.C. Zinyowera, and R.H. Moss. Cambridge University Press. Cambridge (UK): p. 889.
37. CE (1996). *Nationale themadag waterstof*, Centre for Energy Conservation and Environmental Technology: Delft (The Netherlands).
38. TNO and RGD (1996). *Inventarisatie van mogelijkheden voor CO2-opslag in de Nederlandse ondergrond*, TNO/RGD: Haarlem (The Netherlands).
39. Korbol, R. and A. Kaddour (1995). *Sleipner vest CO2 disposal - injection of removed CO2 into the utsira formation.* Energy Conversion and Management. 36(6-9): p. 509-512.
40. van Alphen, K., Q. van Voorst tot Voorst, M.P. Hekkert, and R.E.H.M. Smits (2007). *Societal acceptance of carbon capture and storage technologies.* Energy Policy. 35(8): p. 4368-4380.
41. VROM (1999). *Uitvoeringsnota Klimaatbeleid*, Ministry of Housing, Spatial planning, and Environment (VROM): The Hague (The Netherlands).

42. EZ (2003). *Beleidsnotitie Schoon Fossiel*, Dutch Ministry of Economic Affairs: The Hague (The Netherlands).
43. Dijk, J.W. and P.J. Stollwerk (2002). *CO2 reuse through underground storage (CRUST)—the start-up: an inventory of market opportunities, technology and policy requirements,* CO2 Reduction Plan Project Office: Zwolle (The Netherlands).
44. NAM (2003). *CO_2 reduction by subsurface storage in a depleted gasfield; a feasability study by Shell and NAM. CRUST project*.
45. Lysen, E., A. Faaij, and C. Hendriks (2005). *The CATO programme in the Netherlands on CO2 capture, transport and storage*, Presented at the 7th International Conference on Greenhouse Gas Control Technologies: Vancouver (Canada).
46. Jansen, D. and S. van Egmond (2009). *Recent developments in the Dutch CAPTECH programme.* Energy Procedia. 1(1): p. 1451-1456.
47. Meerman, H., T. Kuramochi, and S. van Egmond (2008). *CO2 Capture Research in the Netherlands*, R. Stuart, ed. CATO, Utrecht University: Utrecht (The Netherlands).
48. IPCC (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*, ed. B. Metz, et al. Cambridge (UK).
49. ECN and NMP (2006). *Optiedocument Energie en Emissies 2010/2020*, B.W. Daniels and J.W.M. Farla, ed. Energy Research Centre of the Netherlands, Dutch Environmental Planning Bureau: Petten (The Netherlands).
50. VROM (2007). *Clean and Efficient: New energy for climate policy,* Ministry of Housing Special Planning and the Environment (VROM): The Hague (The Netherlands).
51. Uyterlinde, M.A., J.R. Ybema, R.W. van den Brink, H. Rösler, and F.J. Blom (2007). *A sustainable energy system in 2050: Promise or possibility? A vision by ECN and NRG*, Energy Research Centre of the Netherlands (ECN).
52. RCI and DCMR (2007). *CO2-afvang en -opslag in Rijnmond,* Milieudienst Rijnmond and Rotterdam Climate Initiative: Rotterdam (The Netherlands).
53. RCI and DCMR (2009). *CO2 Capture, Transport and Storage in Rotterdam. Report 2009*, Milieudienst Rijnmond and Rotterdam Climate Initiative: Rotterdam (The Netherlands).
54. CSLF (2008). *Carbon Sequestration Leadership Forum Recognized Projects*. Available from: www.cslforum.org.
55. Nell, L. (2008). *CATO CO2 catcher pilot plant factsheet*. TNO Science and Industry. Delft (The Netherlands).
56. Chazan, G. (2009). *Shell's plan to lead in storage of carbon dioxide hits a snag*, Wallstreet journal.
57. MER (2009). *Ondergrondse opslag van CO2 in Barendrecht: Toetsingsadvies over het milieueffectrapport,* Commissie voor de milieueffectrapportage.
58. Kliest, A. (2010). *MSc Thesis: Beeldvorming over CO2 afvang en opslag. Analyse van de berichtgeving in Nederlandse landelijke dagbladen,* Utrecht University: Utrecht (The Netherlands).
59. Greenpeace International (2008). *False Hope, why carbon capture and storage won't save the climate*, E. Rochon, et al., ed. Greenpeace International: Amsterdam (The Netherlands). p. 44.
60. European Commission (2009). *Call for proposals concerning a program to aid economic recovery by granting community financial assistance to projects in the field of energy*, Directorate-General for Energy and Transport: Brussels (Belgium).
61. NER 300 (2010). *NER 300: Finance for installations of innovative renewable energy technology and CCS in the EU.* Available from: www.ner300.com.
62. 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,* European Parliament: Brussels (Belgium).
63. ETP ZEP (2008). *EU Demonstration Programme for CO2 Capture and Storage (CCS) – ZEP's proposal,* European Technology Platform for Zero Emission Fossil Fuel Power Plants: Brussels (Belgium).

64. GCCSI (2009). *Strategic Analysis of the Global Status of Carbon Capture & Storage*, Global Carbon Capture and Storage Institute: Canberra (Australia).
65. SenterNovem (2008). *CCS Task Force*. Available from: www.senternovem.nl/taskforceccs/taskforce_ccs/index.asp.
66. European Commission (2008). *Proposal for a directive of the European Parliament and of the council on the geological storage of carbon dioxide and amending Council Directives*, European Commission: Brussels (Belgium).
67. IEA (2008). *CO2 Capture and Storage: A Key Carbon Abatement Option*. IEA/OECD. Paris (France).
68. ECN/MNP (2007). *Verkenning potentieel en kosten van klimaat en energiemaatregelen voor Schoon en Zuinig*, M. Menkveld and R.A. van den Wijngaart, ed. Energieonderzoek Centrum Nederland, Milieu- en Natuurplanbureau: Petten (The Netherlands).
69. Bellona Foundation (2009). *ZEP General Assembly 2009 calls for action on CCS*. Available from: www.bellona.org/articles/articles_2009/zep_2009.
70. 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).
71. de Best-Waldhober, M. and D. Daamen (2006). *Perceptions and Preferences Regarding Large Scale Implementation of Six CO2 Capture and Storage Technologies*, Centre for Energy and Environmental Studies, Leiden University: Leiden (The Netherlands).
72. Jurgen Ganzevles, A. Kets, and R.v. Est (2008). *Schoon fossiel of vuilstort Resultaten focusgroepen met burgers over CO2-opslag in lege aardgasvelden*, Rathenau Instituut: The Hague, Netherlands.
73. LexisNexis (2010). *LexisNexis Nederland*. Available from: http://www.lexisnexis.nl/dutch/.
74. Groenenberg, H. and H. de Coninck (2008). *Effective EU and Member State policies for stimulating CCS.* International Journal of Greenhouse Gas Control. 2(4): p. 653-664.
75. IEA (2010). *2nd International CCS Regulators' Network meeting*. Available from: www.iea.org/work/workshopdetail.asp?WS_ID=444.
76. Damen, K., A. Faaij, and W.C. Turkenburg (2009). *Pathways towards large-scale implementation of CO2 capture and storage: A case study for the Netherlands.* International Journal of Greenhouse Gas Control. 3(2): p. 217-236
77. de Coninck, H., J.C. Stephens, and B. Metz (2009). *Global learning on carbon capture and storage: A call for strong international cooperation on CCS demonstration.* Energy Policy. 37(6): p. 2161-2165.
78. van Alphen, K., M.P. Hekkert, and W.C. Turkenburg (2009). *Comparing the development and deployment of carbon capture and storage technologies in Norway, the Netherlands, Australia, Canada and the United States-An innovation system perspective.* Energy Procedia. 1(1): p. 4591-4599.

Interlude C

The following chapter presents the results of the evaluative analysis of the development and deployment of CCS technologies in the United States. In this case study the analysis of Innovation System Functions is further refined by applying quantitative methods, like social network analysis and project analysis. These methods are applied in addition to the literature review and interviews with key stakeholders that were applied in the case studies for the Netherlands and Norway. This study into the historical dynamics and current performance of the CCS TIS in the United States provides a clear understanding of the current barriers to the technology's future deployment and outlines a policy strategy that would relief these barriers.

The research presented in this chapter was executed in the period 2008 – June 2009 and was originally published as [1]: van Alphen, K., Noothout, P. M., Hekkert, M. P., Turkenburg, W. C. (2010). Evaluating the development of carbon capture and storage technologies in the United States. *Renewable and Sustainable Energy Reviews.* 14 (3): p. 971-986.

4. Evaluating the development of carbon capture and storage technologies in the United States

Abstract

Carbon capture and storage (CCS) is seen as an important solution to solve the twin challenge of reducing GHG emissions, while utilizing fossil fuel reserves to meet future energy requirements. In this study an Innovation System perspective is applied to review the development of CCS technologies in the US between 2000 and 2009 and to come up with policy recommendations for technology managers that wish to accelerate the deployment of CCS. The analysis describes the successful built-up of an Innovation System around CCS and pinpoints the key determinants for this achievement. However, the evaluation of the system's performance also indicates that America's leading role in the development of CCS should not be taken for granted. It shows that the large CCS R&D networks, as well as the extensive CCS knowledge base, which have been accumulated over the past decade, have not yet been valorised by entrepreneurs to explore the market for integrated CCS concepts linked to power generation. Therefore, it is argued that the build-up of the Innovation System has entered a critical phase that is decisive for a further thriving development of CCS technologies in the US. This study provides a clear understanding of the current barriers to the technology's future deployment and outlines a policy strategy that (1) stimulates technological learning; (2) facilitates collaboration and coordination in CCS actor networks; (3) creates financial and market incentives for the technology; and (4) provides supportive regulation and sound communication on CCS.

4.1. Introduction

Carbon dioxide (CO_2) emissions from fossil fuel based power generation contribute close to 40% of the total CO_2 emissions in the US in 2008. This number is expected to increase by 2% in 2030 [2]. To balance the demand of both reducing greenhouse gas (GHG) emissions and assuring a reliable energy supply, the scientific community, industry, and political leaders have identified carbon capture and storage (CCS) as a viable technological option to address both issues [3]. CCS entails separating CO_2 from industrial or energy-related point sources, and then injecting it into underground geologic reservoirs for permanent storage (such as depleted hydrocarbon fields and deep saline aquifers). First assessments indicated that the US might have a storage capacity of more than 1000 times the annual US CO_2 emissions [4].

The US Department of Energy (DOE) is taking a leading role in the advancement of CCS technologies. Through its Carbon Sequestration Program – managed by the office of fossil energy and implemented by the National Energy Technology Laboratory (NETL) – DOE is supporting the development of a large variety of CCS technologies since 2003 [5]. There are three main components to the US CCS activities: core R&D related to CCS; deployment through the Regional Carbon Sequestration Partnerships (RCSPs); and major demonstration projects through the Clean Coal Power Initiative and FutureGen efforts.

Despite a successful start of DOE's CCS support programs, the deployment of large-scale CCS projects suffered severe setbacks in 2007 and 2008. High profile projects were cancelled or postponed, including NRG's Huntley coal gasification plan with CCS in New York State; Hydrogen Energy's zero emissions power plant in Carson, California; and most (in)famously, the desire by US-DOE to restructure the financial arrangements of the FutureGen project in Illinois, because of escalating cost estimates [6]. The rethinking of these 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 [7]. 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 [8], 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 deepened our understanding of innovation processes. Scholars such as Nelson and Winter [9], Freeman [10], Lundvall [11] and Kline and Rosenberg [12] emphasised that organisations are not innovating in isolation but in the context of an Innovation System. The basic idea of an Innovation System is that the innovation process is strongly influenced by a network of actors that are developing, advocating or opposing the technology and by an institutional infrastructure that legitimizes, regulates and standardizes the new technology [13]. A well-performing Innovation System accelerates technological development and increases the success chances of new technology [14].

Over the past few years further progress has been made in determining key processes that need to take place in Innovation Systems in order to perform well [see e.g. 15, 16]. These system functions – e.g. knowledge diffusion and market creation – are decisive processes that foster the shaping and development of a technology [17]. In earlier empirical work the functions approach has been used effectively to deliver explanations for the success or failure of technological trajectories of sustainable energy technologies in various countries [18-23]. Furthermore, their fulfilment can be assessed to derive policy strategies for supporting a specific technology [24-26].

This study applies the Innovation System Functions framework to evaluate the performance of the US CCS Innovation System. We aim to provide insights into the relations between the historical growth of the Innovation System and the system's current performance. Furthermore, we will derive policy and management strategies for technology managers that wish to accelerate the development and deployment of CCS in the US.

4.2. Theoretical framework

From the 1980s onwards, Innovation System studies have pointed out the influence of the social system on innovative performance. Different approaches exist – for an extended review [27, 28], but all studies point to the structure of the Innovation System as the explanatory basis. The structure of an Innovation System consists of actors, their networks, institutions, and also incorporates technological features [29]. We follow Carlsson and Stankiewicz [13] in defining the US CCS Innovation System as those structural elements that directly support (or reject) the development and (future) diffusion of CCS technologies in the US.

According to this definition the formation and growth of a national Technological Innovation System (TIS) can be described by changes in its main components. For example, actors, such as firms looking to exploit the benefits of CCS technologies, enter the system and interact with other organization through cooperation or competition. Actors are organized in networks and networks often interrelate: e.g. industry networks influencing political networks in order to enforce institutional changes. In turn, institutions, such as public resource endowments or technological standards, influence the information flows between (networks of) actors and thereby foster or hamper technological advancement [30].

Yet, whereas it is known that structures need to be built-up, the performance of a certain structure cannot be assessed very easily since many different structures can lead to similar outcomes. Hence, there is no optimal system configuration that identifies the precise attributes of actors, networks and institutions in a well-performing Innovation System [24]. Therefore, we present a framework outlining seven key processes – here labelled as ‘Innovation System Functions’ – which have a direct impact on the development and diffusion of new technologies. The premise is that the components of the system should be successfully arranged to bring about an optimal fulfilment of seven system functions, each of which covers a particular aspect of technological innovation (see Table 4-1 for definitions).

Table 4-1: Functions of Technological Innovation Systems [16].

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 favourable tax regimes, consumption quotas, or other public policy activities.
F6. Resource mobilization	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.

The seven system functions are considered a suitable set of criteria for the performance assessment of an emerging Innovation System structure [15]. To some extent, system functions need to be realized simultaneously, since they can complement, or reinforce each other [29], but an Innovation System may very well collapse due to the absence of a single system function. For example, Kamp [31] has shown that the Dutch wind energy Innovation System was well developed in the 1980s but collapsed as the result from the absence of knowledge exchange (function 3) between the emerging turbine industry and the research community as well the users of the wind turbines, the latter being mainly energy companies. So, there may be particular functions that drive or block the growth of a specific Technological Innovation System. The analytical framework that is outlined below further elucidates this.

4.3. Research design and methods

This analytical framework is based on the assumption that policy interventions directed at stimulating a successful build-up of the US CCS Innovation System should focus on improving functions that are considered to be ‘weak’. In order to determine such an intervention strategy, the historical built-up of the Innovation System structure needs to be assessed first. Subsequently, the performance of this emergent system structure must be evaluated using the Innovation System Functions. Both analytical parts are discussed below.

4.3.1. Part 1: Innovation System structure

The first step is to analyze the formation and growth of the Innovation System structure in terms of institutions, actor networks and technological advancement. We mapped the build up of an institutional infrastructure by conducting an extensive literature review of scientific as well as ‘grey literature’ (e.g. professional journals and policy papers) on regulatory issues regarding CCS.

We applied social network analysis to identify the actor networks involved in the US CCS Innovation System and how the relations between actors change over time.

The social network approach assumes that the structure of linkages among actors can favour or impede the diffusion of innovations in the system [32]. It identifies the network structure as a major factor to help the system evolve [33]. Two dimensions of social networks are positively related to the successful build-up of an Innovation System, network size and network connectivity. The size of the network is determined based on three measures: number of actors, the size of largest component – i.e. connected parts of the network – and average distance between actors in the network. The connectivity of the network is determined based on the average number of linkages per actor (mean degree) and the clustering coefficient, a measure to determine the existence of relative dense clusters in the network [34]. Social network analysis can also be performed on an actor level. The number of linkages of an actor (node degree) and its betweenness are centrality measures indicating the position of an actor in the network.

In this study, two actors are considered to be exchanging knowledge – and thus related – when they are involved in the same CCS project. This could be a cooperative R&D effort, a policy network, but also a commercial joint venture. In order to specify the relations between actors in the Innovation System, a comprehensive project database has been constructed. The database contains over 150 CCS projects that have been carried out in the US between 2000 and 2008, involving more than 350 organisations. To create a network, an adjacency matrix is constructed. In this matrix, actors are placed at the heads of the columns and rows. If a link exists between actors, this is represented by a positive value in the cell. The adjacency matrices are then used in specialized network software to visualize the networks, i.e. Visone [35] and UCINET 6 [36].[1]

The most important sources of information for the construction of our CCS project database are the NETL ‘Carbon Sequestration Project Portfolio's’ [37, 38]. The data is complemented and verified using the CCS database of the IEA GHG R&D program [39] and the Fossil Research and Engineering Database of US-DOE [40] . Additional information has been gathered using various reports, project fact sheets and interviews with project managers in 2008.[2]

Besides the name of the actors involved in CCS projects, the following data has been recorded in order to specify the technological focus and advancement in the CCS knowledge base:

1. The organisational background of the actor (e.g. oil and gas industry or universities).

[1] For more information on Social Network Analysis and data setup we refer to the book of Wasserman and Faust [52].
[2] It is recognized by the authors, that some projects are developed exclusively with private funding and that information on these projects is not always available.

2. The technological focus of the project. Thereby we have distinguished between three categories: CO_2 capture, CO_2 storage, and other CCS areas, including CO_2 transportation, public acceptance and policy analysis. The capture projects are then subdivided into post-, pre-, and oxyfuel combustion; and in storage we distinguish three main types of geological reservoirs, namely saline aquifers, oil and gas fields (both depleted and producing) and coal seams.[3]
3. Each project is classified in terms of 'distance to market'. A project is considered: (a) basic and applied R&D; (b) demonstration (early prototypes up to full-scale working devices); (c) pre-commercial (commercial-scale prototypes and integrated demonstration projects).
4. Finally, the start and end date, as well as the costs of the project are recorded in order to gain insight in distribution of costs among technological options over time.

4.3.2. Part 2: Innovation System performance and system intervention

The second part of the analysis aims at ascertaining to what extent the Innovation System Functions are currently fulfilled by the components of the system. The data for this sub-analysis are collected by extensive literature review and by interviewing the main actors involved in the development of CCS in the US. Hereby we made use of a number of indicative questions that provide insight in the fulfilment of the functions (see Table 4-2). In total, 18 interviews have been conducted with senior representatives from industry, research, government and environmental groups.[4] Also, within stakeholder groups variety was sought (e.g. researchers involved in both capture and storage technologies; 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.

In order to assess system performance, we have the main actors in the system reflect upon the ongoing activities in the system and rate their level of satisfaction with the fulfilment of a particular system function. The interviewees have been asked to score the fulfilment of each system function on a 5 point Likert scale where 1 = very weak, 2 = weak, 3 is sufficient, 4 = good and 5 = very good. In this way, our results from the analysis of the system structure are triangulated with critical evaluations from experts who took part in shaping the technological trajectory for CCS in the US.

Based on the current performance of the system, it is possible to indicate drivers and barriers in terms of how the Innovation System Functions should develop so that system growth is stimulated. Therefore, the respondents have not only evaluated the current functioning of the Innovation System, but also gave their view on what should be done to improve functions that are impeding a higher system performance. This provides the basis for intervention strategies that aim to accelerate the development and deployment of CCS in the US.

---

[3] Note that CCS projects can fall in multiple categories and that R&D projects related deep ocean CO_2 storage and CO_2 mineralization are not included in the database.
[4] Most of the interviews with CCS experts in the US have been conducted in the first half of 2008.

Table 4-2: Indicative questions that reflect the extent to which each function in the Innovation System is fulfilled by the components of the system [see also 15, 16].

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)?

4.4. The structure of the US CCS Innovation System

The development and diffusion of technology can be seen as the outcome of the actions of actors that operate under a particular institutional infrastructure. We will now describe the formation and growth of the US CCS Innovation System by changes in its structural building blocks, namely: (1) institutional infrastructure; (2) the network of actors; and (3) the technology.

4.4.1. Institutional infrastructure

Until 2009, climate change mitigation in the US has been primarily a technology-driven voluntary effort. Nevertheless, CCS has been an important consideration in US climate policy discussions as it is recognized as a possible solution to solve the twin challenge of reducing GHG emissions, while utilizing indigenous coal and gas reserves to meet future energy requirements. Therefore, a number of proposals that involve GHG regulatory requirements and CCS have been considered in the US Congress and in individual States [41]. The proposed policy mechanisms to limit GHG emissions and stimulate the use of CCS vary widely. Carbon taxes, emissions performance standards (EPS), portfolio standards, cap-and-trade systems, direct subsidies, and indirect subsidies such as tax credits, have all been discussed, often in combination with each other [42]. See for example, the Clean Air Planning Act of 2003 [43], the Climate Stewardship and Innovation Act of 2007[44], the Low Carbon Economy Act of 2007 [45], and the Lieberman-Warner Climate Security Act of 2008 [46]. However, it was not until June 2009 that the first climate legislation, known as the American Clean Energy and Security Act (ACES), was approved by the House of Representatives [47].

ACES should establish a cap-and-trade system for GHG emissions from all major emitting sectors including power producers. It requires a 17% emissions reduction by 2020 and over 80% by 2050 compared to 2005 levels. Furthermore, the Bill includes the implementation of emission performance standards (EPS) to prevent continued investment in high emitting power sources and ensure a level playing field for the utility sector. The ACES Act requires that all new coal plants permitted after 2020 must use CCS when they commence operations. Coal plants permitted between 2015 and 2020 that do not use CCS must retrofit CCS by no later than 2025 without federal financial assistance. Coal plants permitted between 2009 and 2015 lose eligibility for federal financial assistance if they do not retrofit CCS within 5 years after commencing operations. The federal financial assistance consists of direct cash payments up to USD 90 per tonne of captured CO_2 and the establishment of a Carbon Storage Research Corporation to be run by the Electric Power Research Institute. The Corporation would use funds collected through a feed-in tariff to issue grants – capped at USD 1 billion per year – for early commercial scale CCS demonstrations [47, 48].

Despite the passage of ACES in the House, the future of the Act remains uncertain, as it faces both opposition and competing bills intended to address climate change in the Senate. For example, the Senate Energy and Natural Resources Committee passed the American Clean Energy Leadership Act in June 2009. This bill addresses several of the same energy issues addressed by ACES, but with a stronger emphasis on enhancing energy efficiency and increasing capitalization for clean energy projects, rather than mandatory emissions reduction [49]. These measures, as well as proposals from other Senate committees, will likely be combined to create the Senate counterpart to the ACES Act. If the Senate passes this combined bill, differences between the Senate and House bills would have to be reconciled, with the final bill passed by both houses, before the bill could be sent to President Obama and signed into law [47].

Even though an overarching climate legislations targeting CCS is not expected to be in place before 2010, the development of CCS has been key in US fossil fuel R&D programs for over a decade now. Next to the Clean Coal Power Initiative and FutureGen efforts, the Carbon Sequestration Program is the most comprehensive CCS R&D program in the US. The objective of this US-DOE sponsored 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% increases in electricity costs by 2012 [50] As part of the Program, DOE has formed a nationwide network of seven Regional Carbon Sequestration Partnerships (RCSPs). The RCSPs are public private partnerships that involve more than 350 organizations covering 42 states and four Canadian provinces. The RCSPs are tasked with determining the most suitable technologies, regulations, infrastructure and public outreach strategies for CCS in their areas of the country. Furthermore, the RCSPs project sites serve as field laboratories to test the core R&D technologies at scale and in real-world conditions, which in turn shapes the requirements for future R&D needs [5].

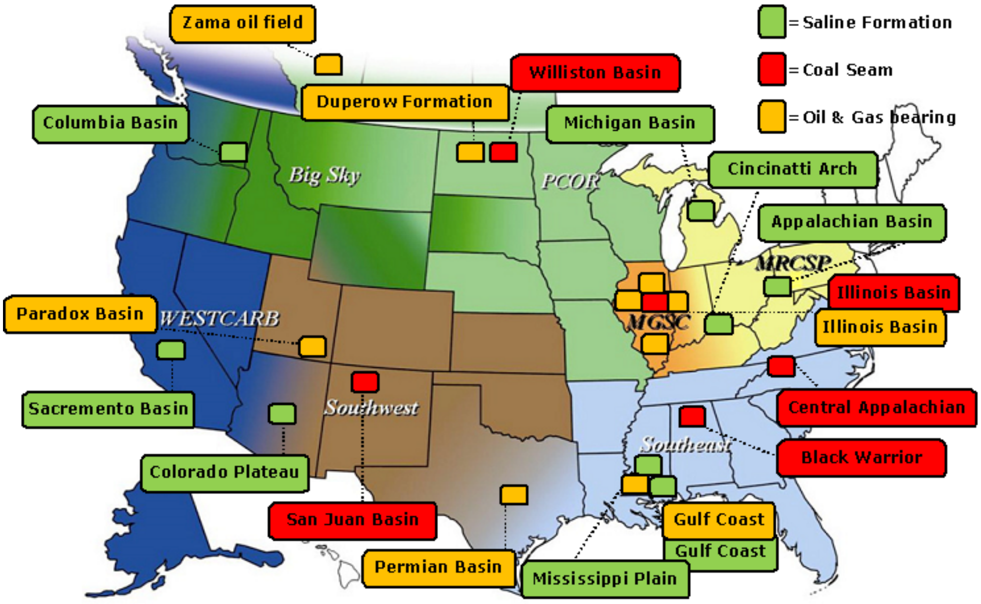


Figure 4-1: Location of regional carbon sequestration partnerships validation phase geological field tests [see also 5, 50, 51, 52]. Partnership abbreviations: Big Sky Carbon Sequestration Partnership (Big Sky); Midwest Geological Sequestration Consortium (MGSC); Midwest Regional Carbon Sequestration Partnership (MRCSP); Plains CO_2 Reduction Partnership (PCOR); Southeast Regional Carbon Sequestration Partnership (SECARB); Southwest Regional Partnership on Carbon Sequestration (SWP); West Coast Regional Carbon Sequestration Partnership (WESTCARB).

The RCSPs are being implemented in three phases. The objective of the first phase (2003–2005) is to collect data on CO_2 sources and sinks; and to identify the most promising storage opportunities taking infrastructural issues into account. After this ‘characterization phase’, the RCSPs started in 2005 with the implementation of 22 small-scale geologic field tests (see Figure 4-1), whereby between 10 and 100 ktCO_2 has been injected at each project site. DOE has invested approximately USD 120 million into the development of field tests and industry is bearing a 40% cost share. The main results of this ‘validation phase’ (2005–2008) have been the validation of simulation modelling and the deployment of monitoring protocols. The lessons learned in the validation phase, which also relate to regulatory requirements and public engagement, are valuable for the final phase (2009–2017), whereby DOE is investing approximately USD 500 million into the development of large-scale CCS projects (>1 Mt/CO_2). The objective of this 'deployment phase' is to demonstrate that large volumes of CO_2 can be injected safely, permanently, and economically into geologic formations [51].

Next to the funding of national CCS projects, the US-DOE is working with the Department of State in several international consortia to plan and implement joint projects all over the globe, including the Asia-Pacific Partnership on Clean Development and Climate, the IEA GHG program and the Carbon Sequestration Leadership Forum (CSLF). The latter is an international ministerial-level, which is tasked with establishing a companion foundation of legislative, regulatory, administrative, and institutional practices that will ensure safe, verifiable CO_2 storage.

At the national level, it is recognized that CO_2 injection and storage can only be partly covered by existing Federal and State legislation on CO_2 for enhanced oil recovery (EOR), natural gas storage and acid gas disposal. Therefore, the US Environmental Protection Agency (EPA) proposed regulation for commercial-scale CO_2 storage under the Underground Injection Control (UIC) program [53]. The rule suggests a new UIC injection well class IV for CO_2 storage wells and includes standards for site characterization, well construction and operation, monitoring and post-closure care. In addition to the national regulators, several states, including Illinois, Kansas and Washington, are actively pursuing CCS through implementing regulations for geological CO_2 storage [6, 54]. Moreover, the ACES Act requires the EPA, in consultation with the heads of other relevant state and federal agencies, to submit to Congress a comprehensive strategy to address the key legal and regulatory barriers to the large-scale deployment of CCS.

4.4.2. Actor networks

Both the increasing amount of funds available for CCS and the cooperative nature of CCS R&D programs, as well as the alignment of the regulatory environment with the technology, have positively influenced the growth of CCS networks in the US. Figure 4-2 visualizes the US CCS network between 2003–2005 and 2006–2008; corresponding to the characterization and validation phases of the DOE's Carbon Sequestration Program.

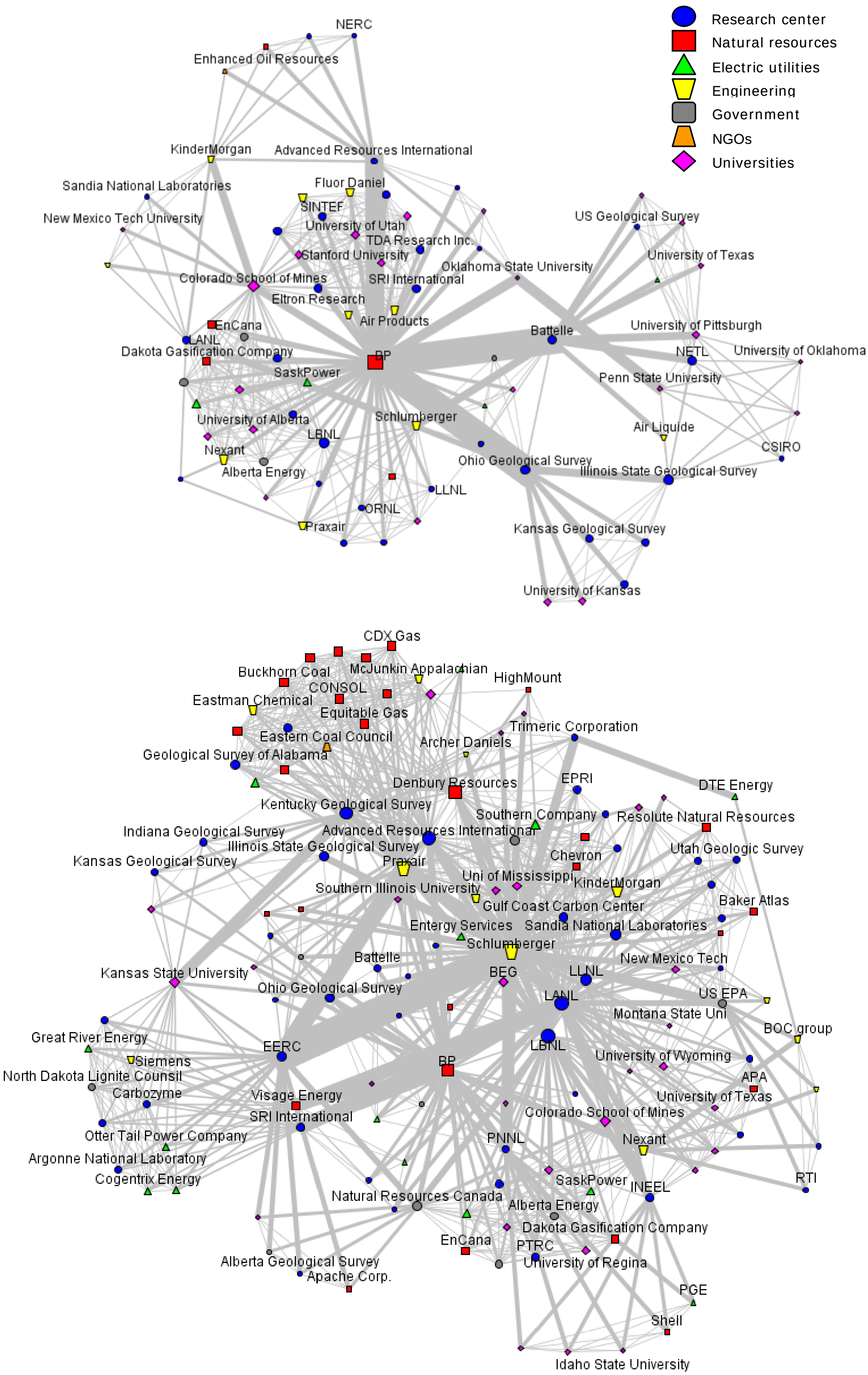


Figure 4-2: Visualization of CCS actor networks between 2003–2005 (top) and 2006–2008 (bottom).

In the visualized networks, the nodes are the actors and the edges are the result from cooperation in CCS projects. The network visualizes only actors that have five or more linkages.[5] The number of linkages (degree) determines the size of a node; the width of an edge is proportional to its betweenness. For example, in the characterization phase BP is positioned in the centre of the network with 51 linkages and the link between BP and Batelle obtains a relatively high betweenness value as it represents the shortest path length between the actors grouped around BP in the centre of the network (e.g. Sask power and the Colorado School of Mines) with the actors clustered in the periphery on the right side of the network (e.g. the Universities of Pittsburgh and Texas).

BP obtains its central position through its involvement in three large CCS projects (in terms of actors), namely Weyburn, Frio Brine and the CO_2 Capture Project (CCP). Until now, the Weyburn project and its related R&D program, is the only commercial-scale CCS project that has been carried out in North America. Since 2000, approximately 1–2 $MtCO_2$ is injected annually to enhance oil recovery from the Weyburn field in Saskatchewan, Canada. The CO_2 that is used in this project is a by-product from a coal gasification plant, located approximately 325 km south of Weyburn, in North Dakota (US). Several American actors are involved in the Weyburn EOR project; e.g. Dakota Gasification Company, Colorado School of Mines, Nexant and Lawrence Berkely National Laboratory (LBNL). These actors have the possibility to transfer the knowledge obtained within the Weyburn cluster (depicted on the left side of the network) with the actors involved the Frio project, depicted at the bottom. Frio Brine is the first project in the US whereby CO_2 is injected into high-permeability sandstone.

The CO_2 Capture Project (CCP) is an international effort led by BP and co-funded by US-DOE. It includes R&D of advanced CO_2 separation and capture technologies in pre-, post- and oxy-combustion. Through its involvement in the CCP, BP is the linking node between the major capture and storage clusters in the network's centre. Some smaller projects that can be identified in the periphery of the network are: the NatCarb project (bottom right), which includes all the major geological surveys in order to identify possible CO_2 sinks; the CO_2 storage test project at Strata's West Pearl Queen oil reservoir in New Mexico (top left); and the COAL-Seq consortium, which is lead by Advanced Resources International (top), and focuses on R&D of CO_2 storage in deep unmineable coal seams and various ECBM processes.[6]

Even though we apply equal time spans for the division of the data and the amount of active projects remains constant between both periods (around 100), the size of the network more than doubles from 89 to 192 unique actors in the second period. The latter can be explained by the implementation of more than 20 small-scale storage field tests that involve a relatively large amount of actors per project. The national laboratories, which play an important role in these projects, can now be found in the core of the network. For example, LBNL has got 67 linkages, which is more than double the amount compared to the first period. Also

---

[5] This restriction is only used for visualization of the network and implies that isolated actors, or isolated components (with less than 5 actors) are not displayed.
[6] Note that these projects are not part of the validation phase field tests depicted in Figure 4-1.

Schlumberger is heavily involved in the partnership projects and therefore obtained the most central position in the network in the second period with 69 linkages; thereby outnumbering other companies like BP, Praxair and Denbury Resources, which all have about 50 linkages in the network.

Due to the considerable size of the field tests, several of them can be identified in the network visualization of the validation phase. For example, SECARB's Central Appalachian Coal Seam Project in Virginia can be found in the upper left of the network. There are more than 20 partners involved in this project, including CNX Gas, Buckhorn Coal, Virginia Tech and Consol Energy. It is notable that other actors involved in smaller coal storage field tests, like the Black Warrior project in Alabama and the Illinois Basin 'Huff 'n Puff' field test are also positioned at the top of the network. This indicates that actors like Denbury Resources, EPRI and Acher Daniels Midland, seek cooperation based on their technological competences, instead of geographical proximity, or organizational background. This notion is strengthened by the clustering of actors involved in oil-bearing and aquifer storage projects right of the centre of the network. For example, Kinder Morgan and Baker Atlas are involved in the Permian Basin EOR project in Texas; and the national laboratories (i.e. LLNL, LANL, and LBNL) are collaborating in the 'Teapot Dome' EOR project in Wyoming. However, the actors involved in the PCORPs' projects that are located in Canada – i.e. the Zama, Fort Nelson and Weyburn EOR projects – are clustered together at the bottom of the network.

On the left side of the network we find the only distinguishable capture clusters. Together with 14 partners Carbozyme Inc. is developing scalable enzyme-based post-combustion capture technology to achieve near-zero emissions from pulverized coal power plants. Furthermore, Visage Energy and SRI International are working together with several partners to develop membranes for pre-combustion based CO_2 capture. Despite the fact that 40% of the projects are capture projects, other capture clusters are not clearly visible in the network. This is mainly caused by the fact that capture projects are of smaller-scale and carried out by single parties or within bilateral partnerships. For example, Praxair is developing oxyfueling together with Alstom and the University of Utah in two separate R&D projects.[7] So the potential for information exchange in R&D of CO_2 capture technologies is rather small if you compare this to the knowledge that is obtained in storage projects, as the storage clusters are highly connected.

Table 4-3 summarizes the descriptive statistics of the network between 2000 and 2008. Over the years we observe a decrease in the number of components, i.e. disconnected parts of the network, and isolated actors. The size of the largest component increased significantly over time. This indicates that the Innovation System is building up. In 2008, 176 actors are connected through the largest component, representing 89% of the total network. The observation from visual inspection that the network has become increasingly connected is confirmed by the mean degree of the network, which increases from 3.45 ties per actor at the end of the characterization phase (2005) to 6.4 at the end of the validation phase (2008). Meaning that more actors cooperate with each other in CCS projects and the potential for

[7] Note that Praxair obtains its central position in the network through its participation into large sequestration projects, like Frio Brine and PCORP's Lignite Field Validation test.

knowledge exchange has increased significantly. Furthermore, we find an (slightly) increasing clustering coefficient in the validation phase.[8] In combination with the increasing path length between actors this could indicate that peripheral actors in the network are becoming stronger connected with each other than to actors in the centre. The decreasing cohesion in the network, but at the same time increasing connectivity between actors, can be interpreted as a stronger focus on core competencies in separate parts of the CCS chain. The latter can be explained by the fact that when an Innovation System matures, groups of actors will look for a certain research or market niche and specialize in specific parts of the value chain.

Table 4-3: Descriptive statistics of CCS actor networks in the US between 2000 and 2008.

	2000	2001	2002	2003	2004	2005	2006	2007	2008
Actors	83	95	121	130	132	123	134	187	198
Number of components	6	6	6	7	8	8	5	4	4
Largest component	47	60	94	93	96	87	110	166	176
Isolates	8	13	19	22	19	18	16	12	8
Mean degree	4.27	4.01	4.44	4.18	4.13	3.65	4.00	5.50	6.41
SD mean degree	3.16	3.16	3.35	3.82	3.78	3.45	3.78	4.66	6.32
Clustering coefficient	0.95	0.94	0.95	0.96	0.94	0.94	0.92	0.96	1.01
Average path length	2.15	2.25	2.83	2.88	2.96	2.89	3.54	3.45	3.73

Figure 4-3 shows that several important shifts can be found in the composition of the network. First of all, we see a growing share of enterprises at the expense of research institutions and universities, indicating that the prominence of technology developers and energy companies is increasing over time. This change is mainly caused by the increasing involvement of oil, gas and coal companies. Also the relative amount of utilities has risen substantially, indicating an increased attention for capture technologies in recent years. The more prominent role of governmental actors in the network, like the EPA, can be explained by the need to resolve regulatory issues that are encountered when demonstrating the technology. These shifts in the actor composition of the CCS network in the US indicate a change from technological R&D towards demonstration and pre-commercialization for CCS.

[8] The overall clustering coefficient is calculated by averaging the clustering coefficients of all actors within the network. The node level clustering coefficients are calculated as the density of the neighbourhood, i.e. the network of actors directly linked to the respective actor [34].

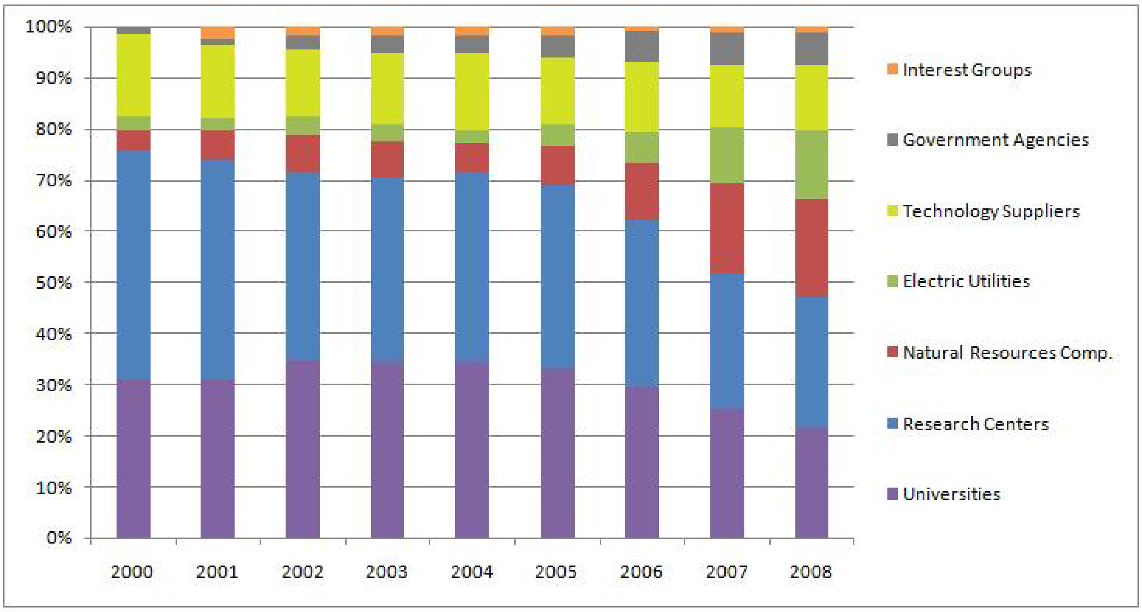


Figure 4-3: Actor composition of CCS networks in the US between 2000 and 2008.

4.4.3. Technological development, demonstration and diffusion

Figure 4-4 shows an increasing amount of funding for CCS research and demonstration over the past decade. Total investments doubled from USD 20 million per year in the beginning of the millennium to USD 40 million in 2005. After that, investments in CCS rose to nearly USD 140 million in 2008. As can be derived from the figure, the steep increase in CCS investments is caused by the relatively large budget that is available for demonstration of CO_2 storage projects through DOE's Carbon Sequestration Program. In terms of storage most funds are allocated to demonstration projects in saline aquifers and hydrocarbon fields. The large investments in CO_2 storage projects related to saline formations can be explained by its large storage potential compared to other reservoir types [4]. Furthermore, considerable experience already exists in CO_2 storage into hydrocarbon fields, through the use of CO_2 for EOR.

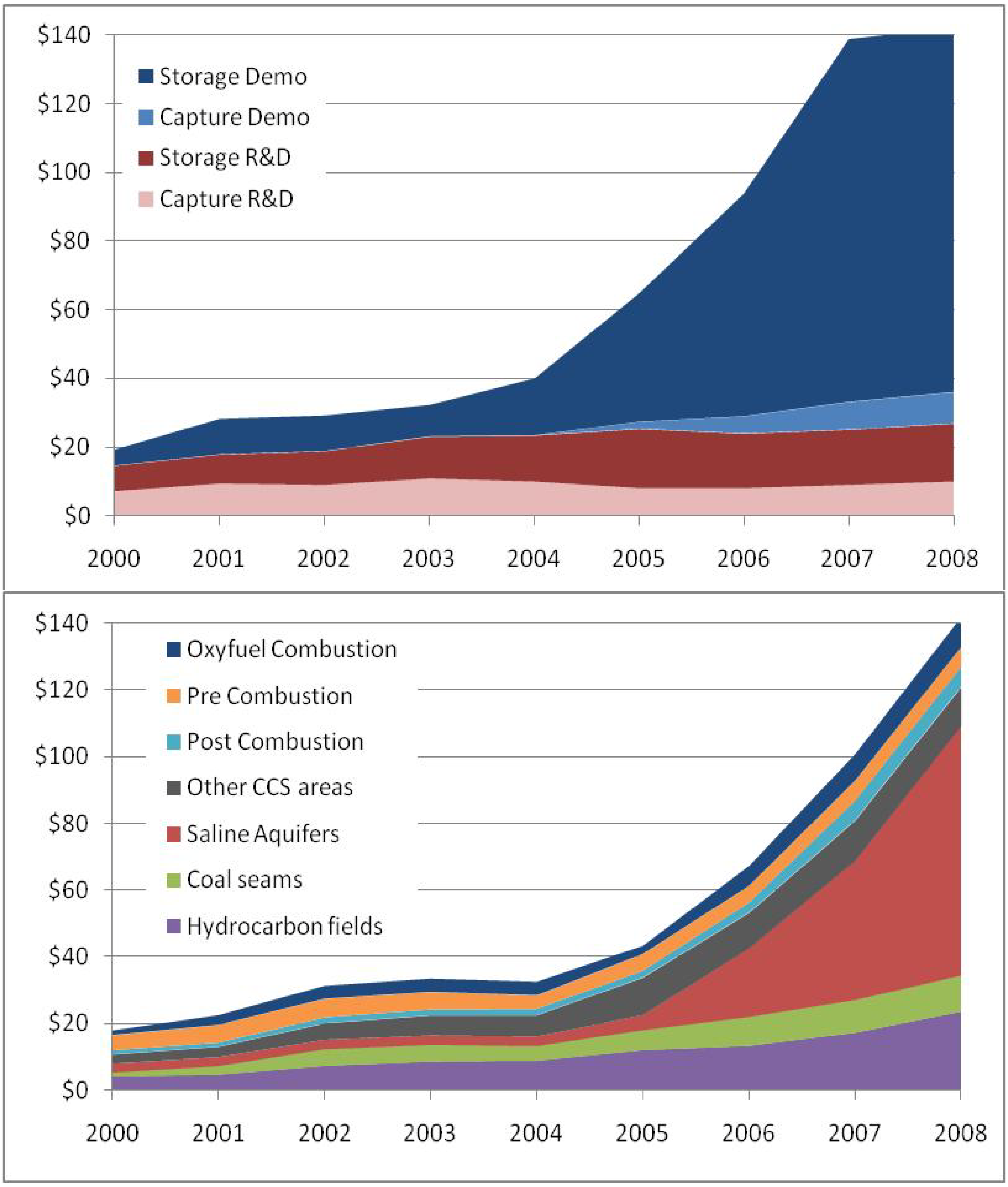


Figure 4-4: Investments in CCS sub-technologies between 2000 and 2008.

Investments in aquifer storage projects will increase further in the near future with the commencement of the deployment phase of the Carbon Sequestration Program. So far, DOE awarded nine grants representing USD 511 million to the regional Partnerships to conduct large-scale field tests, including 8 tests in saline aquifers (see Table 4-4). Major investments into demonstration of CO_2 capture related to power generation are also expected through the US-DOE sponsored Clean Coal Power Initiative and FutureGen efforts.

Table 4-4: RCSPs deployment phase field projects as planned in 2009 [51].

Partnership	Location	Formation	Type	CO_2/year	CO_2 source	Start date
MGSC	Central Illinois	Mount Simon Sandstone	Saline	1 Mt	ADM ethanol facility	December 2009
MRCSP	Western Ohio	Mount Simon/Cincinnati Arch	Saline	1 Mt	TAME ethanol facility	March 2010
PCOR	North Dakota	Williston Basin Carbonate	EOR	1 MT	Basin Electric Antelope Station (post-combustion)	June 2012
PCOR	Fort Nelson (Alberta)	Alberta Basin Sandstone	Saline	4 Mt	Spectra gas processing plant	January 2011
SECARB	Gulf Coast	Tuscaloosa Sandstone	Saline	2.1 Mt	Jackson Dome CO_2 Pipeline/Southern Comp. power plant	January 2009/Jun 2001
SWP	Central Utah	Franham Dome Sandstone	Saline	2 Mt	Farnham Dome natural deposit	March 2010
WestCarb	Kimberlina (California)	Olcese/Vedder Sandstone	Saline	1 Mt	Clean energy systems power plant (oxyfuel)	June 2012
BigSky	Western Wyoming	Moxa Arch Sandstone	Saline	1.5 Mt	Gas processing	January 2010

The FutureGen Alliance, led by the coal-fuelled electric power industry, intends to build a 275 MW coal-fired IGCC power plant with CCS in Mattoon, Illinois. However, in 2007 the costs for FutureGen nearly doubled to USD 1.7 billion and DOE decided in June 2008 to discontinue support for FutureGen and sponsor several smaller pilot projects instead. One year later, in June 2009, DOE reassessed that decision and reached agreement with the Alliance to complete a new preliminary design of the plant and a revised cost estimate. Early 2010 a decision will be made whether to move forward into the subsequent phases of the project. If the FutureGen continues, DOE anticipates committing 1 billion in funds under the American Recovery and Investment Act of 2009 [55]. The remainder of the USD 3.4 billion designated in the Recovery Act for CCS RD&D will finance other industrial-scale CO_2 capture installations at coal-fired power plants and oil refineries. Together with the funding available for early deployment of CCS under the ACES, this will provide a substantial impulse to the relatively low investments in CO_2 capture demonstration projects so far (see Figure 4-4).

In summary can be said that driven by political ambitions, in little over a decade, CCS has changed from a concept of limited interest, to one that is widely regarded as an important option to mitigate climate change. Through the implementation of comprehensive CCS R&D programs and the formation of conducive CCS networks, CO_2 storage operations have advanced towards market maturity, while CO_2 capture technologies are still at brink of being demonstrated at scale.

4.5. Evaluation of Innovation System performance

The patterns in structural growth of the US CCS Innovation System show a consistent build-up of an Innovation System around CCS technologies. This is visible through the increasing availability of funding; changes in legislation; entry of new actors; formation of strong CCS networks; and advancement of the technology. However, the current system structure does not guarantee a thriving development of CCS in the future. The US CCS Innovation System may face challenges that obstruct a further expansion of the system. In order to identify these possible impediments, we use the concept of Innovation System Functions. In our theoretical framework we have shown that these functions make a suitable set of criteria for the performance assessment of an emerging Innovation System. Therefore, the representatives of the main organisations composing the Innovation System have been asked to reflect upon the ongoing activities regarding CCS and rate their level of satisfaction with the fulfilment of each of the seven system functions. All ratings are on a scale of 1–5, whereby 5 equals high level of satisfaction. Based on these expert judgments attributes of the current system structure that are driving, or blocking the future development of CCS technologies can be identified.

4.5.1. Function 1: entrepreneurial activities

Despite the growing amount of demonstration projects and the increasing share of industrial parties in the CCS network, the experts rated their satisfaction of the current fulfilment of this function with a 3.0, which indicates that on average their opinion is moderate. However the relatively high standard deviation (SD) of 1.4 specifies that there is no agreement on this score. The latter can be explained by the difference in technological advancement between capture and storage technologies. Most experts recognize that a significant amount of storage pilot-scale demonstration tests have been carried out, or are planned. Despite this, it is recognized that the variety in storage projects can still be improved. It is argued that even among deep saline formations there is a lot of heterogeneity and that more commercial-scale projects are necessary to improve monitoring techniques and to test the integrity of various reservoir types.

In contrast to storage projects, capture technologies are hardly tested at scale yet. The present high costs of CO_2 capture at power plants – i.e. USD 40–90 per tonne CO_2 captured [41][9] – is 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 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 first to advance technological learning and bring down the costs. Besides demonstrating capture facilities into new power plants, the experts point out that more efforts should be made to deploy retrofit options for existing power plants.

[9] The costs of CO_2 transportation and storage are considerably lower – between USD 10–30/tCO_2 – depending on tradeoffs between injectivity and proximity [41].

Next to demonstrating the different parts of the CCS chain separately, the experts agree on the necessity to implement large-scale integrated CCS projects. Almost all experts referred on this subject to DOE's initial plans of restructuring the FutureGen project and equip multiple smaller-scale coal-fired power plants with CCS. Most of the experts that participated in this study see the original FutureGen as the integrated commercial-scale demonstration project that is crucial in the development of CCS. Therefore they would like to see that the FutureGen Alliance and US-DOE will make the decision to move forward with the project early in 2010.

Related to the issue of project integration is the lacking business interface between the producers of CO_2 – mainly power producers – and those who will be injecting it into the subsurface; mainly oil and gas companies. It is argued that the development of such an intermediary organization is of critical importance for the future success of CCS [6]. 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. Finally, it was noted by many experts that besides investing in large-scale integrated CCS projects, more efforts should be made to 'pick the low hanging fruit' and start more low-cost CCS projects making use of CO_2 from relatively pure industrial CO_2 streams. In short, it is time that entrepreneurs really start 'learning by doing', instead of 'learning by planning'.

4.5.2. Function 2: knowledge development

Although the relative amount of research organizations in the network is decreasing and less new R&D projects started-up recently, experts are satisfied with the knowledge base that has been accumulated over the past decade. On average they scored this function with a 3.9 (SD: 0.8). The main driver behind the fulfilment of this function is the solid funding structure of DOE's Carbon Sequestration Program and the associated RCSPs. The NatCarb project was mentioned as one of the most remarkable R&D outputs of the RCSPs by most of the CCS experts that participated in this study. This joint R&D effort of the RCSPs resulted in an interactive database presenting all potential point sources and geological storage sites for CO_2 in the US and parts of Canada [4]. It is argued that this project has laid the foundation for the storage field tests that are currently carried out in the US.

The knowledge developed regarding storage options is considered as of high quality and sufficient. Some experts noted that more R&D is necessary to develop advanced monitoring techniques and to test the (long-term) integrity of reservoirs as well as CO_2 pipelines. Even though 3400 miles of CO_2 pipelines are already laid out in the US, it is argued that more research is needed to resolve regulatory, financing, siting and safety issues and help ensure that CCS-dedicated CO_2 pipelines are constructed. On the quality and diversity of capture R&D experts are less satisfied. More basic research into new solvents, sorbents and membranes is needed to identify innovative cost-effective capture technologies. Moreover, R&D efforts should diversify towards CO_2 capture related to gas fired generators and retrofit options for existing power plants. Finally, it was noted that more attention should be paid to developments in fuel cell technology as well as in commercial gasification processes, as these research areas offer considerable learning potential for the development of pre-combustion CO_2 capture technology.

Despite the above, the most important stimulus for this function is the implementation of more demonstration projects to test the developed knowledge in commercial-scale experiments. So, it is hard to identify general impediments in the fulfilment of this function other than the need to move several technologies further up the innovation chain to enhance technological learning.

4.5.3. Function 3: knowledge diffusion

Considering the growth and increasing connectivity of the US CCS network over the past decade, it is no surprise that knowledge diffusion is, according to the experts, the best-developed function of the Innovation System with a score of 4.2 (SD: 0.9). The most important drivers for knowledge diffusion are the open knowledge base, conferences, national and international collaborations and the formation of regional partnerships.

The interviewees are satisfied with the amount and quality of shared information in the increasing number of CCS conferences and workshops. The most well known conferences are the annual NETL-conference and the bi-annual International Greenhouse Gas Control Technologies (GHGT) conference series. The largest GHGT conference until 2009 was held in Washington DC, in November 2008. The conference, which hosted nearly 1500 participants from 42 different countries, was organized by MIT in collaboration with the IEA GHG R&D Program, with major sponsorship from the US-DOE.

Next to their involvement in the IEA GHG program, the US-DOE is working with the Department of State in an international ministerial-level panel that discusses the growing body of scientific knowledge on CCS and plans joint projects. This Carbon Sequestration Leadership Forum (CSLF) involves the world's largest blocs of economic activity, including the North America Free Trade Area, the European Union and the leading economies of Asia. Many CSLF recognized projects are meant to identify and further quantify the potential of storage sites. At present, there are 20 projects that have received CSLF recognition, including the RCSPs, the Frio project and the IEA GHG Weyburn-Midale CO_2 Monitoring and Sequestration Project [56]. Other global CCS initiatives that involve American organizations and receive funding through the US-DOE are the GEOSINK project in Ketzin, Germany; the In Salah gas project in Algeria; and the Otway Basin project in Australia [48]. New activities include the first projects in developing nations – two in China and one in India. This is in line with the experts' view that more should be done to develop a complementary set of CCS demonstration projects around the world, including rapidly growing coal-using countries in Asia. An objective that is also strived after by the US led Asia-Pacific Partnership on Clean Development and Climate. This partnership aims to accelerate the development and deployment of clean energy technologies, including CCS.

In terms of national CCS collaborations, the RCSPs fulfil a crucial role in facilitating the exchange of knowledge within CCS networks. Best practices have been made available in order to optimize technological learning. However, several interviewees note that this is mainly true for parties involved in storage projects and less for organizations that develop capture technologies. This is confirmed by the result of our network analysis, which shows a relatively high amount of actors involved in CO_2 storage projects in the centre of the network.

The experts argue that some R&D of capture technologies occurs behind ‘closed doors’ and that the protection of intellectual property hinders an optimal flow of knowledge between the actors. This is mentioned as the most important barrier for the performance of this function and has to be overcome before integrated projects in CCS can be carried out.

4.5.4. Function 4: guidance

On average, the experts rated their satisfaction of this function with a moderate score of 3.2 (SD: 0.9). They are satisfied with the clarity of technological demands articulated by industry towards scientific organizations; the developments in targets and regulations on state and national level, as well as the role of political leaders in advocating the promise of CCS. As part of his “New Energy for America” plan, President Obama wants to develop and deploy CCS as it provides an opportunity to create green jobs. At his website the President stated that “the US-DOE will enter into public private partnerships to develop five first-of-a-kind commercial-scale coal-fired plants with clean CCS technology” [57]. This would be a quarter of the 20 worldwide CCS demonstration projects the G8 called for by 2020 [58].

Even though these envisioned technological trajectories have been documented in several influential Roadmaps [see e.g. 50], it is argued that the industry is not going to invest in CCS unless they can rely on an unambiguous regulatory framework supporting CCS. Such a framework would not only include 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 experts that permitting capture and transportation facilities are not substantially different than for conventional industrial facilities. However, it is anticipated that CO_2 injection can only be partly covered by existing Federal and State legislation on CO_2 for EOR, natural gas storage and acid gas disposal, and that a new set of rules is needed for underground injection and storage of CO_2. The experts argued that additional legislation is most needed with regard to pore space ownership and its interaction with mineral rights, as well as long-term liability, in case CO_2 leakage from the reservoir causes damage to humans or the environment [59, 60].[10]

As mentioned in paragraph 4.1, the ACES Act of 2009 establishes regulations for geological CO_2 storage. The Bill Amends the Clean Air Act and Safe Drinking Water Act to establish rules for geologic storage, including financial responsibility for injected CO_2, monitoring, record keeping, public participation and certification for storage sites. Furthermore, the bill establishes 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 [47].

So, there is strong visionary guidance from political leaders, industry captains and influential scientists regarding the promise of CCS as a low-emission bridge towards a sustainable energy future. Moreover, signs are that regulation and standards that will enable safe and

[10] See Duncan et al. [59] and Wilson et al.[60] for more information on these outstanding regulatory issues.

effective injection of CO_2 for the purposes of storage are within close reach. However, more clear legislation is still needed regarding liability and ownership of the sequestered CO_2.

4.5.5. Function 5: market creation

From the analysis of the Innovation System structure, we know that since the year 2000, CCS technologies have advanced from a science-based technology to an option, of which its separate parts are widely demonstrated by industry. For example, in niche applications such as EOR, whereby relative inexpensive CO_2 from particular industrial operations is utilized to gain extra oil revenues. However, it is unlikely that utilities will adopt CCS on a large-scale until sound climate policies make CO_2 financially worth capturing. It is argued that the main barrier that has been standing in the way for the uptake for integrated commercial-scale CCS projects related to power generation is the absence of a clear regulatory framework that create economic drivers for CCS. The interviewees agreed almost unanimously on this point and therefore rated the fulfilment of this function as weak: score 2.0 (SD: 1.0).

On state level, several initiatives are taken that vary between being committed to reduce GHGs to a multi-state cap-and-trade system. Experts do appreciate these efforts, but they would like to see a federal regulation. The approved ACES Act (H.R. 2545) by the House of Representatives can therefore be seen as a major breakthrough for the creation of a market for CCS. Starting in 2012, ACES should establish annual tonnage limits on CO_2 emissions from large US sources such as electric utilities and oil refineries. Under these caps, GHG emissions must be reduced by 17% by 2020 and 83% by 2050 compared to 2005 levels. To achieve these targets, ACES should establish a cap-and-trade system wherein emission allowances can be traded between participants. This market-based approach provides economic incentives for industry to reduce CO_2 emissions at lowest cost.

Next to introducing electric renewable standards, that require electricity suppliers to produce 20% of its electricity from renewable sources by 2020, ACES uses a combination of regulatory requirements and financial incentives to ensure that new fossil fuel based power plants will operate with CCS technology. ACES requires all new coal plants with a capacity of 250MW or greater that receive permits from 2009 to 2014 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. Plants permitted from 2015 to 2019 must emit less than 500 $kgCO_2$/MWh at the start. 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 [61], implies that the only way to comply with the standards is to use CCS or to switch fuel source (e.g. gas or biomass).

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 to support commercial deployment of CCS [48]. Up to 6 GW of CCS may receive a subsidy of USD 90 per tonne of captured CO_2 for 10 years. Additional allowances are available through a reverse auction, allowing much of the additional CCS projects to receive subsidies greater than USD 50/tCO_2.

In addition to the bonus allowances, ACES establishes 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[11] to issue grants and financial assistance for at least 5 early commercial-scale CCS demonstrations. The importance of financing the first large-scale CCS demonstration projects in order to proof the concept of CCS and lower its costs has been noted by most of the interviewees. They argued that besides creating a clear market for CCS, it is of prime importance that the technology becomes 'market ready'.

4.5.6. Function 6: mobilization of resources

Although investments in CCS have grown substantially over the past decade to a level of roughly USD 140 million in 2008, experts rate their satisfaction on the availability resources with a score of 2.8 (SD: 1.1). Their opinion is that the current availability of financial resources is not sufficient to realize commercial-scale integrated CCS demonstration projects. Taking into account that the carbon price (if there is going to be one) in the early years might not be high or stable enough to trigger enough CCS investment, additional incentives will be needed.

With the half a billion dollar DOE funding for the deployment phase of the Carbon Sequestration Program, several of the regional partnerships have started ambitious collaborations with power generators (see also Section 4.3, Table 4-4). The largest project so far would capture up to 1 $MtCO_2$ annually from the Antelope Valley Station in North Dakota and is expected to start operation in 2012. The US-DOE sponsors USD 100 million of the project investment costs and the Department of Agriculture has offered USD 300 million in loans to the project developers, which will partly be paid back by the extra revenue generated from CO_2 EOR operations [62].

In February 2009, a financial boost for CCS came from the US government's Recovery Act funds for CCS research and demonstration. Much of the USD 3.4 billion designated for fossil fuel R&D – about five times what the DOE now spends annually on such research – will finance commercial-scale CO_2 capture installations at coal-fired power plants and oil refineries. 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 [63].

The DOE approach requires large investments from industry, while the current trend is showing the opposite; industry is reluctant to invest in CCS as they await carbon policies. In order to provide investor certainty, it is believed that the most appropriate form would be a direct cash subsidy for commercial-scale CCS projects whose level declines as cumulative deployment increases. According to the experts, this approach would offer the highest incentives to early projects that have not yet benefited from scale economies and technological learning.

---

[11] Rates are set at 0.043 dollar cent for coal based electricity, 0.022 cents for natural gas and 0.032 cents for oil [47].

In contrast to the availability of financial capital, it is argued that there is enough trained and educated personnel that can work in the field of CCS. However, the experts are a little worried about the availability of human capital in the future, as CCS has the potential to become an industrial sector that is comparable to the current oil and gas industry. Especially if you take into account that current petroleum-engineering departments are already operating up or above capacity [64]. Experts see the solution for this potential problem to introduce educational programs at universities to get future engineers acquainted with specific CCS knowledge.

4.5.7. Function 7: creation of legitimacy

The current fulfilment of this function is scored 2.9. Although moderate, the creation of legitimacy is a somewhat difficult function in the US CCS Innovation System. The legitimacy for CCS is different for each of the stakeholders, ranging from politicians, coal lobby groups and communities that are encountered with storage projects under their back yards. This is one of the reasons that the scores on this function diverge from 1 to 5 causing a relatively high standard deviation of 1.4.

As politicians embrace CCS as one of the options in a broad mitigation portfolio, necessary to reach their climate ambitions, and the fossil fuel industries see CCS as an opportunity to stay in business in a low carbon economy, the major bottleneck in the fulfilment of this function lies in possible public resistance towards the technology. Even thought the fast majority of the US citizens are not familiar with the concept of CCS, the issue of public perception is regarded as very important for the future deployment of the technology [65]. It is argued by the experts 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.

CCS is often portrayed as an experimental technology by sceptics, and as a lifeline for the continued use of coal and other fossil fuels that detracts from efforts to shift to a truly sustainable energy system [66].[12] Furthermore, local communities living close to a geological storage site are concerned with the risks involved with CO_2 transportation, injection and storage. Even though CO_2 is a normal constituent of the atmosphere and safely used in a variety of industrial applications (e.g. food preservation), CO_2 is dangerous to humans at ambient concentrations greater than about 3%, and must be safely managed in order to avoid such concentrations [53]. Many experts, including the US EPA, have argued that a rapid release of injected CO_2, which could lead to such concentrations, is unlikely because of the physical characteristics of geologic confining units [53]. Yet the perceived risk of such a release is significant.

In relation to the issue of risk perception, the interviewees often referred to BP's Carson project in California. Early 2006, BP and the Edison Mission Group announced their plans to build a USD 1 billion petroleum coke fuelled power plant in California with a minimum of CO_2 emissions. Despite the fact that BP conducted outreach for 2 years – briefing more than

[12] See for example the short movie ‘Get clean coal clean: a new air refreshner’ by the directors Joel and Ethan Coen, wherein they proclaim that the idea of “clean coal” is, at least for now, nonsense [66].

300 people including federal, state and local officials, community leaders and environmental organizations [67] – local environment groups seized on the project as a rallying point for their opposition to a State bill designed to set standards for CCS. In April 2007, ten environmental justice groups protested to the project, saying "CO_2 releases are deadly for communities".[13]

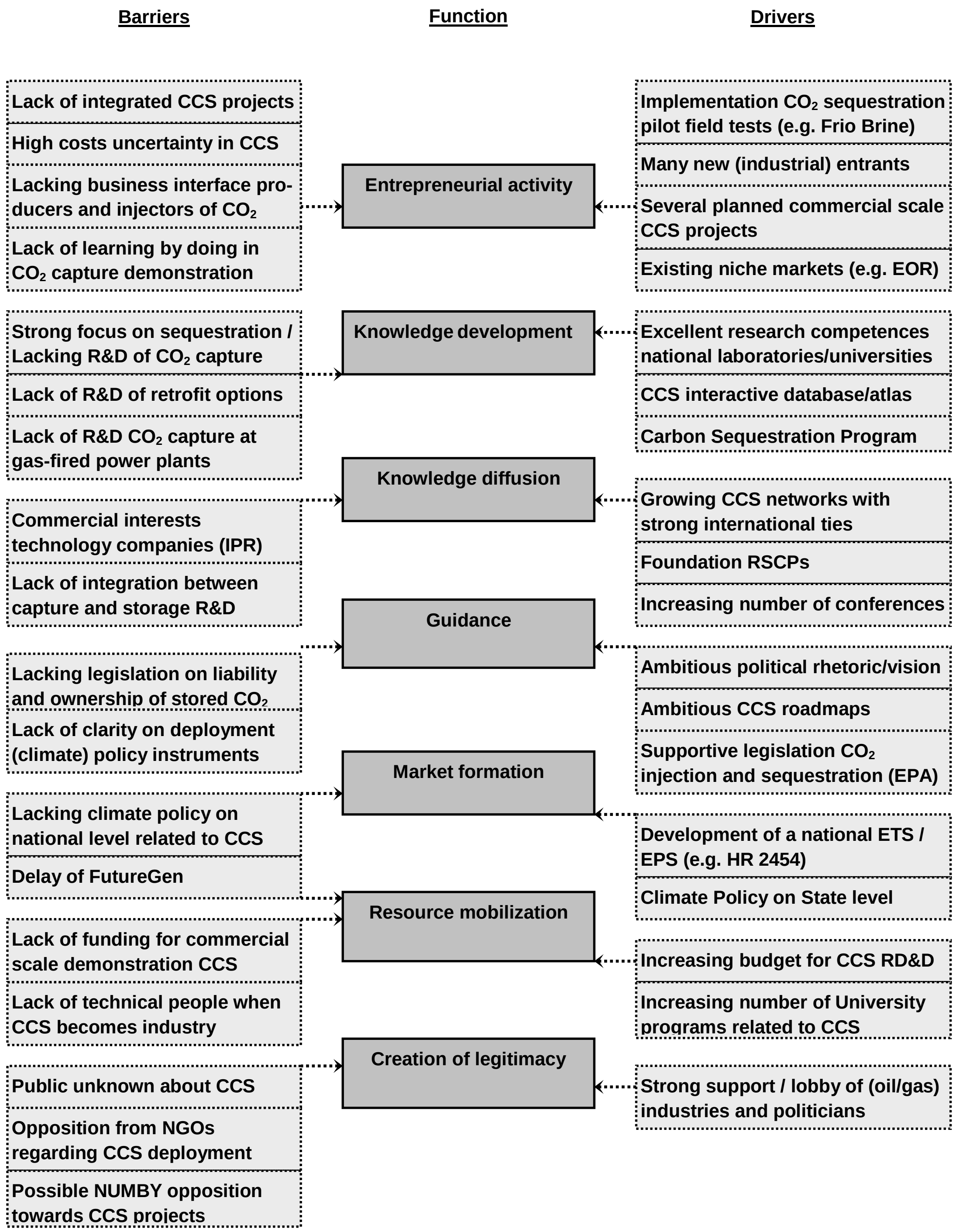
This example points out that in order to increase public support; more should be done to engage the public and environmental NGOs in the siting of CCS projects. Thereby it is of prime importance to pay attention to the significant body of literature that is available on public perception of CCS (see Ashworth et al. [68] for an overview) and to take advantage of successful public outreach strategies applied in other CCS projects, like FutureGen [69]. It is argued that (risk) communication on CCS cannot start early enough and that without public engagement, CCS projects risk being unsiteable. 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. Any communication on CCS needs to be in the context of climate change, namely CCS as part of a portfolio of mitigation options and not at the expense of renewables.

4.6. System intervention: implications for policy

In order to improve the performance of the Innovation System and accelerate the deployment of more advanced CCS concepts in the US, it is necessary to direct policy initiatives at the structural attributes of the system that drive or block a fulfilment of a particular system function (see Figure 4-5). Below we will discuss a policy strategy that would stimulate a thriving development of CCS in the US. This strategy consists of four integrated elements that target different sets of system functions, namely (1) stimulate learning by doing; (2) facilitate coordination and collaboration; (3) create financial and market incentives; and (4) regulate and communicate.

[13] A year later, the project was relocated in close proximity to the Elk Hills oil field in rural Kern County. According to BP the opportunities for EOR where better at this new location. Furthermore this project received USD 308 million funding from DOE Clean Coal Power Initiative in June 2009 [62].

Figure 4-5: Main drivers and barriers for CCS development and deployment in the US as of June 2008.



4.6.1. Stimulate learning by doing (functions 1 and 2)

The performance assessment of the US CCS Innovation System shows that the extensive knowledge base and CCS knowledge networks, accumulated over the past years, have not yet been valorised by entrepreneurs to explore markets for CO_2 capture concepts linked to power generation. In contrast to storage projects, capture technologies are hardly tested at scale. It is argued that besides continuing laboratory R&D of innovative capture techniques and retrofit options, various promising technologies should be demonstrated at commercial-scale to advance technological learning and bring down its costs. Furthermore, it is of prime importance that, besides demonstrating the different parts of the CCS chain separately, a number of integrated large-scale CCS projects are implemented in order to prove the concept.

In contrast to the relatively slow technological advancements in the capture part of the CCS chain, a significant amount of storage field tests have been carried out, or are planned. Despite this, it is recognized that variety among storage projects can still be improved, as more work is needed to advance and commercialize monitoring techniques. This can be done by starting up more low-cost CCS projects that make use of CO_2 from relatively pure industrial CO_2 streams, e.g. refineries and natural gas processing. In short, it is time that entrepreneurs really start learning by doing, instead of 'learning by planning'.

4.6.2. Facilitate coordination and collaboration (function 3)

To facilitate the development of integrated CCS demonstration projects changes in (inter)national collaborative networks are necessary. Despite the growth and the increasing connectivity within the network of actors that are involved in CCS in the US, we see a stronger focus on core competences in separate parts of the CCS value chain. Furthermore, it is recognized that now CCS technologies are maturing, the protection of intellectual property hinders an optimal flow of knowledge between organizations. In order to solve IP issues, integrate the CCS chain, and take optimal advantage of the available learning potential, coordinated action is necessary. More should be done to develop a complementary set of CCS demonstration projects in the US, but also internationally, including rapidly growing coal-using economies like China and India.

Demonstration projects should be designed to maximize and accelerate technological learning by integrating different individual components of a complete CCS system, and enabling transparency of knowledge that would otherwise remain hidden. With the introduction of intermediary organizations, best practices could be made available in order to gain potential cost reductions and ensure consistency in safety and integrity of CCS projects. Such a coordinating body does not necessarily have to be a governmental agency, but might as well be a private enterprise, as there is a lacking business interface between the producers of CO_2, like utilities, and those who will be injecting it into the subsurface, mainly oil and gas companies.

4.6.3. Create financial and market incentives (functions 5 and 6)

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 (investment) costs of power generation with CCS. Therefore, it is necessary that the federal government changes ‘the rules of the game’. It is believed that the proposed nationwide cap-and-trade system – with bonus allowances for CCS projects – in combination with EPS’ for generators 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. It is argued that public private partnerships are the way to go in establishing early commercial-scale CCS demonstration projects. Government agencies can provide investor certainty by funding a substantial part of the billions of dollars necessary to deploy the first set of integrated CCS projects. The level of public financing than declines as cumulative deployment increases. Such a direct subsidy scheme would offer the highest incentives to early projects that have not yet benefited from scale economies, technological improvement and learning.

The foundation of a Carbon Storage Research Corporation, as proposed under the ECAS Act of 2009, provides opportunities to create the necessary financial assistance to implement the first set of integrated CCS projects and the construction of a CO_2 pipeline infrastructure. For now, substantial funds for CCS demonstration have become available through the US government's economic stimulus package. Although essential, we would argue that such investments are futile in the absence of an overarching long-term climate policy. Sound alteration of short-term financial incentives to stimulate learning by doing and long-term market incentives is therefore of prime importance to accelerate the deployment CCS in the US.

4.6.4. Regulate and communicate (functions 4 and 7)

Over the past decade CCS has become an important consideration in US climate policy discussions and political rhetoric. In order to give meaning to their ambitious discourse, political and industrial leaders can foster the implementation of CCS technologies by providing clarity on the set of policy instruments that will be used to meet their ambitions. Such a regulatory framework is not limited to clear climate policies and financial incentives, like the ECAS Act, but should also include regulation and standards that will enable safe and effective CCS projects.

Several states are actively pursuing CCS through implementing environmental regulations. Furthermore, the US EPA already proposed regulation for commercial-scale CO_2 storage that will include standards for site characterization, well construction and operation, monitoring and post-closure care. However, there are some questions that the proposed legislation leaves unanswered. Notably, legal issues around pore space ownership and its interaction with mineral rights, as well as long-term liability for possible environmental damages in case the CO_2might leak from the reservoir. 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 write the rules for broader application of future CCS projects.

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 part 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.

4.7. Discussion

The analysis of the historical growth of the US CCS Innovation System and the evaluation of its current performance have resulted in a policy strategy that may accelerate the deployment of CCS in the US. However, when implementing a specific set of policy instruments one should also take into account the possible effects on the development of other (competing) sustainable energy technologies and vice versa. Moreover, it might be possible that new and more influential Innovation System dynamics start off as part of developments in other countries. Due to the extensive international relationships in this technological field, a policy maker at the national level should be aware of the increasing importance of these global innovation processes for local activities. In order to analyze these global trends in the development of CCS technologies, it is desirable to apply the analytical framework presented in this study to other countries as well. These analyses would not only allow for cross-national comparison on a function level – e.g. differences between R&D expenditures, technological focus, or market incentives – but would also provide an opportunity to learn from other countries in overcoming the obstacles encountered in the development of CCS technologies [70].

Furthermore, this study focuses on a wide variety of aspects that are decisive for successful CCS deployment in order to formulate an overall policy framework. 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 [71] on policies related to the creation of a market for CCS in Europe; Pollak and Wilson [54] on providing regulatory guidance for CCS in the US; Ashworth et al. [68] regarding legitimacy and public acceptance of CCS; or de Coninck et al.

[72] on knowledge diffusion and global technological learning. We would argue that these in depth studies could fill in the guiding policy strategy that is sketched in this study.

Despite the technological and geographical delineations applied in this study, the results contain important insights in the dynamics and performance of the US CCS Innovation System and identified several key policy issues that need to be addressed in order to stimulate the further growth of the system. These insights are not only of specific use for policy decisions regarding the deployment of CCS in the US, but can also be of value for decision makers in other countries that wish to accelerate the development of CCS.

4.8. Concluding remarks

The analysis of the US CCS Innovation System provides insights into the relations between the historical growth of the system and the system's current performance. The results show a remarkable consistent build-up of a national CCS Innovation System. Throughout the evolution of the system, conditions have been supportive for this to happen. Converging perspectives on the importance of CCS in the energy system by researchers, (industrial) entrepreneurs, and governments have resulted in a steady growth of the Innovation System as a whole. This is visible through the entry of new actors in the system; extension of the knowledge base; increasing connectivity in CCS networks; successful entrepreneurial projects; increasing availability of public and private funding into CCS; changes in legislation; creation of strong advocacy coalitions; and a guiding government fostering the development of CCS.

The build-up of a well-performing CCS Innovation System has given the US an international leadership position in the field of CCS. However, it is realized by the experts participating in the study that America's leading role in the development of CCS should not be taken for granted. Their evaluation shows that the extensive knowledge base and knowledge networks, which have been accumulated over the past years, have not yet been valorised by entrepreneurs to explore the market for integrated CCS concepts linked to power generation. It is recognized that CO_2 storage operations have advanced towards market maturity, while CO_2 capture technologies are still at brink of being demonstrated at scale. Therefore, it is argued that the build-up of the Innovation System has entered a critical phase that is decisive for a further thriving development of CCS in the US. The evaluation of the current Innovation System performance identified several barriers that block continuing positive system dynamics and stress the need for an integrated strategy that would target malfunctioning of the Innovation System.

The proposed policy strategy consists of four main elements, namely (1) stimulate learning by doing; (2) facilitate integration and collaboration; (3) create financial and market incentives; and (4) regulate and communicate. In order to provide investor certainty in the near future, it is believed that the most appropriate form would be public private partnerships combined with a direct subsidy for a wide variety of commercial-scale integrated CCS projects whose level declines as cumulative deployment increases. The creation of such public private partnerships would offer the highest incentives to early projects that have not yet benefited from scale economies and technological improvement. In order to bring down the costs of the (first) projects and advance technological learning in commercial-scale CCS applications, (international) cooperation and knowledge exchange is of prime importance. Such a collaborative 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 also help to gain public trust in the technology. Open and effective two-way communication with stakeholders, the media and the general public about benefits, risks and other legitimate concerns should be an integral part of every CCS project plan. Although necessary, we would argue that all these efforts are futile in the absence of overarching long-term climate policies such as the ACES Act of 2009. It is necessary that the federal government changes 'the rules of the game' by implementing a nationwide cap-and-trade system – possibly with bonus allowances for CCS projects – in combination with EPS' for generators. Sound alteration of short-term financial incentives to stimulate learning by doing and long-term market incentives is key in the development and commercialization of CCS technologies in the US.

Acknowledgements

We would like to gratefully acknowledge Granger Morgan and Sean McCoy (Carnegie Mellon University), for their cooperation with Paul Noothout during his internship at the Department of Engineering and Public Policy, Carnegie Mellon University. Furthermore, we thank the participants of the Technology Management and Policy Consortium 2009 in Vancouver for their inspiring comments on earlier versions of this paper. The authors are especially grateful to the interviewees for their willingness to participate in this study and for their valuable contributions. This research is part of the CATO program, the Dutch national research program on CCS.

References

1. van Alphen, K., P.M. Noothout, M.P. Hekkert, and W.C. Turkenburg (2010). *Evaluating the development of carbon capture and storage technologies in the United States.* Renewable and Sustainable Energy Reviews. 14(3): p. 971-986
2. EIA (2009). *Annual energy outlook 2009: With Projections to 2030*, Energy Information Administration: Washington D.C. (USA).
3. IPCC (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*, ed. B. Metz, et al. Cambridge (UK).
4. NETL (2007). *National carbon sequestration atlas of the United States and Canada, National Energy Technology Laboratory*, National Energy Technology Laboratory, United States Department of Energy (DOE): Pittsburgh (USA).
5. Litynski, J.T., S. Plasynski, H.G. McIlvried, C. Mahoney, and R.D. Srivastava (2008). *The United States Department of Energy's Regional Carbon Sequestration Partnerships Program Validation Phase.* Environment International. 34(1): p. 127-138.
6. Hawkins, D., G. Peridas, and J. Steelman (2009). *Twelve years after Sleipner: Moving CCS from hype to pipe.* Energy Procedia. 1(1): p. 4403-4410.
7. Murphy, L.M. and P.L. Edwards (2008). *Bridging the Valley of Death: Transitioning from Public to Private Finance*, National Renewable Energy Laboratory (NREL): Colorado, USA.
8. IPCC (2007). *Climate Change 2007: Mitigation of climate change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. B. Metz, et al. Cambridge University Press. Cambridge (UK), New York (USA).
9. Nelson, R.R. and S.G. Winter (1977). *In search of useful theory of innovation.* Research Policy. 6(1): p. 36-76.
10. Freeman, C. (1995). *The 'National System of Innovation' in historical perspective.* Cambridge Journal of Economics. 19(1): p. 524.
11. Lundvall, B.Å. (1992). *National Systems of innovation: Towards a theory of innovation and interactive learning* Pinter Publishers. London (UK).
12. Kline, S.J. and N.R. Rosenberg (1986). *An overview of innovation*, in *The Positive Sum Strategy Harnessing Technology for Economic Growth*, R. Landau and N. Rosenberg, ed. National Academy Press: Washington D.C. (USA). p. 275-306.
13. Carlsson, B. and R. Stankiewicz (1991). *On the nature, function and composition of technological systems.* Journal of Evolutionary Economics. 1(2): p. 1432-1386.
14. Hekkert, M.P. and S.O. Negro (2009). *Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims.* Technological Forecasting and Social Change. 76(4): p. 584-594.
15. Bergek, A., S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne (2008). *Analyzing the functional dynamics of technological innovation systems: A scheme of analysis.* Research Policy. 37(3): p. 407-429.
16. Hekkert, M.P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann, and R.E.H.M. Smits (2007). *Functions of innovation systems: A new approach for analysing technological change.* Technological Forecasting and Social Change. 74(4): p. 413-432.
17. Edquist, C. (2004). *Reflections on the systems of innovation approach.* Science and Public Policy. 31(6): p. 485-489.
18. Hekkert, M.P., R. Harmsen, and A. de Jong (2007). *Explaining the rapid diffusion of Dutch cogeneration by innovation system functioning.* Energy Policy. 35(9): p. 4677-4687.
19. Jacobsson, S. and A. Bergek (2004). *Transforming the energy sector: the evolution of technological systems in renewable energy technology.* Industrial and Corporate Change 13(5): p. 815–849.
20. Jacobsson, S. and V. Lauber (2006). *The politics and policy of energy system transformation--explaining the German diffusion of renewable energy technology*. Energy Policy. 34(3): p. 256-276.

21. Negro, S.O. and M.P. Hekkert (2008). *Explaining the success of emerging technologies by innovation system functioning: the case of biomass digestion in Germany*. Technology Analysis and Strategic Management. 20(4): p. 456–482.
22. Suurs, R.A.A. and M.P. Hekkert (2009). *Competition between first and second generation technologies: Lessons from the formation of a biofuels innovation system in the Netherlands.* Energy. 34(5): p. 669-679.
23. van Alphen, K., M.P. Hekkert, and W.G.J.H.M. van Sark (2008). *Renewable energy technologies in the Maldives--Realizing the potential.* Renewable and Sustainable Energy Reviews. 12(1): p. 162-180.
24. Jacobsson, S. (2008). *The emergence and troubled growth of a 'biopower' innovation system in Sweden.* Energy Policy. 36: p. 1491–1508.
25. Negro, S.O., M.P. Hekkert, and R.E.H.M. Smits (2008). *Stimulating renewable energy technologies by innovation policy.* Science and Public Policy 35(6): p. 403–415.
26. van Alphen, K., J. van Ruijven, S. Kasa, M. Hekkert, and W. Turkenburg (2009). *The performance of the Norwegian carbon dioxide, capture and storage innovation system.* Energy Policy. 37(1): p. 43-55.
27. Carlsson, B., S. Jacobsson, M. Holmén, and A. Rickne (2002). *Innovation systems: analytical and methodological issues.* Research Policy. 31(2): p. 233-245.
28. Lundvall, B.Å. (2007). *Post script: innovation system research: where it came from and where it might go*, in *National systems of innovation: toward a theory of innovation and interactive learning*, Lundvall B.Å., ed. Aalborg University Department of Business Studies: Aalborg (Denmark).
29. Suurs, R.A.A. and M.P. Hekkert (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): p. 1003-1020.
30. Van de Ven, A.H., D.E. Polley, R. Garud, and S. Venkataraman (1999). *The Innovation Journey*. Oxford University press. New York (USA).
31. Kamp, L.M., R.E.H.M. Smits, and C.D. Andriesse (2004). *Notions on learning applied to wind turbine development in the Netherlands and Denmark.* Energy Policy. 32(14): p. 1625-1637.
32. Deroïan, F. (2002). *Formation of social networks and diffusion of innovations.* Research Policy. 31(5): p. 835-846.
33. Kim, H. and Y. Park (2009). *Structural effects of R&D collaboration network on knowledge diffusion performance.* Expert Systems with Applications. 36(5): p. 8986-8992.
34. Cantner, U. and H. Graf (2006). *The network of innovators in Jena: An application of social network analysis.* Research Policy. 35(4): p. 463-480.
35. Baur, M. (2009). *Thesis: Visone: software for the analysis and visualization of social networks*, University of Karlsruhe: Karlsruhe (Germany).
36. Borgatti, S.P., M.G. Everett, and L.C. Freeman (2009). *Ucinet for Windows: software for social network analysis*, Analytic Technologies: Lexington (USA).
37. NETL (2007). *Carbon Sequestration Project Portfolio 2007*. Available from: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2007/table_contents.pdf.
38. NETL (2008). *Carbon Sequestration Project Portfolio 2008*. Available from: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2008/index.html.
39. IEA (2008). *CO2 capture and storage RD&D projects database*, Greenhouse Gas R&D Programme International Energy Agency: Cheltenham (UK).
40. US DOE (FRED) *Fossil research and engineering database—carbon sequestration research projects*, US Department of Energy (McLean).
41. IEA (2008). *CO2 Capture and Storage: A Key Carbon Abatement Option*. IEA/OECD. Paris (France).
42. Hamilton, M.R., H.J. Herzog, and J.E. Parsons (2009). *Cost and U.S. public policy for new coal power plants with carbon capture and sequestration.* Energy Procedia. 1(1): p. 4487-4494.

43. EIA (2004). *Analysis of the clear skies, clean air planning and clean power acts of 2003*, Energy Information Administration: Washington D.C. (USA).
44. EIA (2007). *Energy market and economic impacts of S.280, the Climate Stewardship and Innovation Act of 2007*, Energy Information Administration: Washington D.C. (USA).
45. EIA (2007). *Energy market and economic impacts of S.1766, the Low Carbon Economy Act of 2007*, Energy Information Administration: Washington D.C. (USA).
46. EIA (2009). *Energy market and economic impacts of S.2191, the Lieberman–Warner Climate Security Act of 2007*, Energy Information Administration: Washington D.C. (USA).
47. Waxman, H.A. and E.J. Markey (2009). *Summary of H.R. 2454, the American Clean Energy and Security Act of 2009*, Pew Centre on Global Climate Change: Arlington (USA).
48. Forbes, S. (2009). *Carbon Capture and Storage and The American Clean Energy and Security Act*, World Resources Institute: Washington D.C. (USA).
49. Bingaman, J. (2009). *S1462: The American Clean Energy Leadership Act of 2009*, Committee on Energy and Natural Resources.
50. NETL (2007). *Carbon Sequestration Technology Roadmap and Program Plan*, National Energy Technology Laboratory, United States Department of Energy (DOE): Pittsburgh (USA).
51. Litynski, J., S. Plasynski, L. Spangler, R. Finley, E. Steadman, D. Ball, K.J. Nemeth, B. McPherson, and L. Myer (2009). *U.S. Department of Energy's Regional Carbon Sequestration Partnership Program: Overview*. Energy Procedia. 1(1): p. 3959-3967.
52. Wassermann, F. and K. Faust (1994). *Social network analysis: methods and applications*. Cambridge University Press. Cambridge (UK).
53. US EPA (2008). *Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO2) Geologic Sequestration (GS) Wells: Proposed Rule*, Federal Register p. 43492–43541.
54. Pollak, M.F. and W.J. Wilson (2009). *Regulating geologic sequestration in the united states: early rules take divergent approaches*. Environmental Science and Technology 43: p. 3035–3041.
55. CRS (2009). *Energy Provisions in the American Recovery and Reinvestment Act of 2009 (P.L. 111-5)*, Congressional Research Reports for the People (CRS): Washington D.C. (USA). p. 23.
56. CSLF (2008). *Carbon Sequestration Leadership Forum Recognized Projects*. Available from: www.cslforum.org.
57. Obama, B. (2008). *Barack Obama and Joe Biden: New Energy for America*, Obama for America.
58. G8 (2008). *Joint Statement by G8 Energy Ministers*: Aomori (Japan).
59. Duncan, I.J., S. Anderson, and J.-P. Nicot (2009). *Pore space ownership issues for CO2 sequestration in the US*. Energy Procedia. 1(1): p. 4427-4431.
60. Wilson, E.J., A.B. Klass, and S. Bergan (2009). *Assessing a Liability Regime for Carbon Capture and Storage*. Energy Procedia. 1(1): p. 4575-4582.
61. Rubin, E.S. (2009). *A Performance Standards Approach to Reducing CO2 Emissions from Electric Power Plants*, Coal Initiative Reports, White Paper Series, Pew Centre on Global Climate Change, Carnegie Mellon University: Arlington (USA).
62. US DOE (2009). *Secretary Chu Announces Two New Projects to Reduce Emissions from Coal Plants*. Available from: http://www.energy.gov/news2009/7559.htm.
63. Charles, D. (2009). *Stimulus gives DOE billions for carbon-capture projects*. Science. 323(5918): p. 1158.
64. Bryant, S. and J. Olson (2009). *Training carbon management engineers: why new educational capacity is the single biggest hurdle for geologic CO2 storage*. Energy Procedia. 1(1): p. 4741-4748.
65. Curry, T.E., S. Ansolabehere, and H.J. Herzog (2007). *A survey of public attitudes towards climate change and climate change mitigation technologies in the United States*, Massachusetts Institute of Technology: Boston (USA).
66. Zeller, T. (2009). *The Coen brothers do clean coal*, New York Times: New York (USA), February 26.

67. Bielicki, J.M. and J.C. Stephens (2008). *Public perception of carbon capture and storage technology*, Harvard Workshop on Public Perception of Carbon Capture and Storage Technology Belfer Center for Science and International Affairs at Harvard University's John F. Kennedy School of Government: Cambridge Massachusetts (USA).
68. Ashworth, P., N. Boughen, M. Mayhew, and F. Millar (2009). *An integrated roadmap of communication activities around carbon capture and storage in Australia and beyond.* Energy Procedia. 1(1): p. 4749-4756.
69. Hund, G. and K. Judd (2008). *Stakeholder Acceptance Issues Concerning CCS*, Presented at the Ninth International Conference on Greenhouse Gas Control Technologies — Lessons Learned from FutureGen: Washington D.C. (USA).
70. van Alphen, K., M.P. Hekkert, and W.C. Turkenburg (2009). *Comparing the development and deployment of carbon capture and storage technologies in Norway, the Netherlands, Australia, Canada and the United States-An innovation system perspective.* Energy Procedia. 1(1): p. 4591-4599.
71. Groenenberg, H. and H. de Coninck (2008). *Effective EU and Member State policies for stimulating CCS.* International Journal of Greenhouse Gas Control. 2(4): p. 653-664.
72. de Coninck, H., J.C. Stephens, and B. Metz (2009). *Global learning on carbon capture and storage: A call for strong international cooperation on CCS demonstration.* Energy Policy. 37(6): p. 2161-2165.

Interlude D

The following chapter presents the results of the fourth case study, i.e. the Canadian CCS Innovation System. This study applies a range of quantitative and qualitative measures to gain insight in the fulfilment of Innovation System Functions. Furthermore, this chapter demonstrates how these insights can be useful to technology managers and policy makers in Canada who wish to strengthen their CCS support programs.

The research presented in this chapter was executed in the period 2008 – June 2009 and was has been submitted for publication in a scientific journal [1]: van Alphen, K., Eveleens, C., Hekkert, M.P., Smits, R.E.H.M., Turkenburg, W. C. *Evaluating the build-up of a carbon capture and storage Innovation System in Canada*.

5. Evaluating the build-up of a carbon capture and storage Innovation System in Canada

Abstract

Led by the growth of Canada's energy sector GHG emissions increased tremendously over the past 20 years. As a technology that reduces CO_2-emissions, while allowing oil and gas industry expansion, carbon capture and storage (CCS) enjoys broad government and industrial support. This study applies the Innovation System Functions approach to provide insight into the wide range of processes that have influenced the development of CCS technologies in Canada between 2000-2009. Furthermore, we demonstrate how these insights can be useful to technology managers and policy makers that wish to strengthen their CCS support programs. The analysis shows that the rapid build-up of an Innovation System around CCS technologies in Canada has entered a critical phase, as entrepreneurs have not yet utilized the extensive knowledge base and knowledge networks, to explore the market for power generation with CCS. In order to move the CCS Innovation System through this present difficult episode and accelerate the deployment of large-scale CCS projects, it is necessary to direct policy initiatives at the identified weak system functions; i.e. market creation and the mobilization of resources. Moreover, regulatory guidance and the creation of legitimacy require improvement. Therefore, we outline a policy strategy that would enhance the performance of the Innovation System by: 1) supporting technological learning; 2) altering short-term financial stimuli and long-term market incentives; and 3) improving supportive regulation and sound communication on CCS.

5.1. Introduction

Canada's oil, natural gas and coal resources place the country firmly on the map of world-class energy locations. At 180 billion barrels of recoverable reserves (170 of which are oil sands), Canada is second to Saudi Arabia in national oil reserves [2]. The country's low cost of energy resources provide important export opportunities and makes domestic heavy industries (like refining, smelting, and manufacturing) internationally competitive. Led by the growth of Canada's energy sector, notably the development of oil sands in Alberta in Western Canada, GHG emissions increased tremendously over the past 20 years. In 2006, Canada's GHG emissions amounted to 721 mega tonnes of CO_2 equivalent ($MtCO_2$-e), which is 22% over 1990 emission levels and 28% above its commitments under the Kyoto Protocol Kyoto target [3].

The importance of fossil fuels in Canada's economy, the security of energy supply, a growing electricity demand and a slow diffusion of renewable energy, are all factors that have led to the increased attention for carbon capture and storage (CCS) technologies. The CCS chain comprises the separation of CO_2 from industrial and energy related sources, transport to a storage location (e.g. saline aquifers and depleted hydrocarbon fields), and long-term isolation from the atmosphere [4]. The provinces that are responsible for most of the increase in GHG emissions are situated on the Western Canadian Sedimentary Basin, a location with a potential to store approximately 3700 $MtCO_2$ in depleted oil and gas reservoirs and 4000Gt CO_2 in deep saline aquifers, which is enough to store decades' worth of Canada's CO_2 emissions. The co-location of Canada's major emission sources and potential storage reservoirs provides an important opportunity for Canada to implement CCS in order to limit its GHG emissions [5].

As a technology that renders oil and gas industry expansion and GHG reduction no longer mutually exclusive, CCS not only enjoys government and industrial support in Canada, but also in other countries that depend heavily on fossil fuels for secure (coal based) electricity generation and export income, notably Western Europe, Australia, and the US [see e.g. 6]. Despite the growing international interest in CCS, no fully integrated power plants with CCS have yet been built at commercial scale. De Coninck et al. [7] argue that a large gap has emerged between the political discourse surrounding the promise of CCS and the scale of technological learning that still needs to occur before the technology can contribute to meaningful CO_2 reductions.

The pattern of difficulty at the demonstration phase, whereby new technologies fail to negotiate the various market and institutional barriers that confront them, is particularly pronounced in comprehensive, capital-intensive technologies, like CCS (ibid). Innovation scholars have argued that this transitional period between basic R&D and commercialization – a period also known as the "Valley of Death" [8] - is very complex and characterized by high technological uncertainty, high capital requirements and many forces that interact and influence the final outcome of this phase. If this period is not well managed, either by policy makers or entrepreneurs, this could lead to the development of technologies that do not match market demands or result in the absence of technological development altogether [9, 10].

One of the frameworks that may provide insight in the process of bridging the technological 'valley of death', is that of Technological Innovation Systems (TIS). This approach implies that a new technology is developed, demonstrated and eventually commercially deployed in the context of an Innovation System. A TIS is defined as the network of actors (organisations) and institutions (norms, regulations) that influences the development and diffusion of emerging technologies [11]. 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 by studying a set of seven key activities or 'system functions' that are decisive for successful technology development: entrepreneurial activities, knowledge development, knowledge diffusion, guidance, market creation, mobilization of resources, and the creation of legitimacy [12]. In earlier empirical work the Innovation System Functions approach has been used effectively to explain why certain technological trajectories of sustainable energy technologies have either become stranded, or passed through the technological 'valley of death' [see e.g. 13, 14-19].

This study applies the Innovation System Functions framework to provide insight into the wide range of processes that drive or block the development of CCS technologies in Canada. Furthermore, we aim to demonstrate how these insights can be useful to technology managers that wish to accelerate the future (commercial) deployment of CCS by strengthening the performance of the CCS Innovation System.

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

5.2. Analytical framework and methods

The basic idea of a Technological Innovation System is based on insights from the broader innovation literature it stems from [see e.g. 20, 21-23], and states that the innovation process is strongly influenced by a network of actors that are developing, advocating or opposing the technology and by an institutional infrastructure that selects, legitimizes, regulates and standardizes the new technology [11]. In a well performing TIS the structural elements of the system –actors, networks and institutions- should be successfully developed and linked together to accelerate technological development [24]. A commonly used indicator for the performance of a TIS is the diffusion (e.g. market share) of the innovative technology or product under study [25]. This indicator however is not suitable for emerging Innovation Systems wherein the system still has to take its form and technology diffusion is absent [26]. Instead, indicators highlighting the state of the build-up the Innovation System are much more important in this phase [27].

Recent studies have shown great progress in understanding the dynamics and performance of an emerging TIS. Following Jacobsson and Johnson [28], Rickne [29], Liu and White [30], Jacobsson et al.[16] , Edquist [31], Hekkert et al., [12], Bergek et al. [25], the build-up, or break-down, of Innovation System structures can be conceptualized in terms of key activities, or system functions; each of which cover a particular aspect of technological innovation (see Table 5-1). The seven system functions are decisive processes that foster the development of a technology and are considered a suitable set of criteria for the performance assessment of an emerging TIS [25]. Furthermore, on the basis of system functions scholars are able to arrive at policy recommendations with the goal to improve system performance and support the development of a specific emerging technology [27].

Table 5-1: Functions of Technological Innovation Systems [12].

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 hetero-geneous 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 favourable tax regimes, consumption quotas, or other public policy activities.
F6. Resource Mobilization	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.

So far, the methods that have been used to analyze the build-up and performance of a TIS are literature review, history event analysis [32], interviews with key actors [25], or a combination of both [33]. We aim to complement these by applying quantitative methods that stem from other fields of innovation research: social network analysis; bibliometric analysis, and project analysis. We apply social network analysis to detect network formation, and gain more insight in the function “knowledge diffusion”. The bibliometric- and project analyses will be used to assess the fulfilment of the functions “knowledge development” and “entrepreneurial activities”. Although the possible benefits of these methods for TIS research has been mentioned several times in literature [see e.g. 26, 27], they have not yet been applied in empirical work to study the build-up of a particular TIS. The methods used in this study are described below.

5.2.1. Interviews and literature review

In order to ascertain to what extent the Innovation System Functions have been fulfilled, we conducted semi-structured interviews with the main stakeholder involved in the development of CCS in Canada. Hereby we made use of a number of indicative questions that provide insight in the fulfilment of the functions (see Table 5-2). In total, 22 interviews have been conducted with senior representatives from industry, research, government and environmental groups in the first half of 2008.[1] With cross-referencing as well as external justification, the validity of the interviewees was guaranteed. The results of the interviews were verified and complemented by an additional literature review of scientific and other 'grey literature' (e.g. professional journals, financial yearbooks, roadmaps and policy papers).

Table 5-2: Indicative questions that reflect the extent to which each function in the Innovation System is fulfilled by the components of the system [see also 25].

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)?

[1]Four experts from industry, government, NGO, research, have been interviewed by phone in the June 2009 to verify the main results and report on major changes in de dynamics of the Canadian CCS TIS since June 2008.

To minimise the personal bias of the researchers and to further assess the system's performance, interviewees had to reflect upon the ongoing activities in the system. The interviewees were 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 also gave their view on what should be done to improve the fulfilment of system functions that are impeding a higher performance of the system. This provides the basis for advice on policy strategies to enhance the development of deployment of CCS.

5.2.2. Project analysis

In order to assess the variety and advancement in the CCS knowledge base a comprehensive project database has been constructed. The database contains over 130 CCS projects that have been carried out in Canada between 2000-2008, involving more than 160 actors. The most important source of information for the construction of our database is the Canadian CCS Compendium [34]. The data is complemented and verified using the CCS database of the IEA GHG R&D program [35]. Additional information has been gathered using various reports, project fact sheets and interviews with project managers[2]. The following data has been recorded for each project in the database:

1. The name and organisational background (e.g. oil and gas industry, universities) of the actors involved in a project.
2. The technological focus of the project, distinguishing between three categories: CO_2 capture, CO_2 storage, and other CCS areas, including CO_2 transportation, public acceptance and policy analysis. The capture projects are then subdivided into post-, pre-, and oxyfuel combustion; and in storage we distinguish three main types of geological reservoirs, i.e. saline aquifers, oil & gas fields (depleted and producing) and coal seams[3].
3. Each project is classified in terms of 'distance to market'. A project is considered: a) basic and applied R&D; b) demonstration (early prototypes up to full-scale working devices) and c) pre-commercial (commercial scale- and integrated demonstration projects).
4. Finally, the start and end date, as well as the costs of the project are recorded in order to gain insight into the distribution of costs among the CCS component technologies over time.

5.2.3. Bibliometric analysis

We systematically analysed the scientific output of Canadian research institutes between 2000 and 2008, as documented in the Scopus abstract and indexing database. The Scopus database covers over 15,000 peer-reviewed journal titles and is thereby the largest of the currently available databases for scientific searches [36]. The analysis included 138 selected articles for

[2] It is recognized by the authors, that some projects are developed exclusively with private funding and that information on these projects is not always available. We will come back to this issue in section 5.5.
[3] Note that CCS projects can fall into multiple categories and that R&D projects related deep-ocean CO_2 storage and CO_2 mineralization are not included in the database.

"CCS" or a combination of "Carbon/CO_2, Capture/Separation, and Storage/Sequestration" in the title, abstract, or key words. Analyzed parameters included affiliation and the technological focus of the study.

5.2.4. Social network analysis

We applied social network analysis to identify the actor networks involved in the Canadian CCS Innovation System between 2000 and 2008. The social network approach assumes that the linkages among actors can favour or impede the development of innovations in the system [37]. The analysis identifies size and connectivity of the network structure as a major factor to help the system evolve [38]. The size of the network is characterized by three measures: number of actors, the size of the largest component –i.e. connected parts of the network- and average distance between actors in the network. The connectivity of the network is determined based on the average number of linkages per actor (mean degree) and the clustering coefficient, a measure to determine the existence of relatively dense clusters in the network [39]. Social network analysis can also be performed on an actor level. The number of linkages to an actor (node degree) and its betweenness (a proximity measure) are centrality measures indicating the position of an actor in the network. The betweenness of an actor is determined by the number of times that it is positioned on the shortest path between other actors.

In this study, two actors are considered to be related when they are involved in the same CCS project. Involvement could take the form of a cooperative R&D effort, a policy network, but also a commercial joint venture. In order to specify the relations between actors in the Innovation System, we made use of our project database (section 2.2). To create a network, an adjacency matrix A was created. In this matrix, actors are placed on top of the columns and rows. If a link exists between actors, this is represented by a positive value in the cell. The Adjacency matrices are then analyzed by specialized network software to visualize the networks, i.e. Visone [40] and UCINET 6 [41].[4]

5.3. Results: the performance of the Canadian CCS Innovation System

This section applies the methods described above to ascertain to what extent the Innovation System Functions have been fulfilled between 2000-2009. For the first three functions –i.e. 'entrepreneurial activity', 'knowledge development' and 'knowledge diffusion', the results of our literature review and interviews with key stakeholders are complemented by the outcomes of the project analysis, bibliometric analysis and social network analysis. Furthermore, we discuss the performance evaluation made by the experts for each of the seven functions. Based on these expert judgments, mechanisms that are currently driving, or blocking the future deployment of CCS in Canada are identified.

[4] For more information on Social Network Analysis and data setup we refer to the widely cited book of Wasserman and Faust [43].

5.3.1. Entrepreneurial activity

Industries in Canada has accumulated decades of experience with underground injection technology through acid gas disposal, and enhanced oil recovery (EOR) whereby CO_2 is injected into oil reservoirs to increase oil production [5, 42]. However, the injected volumes of CO_2 for EOR are relatively small. An exception is the EOR operation in Weyburn, Saskatchewan, where upwards of 2.8 $MtCO_2$/year is stored in the producing oil reservoir. In 1997, the Dakota Gasification Company (US) agreed to transport waste gas (96% CO_2) from its lignite-fired Great Plains Synfuels Plant through a pipeline to the Weyburn oil field, with delivery beginning in 2000 [4]. Currently the project, which is operated by two of Canada's largest oil company Encana, Cenovus and Apache Canada, is considered as one of the three largest CCS projects in the world, along with the Sleipner project in the Norwegian North Sea and the In Salah project in Algeria. Although no other large-scale CCS projects (capturing and storing over 1$MtCO_2$/year) have been fully implemented since the start of Weyburn, many new organisations have entered the Canadian CCS Innovation System since then. The amount of organisations involved in Canadian CCS projects nearly doubled from 62 in 2000 to 120 actors in 2008 [43][5]. With their involvement in CCS pilot and demonstration projects, they have contributed to a considerable amount of entrepreneurial activities regarding CCS in Canada, which we will discuss below.

As an initial step in creating a CO_2 EOR industry, the Albertan Department of Energy introduced in 2004 a five-year program of royalty credits for projects that demonstrate the use of CO_2 for EOR. The reduction of royalty payments of up to 15 million Canadian dollars (CAD)[6] offsets some of the technical and financial risks encountered by CO_2 EOR project developers [44]. Most CCS projects face high initial investments because of the cost to capture CO_2 from large sources (such as oil sands up-graders or power plants) and from investments in pipelines to move the CO_2 to the storage reservoir for injection. Costs are further increased by the need for additional injection wells and upgraded metallurgy to handle CO_2. The introduction of the Albertan royalty credit scheme have resulted in CAD 50 million in additional industry investments in four small-scale CCS projects (see Table 5-3).

Table 5-3: EOR projects supported by the Alberta tax credit scheme [34].

Name/Location	Partners	Injection rate
Pembina Cardium oil reservoir	Penn West, ARC, Alberta Geological Survey, universities of Alberta and Calgary	79 tCO_2/day
Swann Hills	Devon Canada, Apache Canada Ltd	110 tCO_2/day
Enchant Arcs AB CO_2 Pilot Project	Anadarko Canada Corporation	85 tCO_2/day
Zama	PCOR, Apache Canada Ltd	67 tCO_2/day

[5] We will further elaborate on the expansion of CCS networks in Canada in section 5.3.3 'knowledge diffusion'.
[6] As of June 2009, 1 CAD = 0.92 USD and 0.63 Euro.

Next to using CO_2 for EOR, CO_2 rich gases can be utilized to enhance the production of coal bed methane (CBM). By displacing the methane in the coal a storage site for CO_2 is created. Canada has an abundant CBM resource. In Alberta alone, approximately 200 Trillion cubic feet CBM is adsorbed in the coal layers, which is more than 35 times the current annual production of natural gas in Canada [45]. In order to improve the economics of CBM recovery technology the Alberta Research Council (ARC) is leading an international research consortium, which started in 2002 with the design and implementation of a pilot test whereby CO_2 was injected into an existing CBM well, located at Fenn–Big Valley, Alberta [46]. In 2008 the final phase of the program commenced, which includes several multi-well CBM recovery projects. In one of these projects, the ARC is collaborating with Suncor Energy, which is the main operator of the CAD 4 million CO_2 storage and enhanced methane production (CSEMP) pilot project. This first of a kind project started in 2005 and utilizes CO_2 from a fermentation plant to test the technical and economical feasibility of enhanced CBM production from multiple wells [47].

Along with these early investments in value added CCS projects related to CBM recovery and EOR, demonstration of CO_2 storage in saline aquifers has also commencement with the Aquistore project, the Wabamum Area Sequestration Project, the Heartland Area Redwater Project (HARP) and the Fort Nelson Project. The Fort Nelson project will store approximately 1.6 $MtCO_2$/year in North-eastern British Columbia, captured from Spectra Energy's Fort Nelson natural gas processing facility [48]. The HARP is designed to demonstrate the feasibility of CO_2 storage in the Redwater Leduc Reef, northeast of Edmonton, Alberta. This saline aquifer could absorb more than 20 years of CO_2 emissions (approximately 1 $GtCO_2$) from the large emitting facilities - existing and planned - for the Industrial Heartland Area [49].

These aquifer storage projects have received funding from the CAD 230-million ecoENERGY Technology initiative, which was launched in 2007 to increase Canada's supply of clean energy (see Table 5-4). Moreover, in March 2008, the federal government committed CAD 240 million to SaskPower's proposed CCS project, which involves retrofitting part of the Boundary Dam coal fired power station to capture 1 $MtCO_2$/year.[7] When finished, this could be the first commercial-scale post-combustion CO_2 capture demonstration in the world.

[7] The project has been re-sized from an earlier plan to build a 300MW clean coal facility near Estevan (Saskatschewan), which had been shelved because of its escalating cost (from CAD1.5 billion to CAD3.8 billion).

Table 5-4: CCS projects supported through the EcoEnergy technology Initiative [50].

Project name	Lead proponent	Reservoir type	CO_2 Source	Injection rate
Heartland Area Redwater Project (HARP)	ARC Resources	Saline Aquifer	Industrial facilities in heartland Area	>1 Mt/year
Alberta Carbon Trunkline	Enhance Energy	EOR	Fertilizer plant and oil sand upgrader	1.9 Mt/year
Fort Nelson	Spectra Energy	Saline Aquifer	Gas processing	1.3-1.6 Mt/year
Pioneer	TranAlta	EOR	Coal power plant– post combustion	unknown
Belle Plaine - PolyGen	TransCanada	EOR	Coal/Petcoke – pre combustion	4.7 Mt/year
CO_2 in Heavy Oil Reservoirs	Husky Energy Inc.	EOR	Upgrader/ethanol plant	0.3 Mt/year
Alberta Saline Aquifer Project (ASAP) / Genesee Plant	Enbridge and Capital Power Corporation	Saline Aquifer	Coal power plant – post-combustion	1 Mt/year

Next to federal ecoENERGY support program, the provincial Government of Alberta has awarded 3 grants representing CAD 2 billion to construct large-scale CCS facilities in its province by 2015 [51]. Transalta was selected for its plan to retrofit CO_2 capture on to a soon to be completed coal-fired power station, using Alstom's chilled ammonia capture technology (see also Table 5-4). The CO_2 from this Pioneer project will then be used for EOR. The second project receiving funding is the Alberta Carbon Trunk Line. This project, which is lead by Enhance Energy, involves the capture of CO_2 from two sources: a large fertilizer plant operated by Agrium and North West's oil sands upgrading facility in order to demonstrate the feasibility of a single pipeline network to collect CO_2 from a large number of industrial emitters in the Alberta Industrial Heartland. The CO_2 will be transported to oil reservoirs in central Alberta and utilized for EOR purposes, simultaneously storing up to 5 $MtCO_2$/year [52]. The third grant is awarded to a Shell, Chevron and Marathon Oil Sands for the development of their Quest project. In this project CO_2 will be captured from the Scotford upgrader near Fort Saskatchewan and used for EOR operations [53]. The fourth and last project receiving money under Alberta CCS funding program is the Swan Hills Synfuels CCS Project that is an in-situ coal gasification project, where the syngas will be used for power generation, and the resulting CO2 will be captured and used for EOR.

5.3.1.1. Expert evaluation of entrepreneurial activity

Interviewees rated their satisfaction with the fulfilment of the function 'entrepreneurial activity' as 3.2 out of 5, which is relatively high compared to other functions. Most experts recognize the significant importance of CCS demonstration projects that are being carried out, or are still planned, and confirm the increasing amount of (industrial) organisations involved in CCS. Oil and gas firms as well as power suppliers are regarded as key players in the Canadian CCS Innovation System, in the sense that they have the financial resources, relevant experience, and the opportunity for developing the technology.

It is argued that the Weyburn project has shown what is possible, not just in terms of storage but in EOR as well, and that this has triggered many other enterprises to engage in CCS projects. However, experts would like to see more entrepreneurs engaging in integrated CCS projects related to power production, along with 'picking low hanging fruit' by investing in other relatively low-cost CCS projects. Furthermore, it was noted by several of the interviewees that the lack of a 'backbone' CO_2 infrastructure hampers the implementation of more entrepreneurial experiments with the technology. Therefore they welcome that the Integrated CO_2 Network, a coalition of major emitters in the oil and gas and coal-fired power sectors, has formulated the goal of creating such a pipeline infrastructure. It is argued by most of the interviewees that such coalitions provide a crucial interface between the producers of CO_2 –e.g. power producers– and those who will be injecting it into the subsurface; mainly oil and gas companies.

5.3.2. Knowledge development

Many R&D projects have been initiated since the beginning of the millennium, starting with 7 projects in 2000 to nearly 80 projects in 2008. Figure 5-1 shows an increasing amount of investments in CCS R&D over this period to nearly CAD 60 million in 2008. The majority of this money has been invested in applied R&D related to large-scale CO_2 storage operations.

The most significant R&D project in Canada is the IEA GHG programme's Weyburn-Midale monitoring and storage project. In this project a large group of international actors gains practical knowledge at Cenovus' and Apache Canada's EOR project site. Applied R&D is further stimulated by the CCS projects supported under the Albertan royalty credits scheme and the ecoEnergy technology initiative (see Tables 5-2 and 5-3). Also the earlier mentioned ARC lead ECBM pilot projects include a major R&D component. In terms of capture there are several important R&D projects that are centred around the Petroleum Technology Research Centre, the University of Regina (mainly post-combustion), and the oxyfuel pilot plant operated by the CANMET Energy Technology Centre-Ottawa (CETC-O).

Figure 5-1 shows an increasing variety in the Canadian CCS knowledge base, as more investments are made in aquifer storage projects and R&D in pre-combustion CO_2 capture. Furthermore, the amount of studies that focus on non-technical aspects of CCS is increasing over time ('other category'). It seems that in recent years, more funds are available for road mapping exercises, as well as research into regulatory issues and public attitudes towards CSS. The bibliometric analysis confirms the increased attention for non-technical aspects of CCS. The relative amount of non-technical papers increased from 3% between 2000-2004 to 8% in the second period (2005-2008).

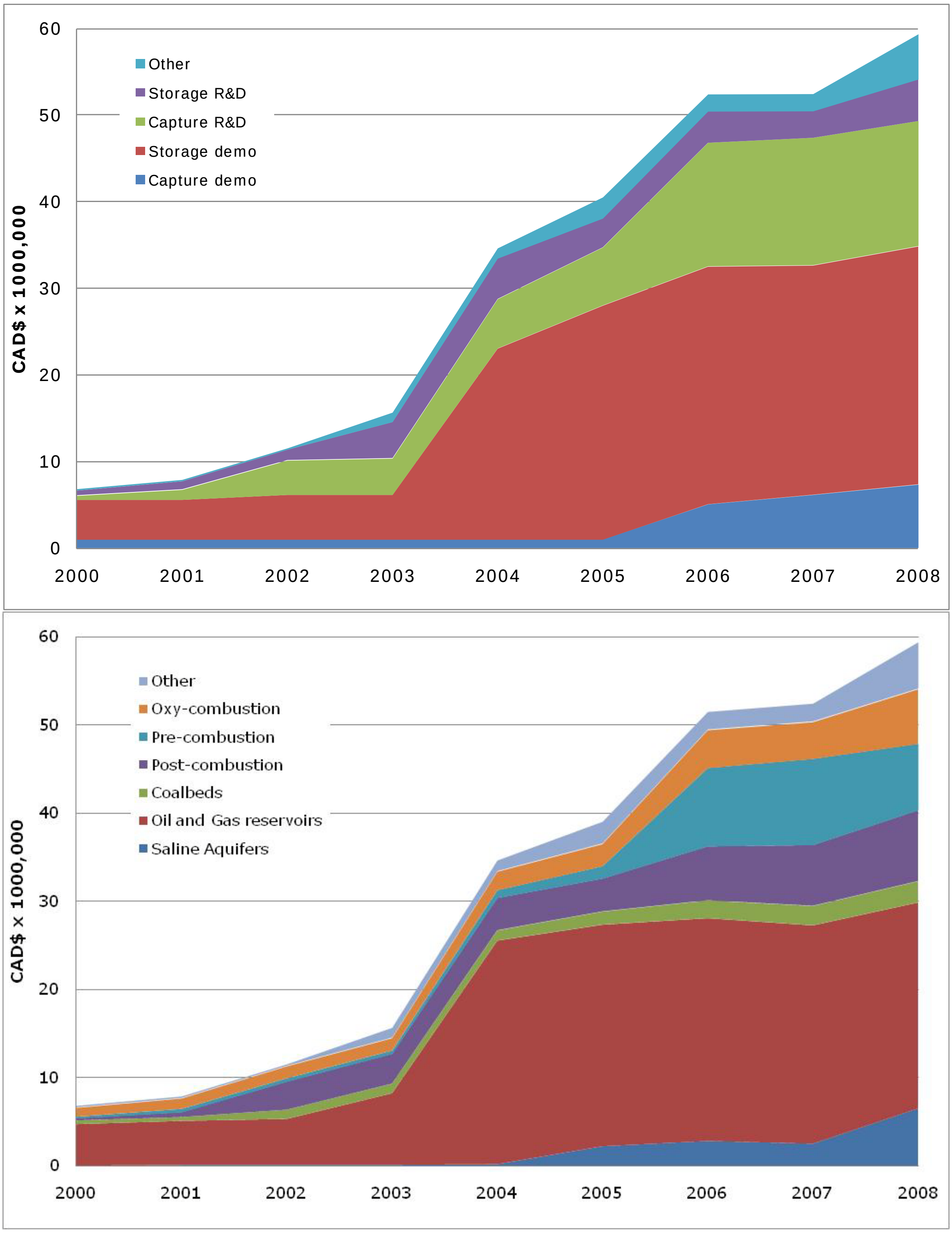


Figure 5-1: Investments in CCS sub-technologies between 2000-2008.

Figure 5-2 also shows that the focus of scientific publications has switched from studies focusing on CO_2 storage towards research into capture technologies. The latter can be explained by the fact that CO_2 storage is now increasingly tested in large-scale projects operated by private industries, while capture technologies are still mainly in the R&D phase, a trend that was confirmed by the experts surveyed in this study.

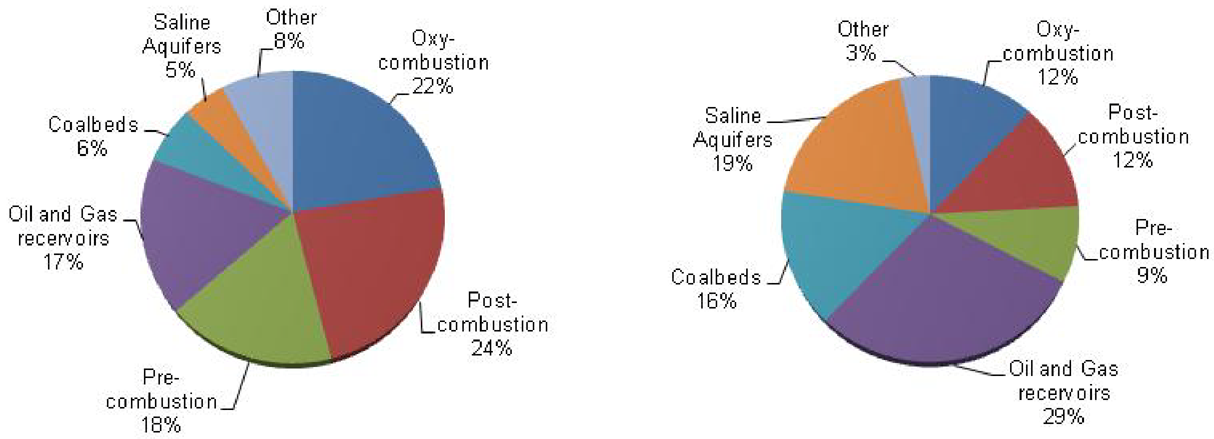


Figure 5-2: Shifts in research focus of scientific publications by Canadian research institutes. Based on a total of 64 articles between 2000-2004 and 74 articles published between 2005-2008.

5.3.2.1. Expert evaluation of knowledge development

Although the relative amount of research organizations in the network is decreasing and less new R&D projects have started-up recently, experts 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 score of all functions. Despite this, the experts participating in this study stressed the need to continue R&D for all components of the CCS value chain.

The knowledge developed regarding CO_2 storage is considered to be of high standards. According to the experts, this is the result of a rich history of oil and gas activities as well as the scientific quality of Canadian research institutes. In order to advance the current knowledge regarding CO_2 storage, experts identified several research priorities for the future, including the development of advanced monitoring, measurement and verification (MMV) technologies, like remote sensing and subsurface biological and chemical tools. Furthermore, improvement is needed in validating numerical models to determine the (long-term) integrity for a large variety of reservoir types. Finally, several experts have stressed the need to complete the Canadian CO_2 storage atlas to get an overview of the most suitable storage sites in Canada.

In terms of R&D for CO_2 capture technologies, the experts applaud the work done by CETC-O and the University of Regina. However, it is realized that more basic research into new solvents, sorbents, catalysts and membranes is needed to identify innovative cost-effective capture technologies. Moreover, R&D efforts should diversify towards CO_2 capture related to gas fired generators (instead of coal) and retrofit options for existing power plants. Overall, interviewees argue that capture knowledge in Canada is not the world's best, but sufficient in order to keep up with international developments in this area.

While advocating the continuation of basic research, the respondents once again stress the need to implement large-scale CCS projects that integrate CO_2 capture at power plants and oil sands upgraders. It is argued that the most important stimulus for this function is to test the developed knowledge (in particular regarding all three major capture options) under real world conditions; not only to increase technological learning, but also to gain experience with the regulatory requirements of such projects and to improve public outreach strategies.

5.3.3. Knowledge diffusion

Both the increasing amount of funds available for CCS RD&D and the cooperative nature of CCS projects have positively influenced the growth and connectivity of CCS networks in Canada. Figure 5-3 visualizes the Canadian CCS network between 2000-2004 and 2005-2008. In the visualized networks, the nodes are the actors and the edges are the result from cooperation in CCS projects. The network visualizes only actors that have five or more linkages. The number of linkages (degree) determines the size of a node; the width of an edge is proportional to the number of projects two actors are cooperating in. For example, in the first period (2004-2008), Encana (since 2008 better named Cenovus) is positioned in the centre of the network with 82 linkages.

EnCana (now named Cenovus) obtains its central position in the network through its involvement in three large CCS projects (in terms of actors): the Weyburn monitoring R&D project; the ECBM project led by the ARC; and their participation in the University of Regina International Test Centre Consortium Program. The 1st phase of the Weyburn project involves 26 actors and most of them are depicted on the left side of the network. The consortium includes geological surveys from various countries (e.g. Canada, UK, and Denmark), as well as research organisations like Ecomaters and the Canadian Energy Research Institute (CERI). Most of the 28 actors involved in ARC's CBM project are depicted in the bottom right corner of the network. These are mainly natural resource companies, like Burlington, Exxon, Husky and Conoco, but also foreign research organisations like the Netherlands Organisation for Applied Scientific Research (TNO) and Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO).[8] Most of the 18 actors that are participating in the University of Regina International Test Centre consortium are depicted in the upper right corner of the network. This cluster includes several technology companies like Babcock & Wilcox (B&W), HTC pure energy and Fluor Daniel. Note that the Universities of Calgary and Regina, as well as the government of Saskatchewan and the Petroleum Technology Research Centre (PTRC) are involved in both the Weyburn project and the University of Regina International Test Centre and are therefore positioned between these two clusters.

Besides the three large CCS projects described above, we identified 53 other projects between 2000 and 2004. Notable CCS consortia are the US-Canadian Zero Emission Coal Alliance

[8] Note that the Canadian CCS network includes a substantial number of foreign actors. Approximately 30 non-Canadian actors are active in both periods, representing more than a quarter of the total network. Half of these foreign organizations are US based and are directly involved in Canadian projects, or part of US-Canadian partnerships, like the ZECA and the Plains CO2 Reduction Partnership (PCOR).

(ZECA) and the Canadian Clean Coal Power Coalition (CCPC), which include power companies like ATCO, Saskpower, Emera, Epcor, TransAlta and Nova Scotia Power. These consortia perform research and demonstration projects of several promising capture technologies, including coal gasification, amine solvent stripping, and oxyfuel combustion. Therefore, it is no surprise that the other major player in gasification and oxyfuel combustion research (CETC-O) is positioned in close proximity to these power suppliers.

The size of the network increases from 92 unique organizations in the first period to 132 in the second. The latter can be explained by the increasing number of CO_2 storage pilot projects that involve a relatively large amount of actors per project. More industrial actors, which play an important role in these projects, can be found in the core of the network. For example, EPCOR (since 2009 called Capital Power Corporation) and BP both have 90 linkages, which is more than double the number of linkages compared to the first period. Transalta obtained the most central position in the network between 2005-2008 with 109 linkages thereby outnumbering other companies like Schlumberger and Suncor, which both have about 70 linkages in the network.

Due to the considerable size of the consortia involved in the CCS projects, several of them can be identified in the network visualization of the second period. For example, the majority of the 30 actors involved in the Alberta Saline Aquifer Project are situated in the upper right of the network, including major oil companies, like Total, Chevron StatoilHydro. It is notable that actors involved in other EOR projects, like Zama; Pembina; Shell Quest; and Weyburn phase two, are also positioned in the top right corner of the network. This indicates that actors seek cooperation based on their technological competences. This notion is strengthened by the clustering of actors involved in CBM projects at the bottom of the network (e.g. Husky, Suncor and Burlington). On the left side of the network we find the only evident capture clusters, which are centered around the University of Regina’s ITC (12 projects) and the oxyfuel research centre lead by CETC-O (17 projects). Note that the majority of actors clustered around these capture projects are research organizations, universities and utilities, while natural resource companies are dominant in the visible storage clusters.

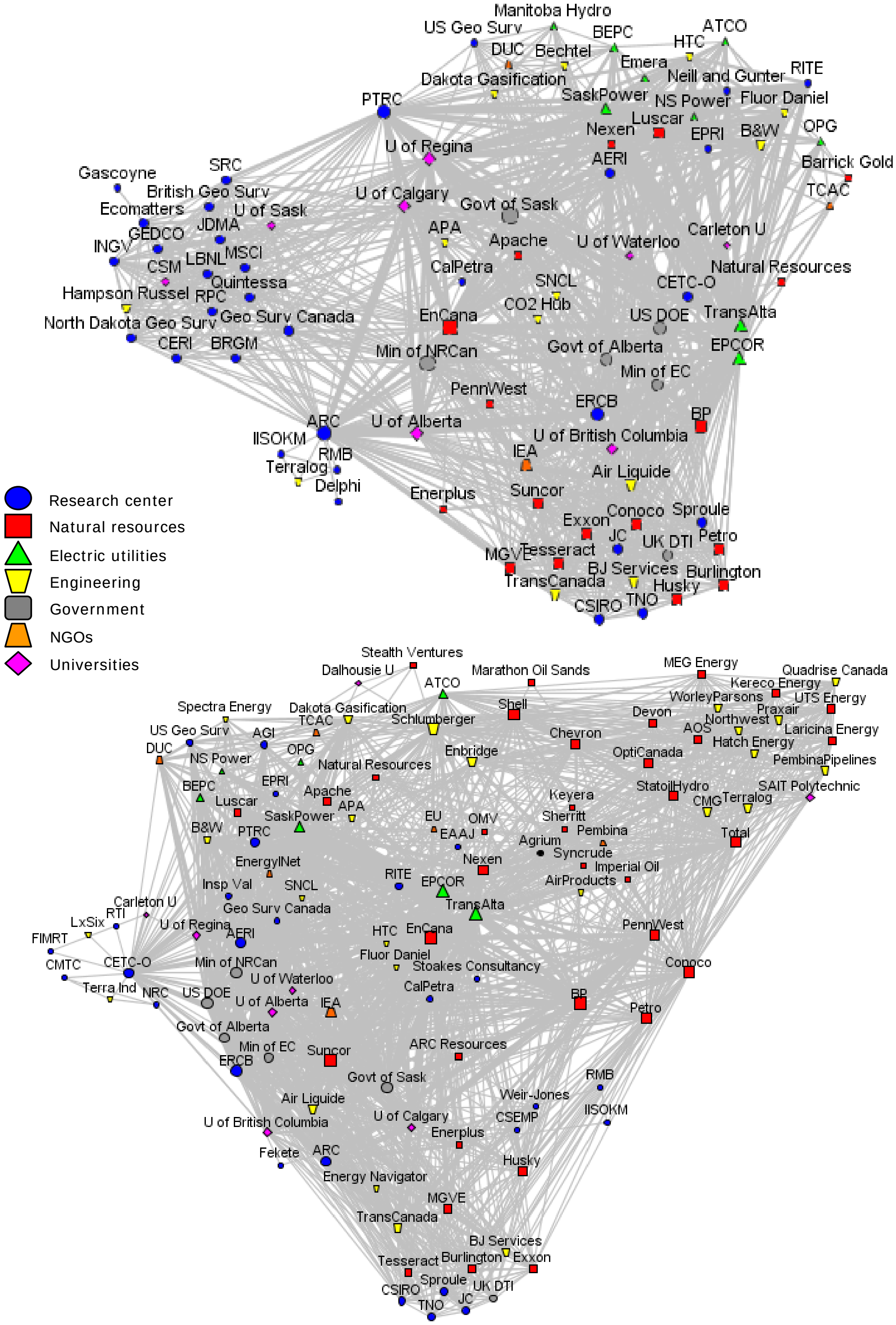


Figure 5-3: CCS actor networks in Canada between 2000-2004 (top) and 2005-2008 (bottom).

Table 5-5 summarizes the descriptive statistics of the network between 2000 and 2008. The increasing size of the network in terms of actors indicates that the Innovation System is building up. The observation, based on visual inspection, that the network has become increasingly connected is confirmed by the average number of linkages per actor (mean degree), which has increased from 27.5 ties per actor in 2000 to 32.8 in the beginning of 2009. This means that more actors cooperate with each other in CCS projects and the potential for knowledge exchange has risen. Furthermore, we find an increasing clustering coefficient over time. The clustering coefficient indicates to what extent there are relatively dense groups within the total network (neighbourhood density). In combination with the increasing path length between actors this indicates that peripheral actors in the network are becoming more strongly connected to each other than to actors in the centre. The combination of increasing connectivity within the total network and - at the same time- a decreasing cohesion can be interpreted as a stronger focus on core competencies in specific CCS components. The latter can be explained by the fact that when an Innovation System matures, groups of actors will look for specific research- or market niches and specialize in separate parts of the CCS value chain.

Table 5-5: Descriptive statistics of the CCS actor networks in Canada between 2000-2008.

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008
Actors	62	67	80	88	96	99	105	110	119
Largest component (%)	100	97	95	94	94	93	93	96	98
Mean Degree	27.5	28.2	28.4	28.6	30.7	31.2	31.9	32.1	32.8
Clustering Coefficient	1.02	1.07	1.09	1.09	1.23	1.31	1.33	1.35	1.38
Pathlength	1.68	1.64	1.72	1.75	1.80	1.92	1.93	1.95	1.96

Figure 5-4 shows that several important shifts can be found in the composition of the network. First of all, we see a growing share of private industries at the expense of research institutions and universities, indicating that the prominence of technology developers and energy companies is increasing over time. The more prominent position of oil and gas firms in the network – e.g. TransAlta, Shell, Encana, and BP – is confirmed by Figure 5-5, which shows the centrality of organisation based on the number of direct linkages in the network. The size of the node reflects the actor's betweenness. For example, in the second period the CETC-O has a lower amount of direct linkages than the actors positioned in the centre of the network, but this organization finds itself many times on the shortest path between other actors in the network and may therefore fulfil an important role as 'knowledge broker' within the network.

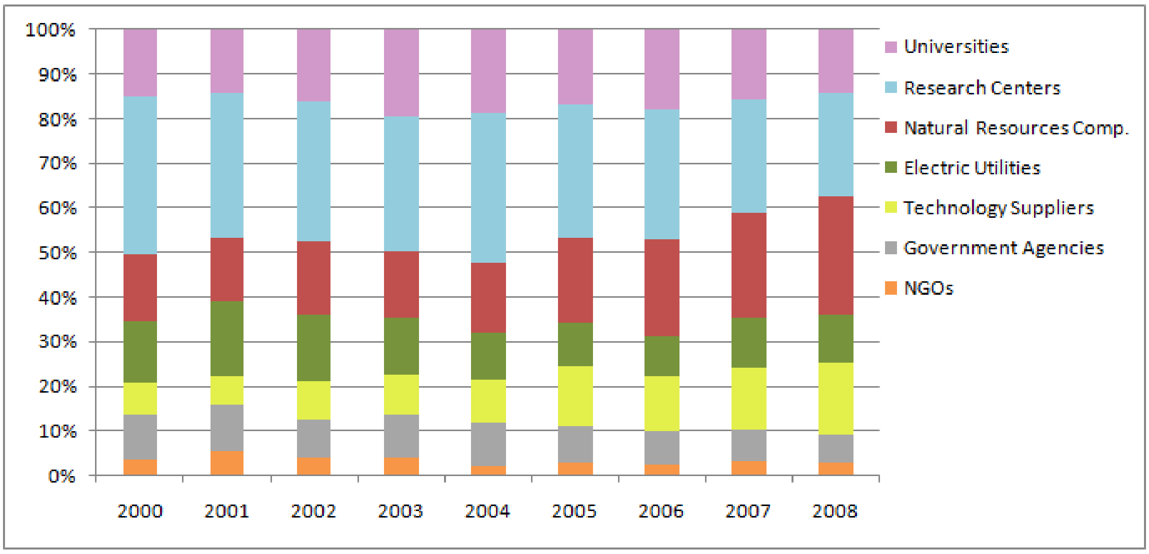


Figure 5-4: Number of actors and composition of the CCS networks in Canada between 2000-2008.

Figures 5-4 and 5-5 also show that the share of supportive industries –mainly technology providers– has increased over time. Part of these technology providers are established firms, like Schlumberger, Babcock and Wilcox, Air Liquide and SNC Lavalin. In the periphery of the network, however new firms that base their future on a specific part of the CCS value chain can be identified, e.g. HTC Purenergy, Cansolve and CO_2 Solutions. The increasing number of new specialized firms entering the system, as well as the more central position of private enterprises in the Canadian CCS network indicates a change from an R&D based system towards an Innovation System that is conducive to the commercialization of CCS technologies.

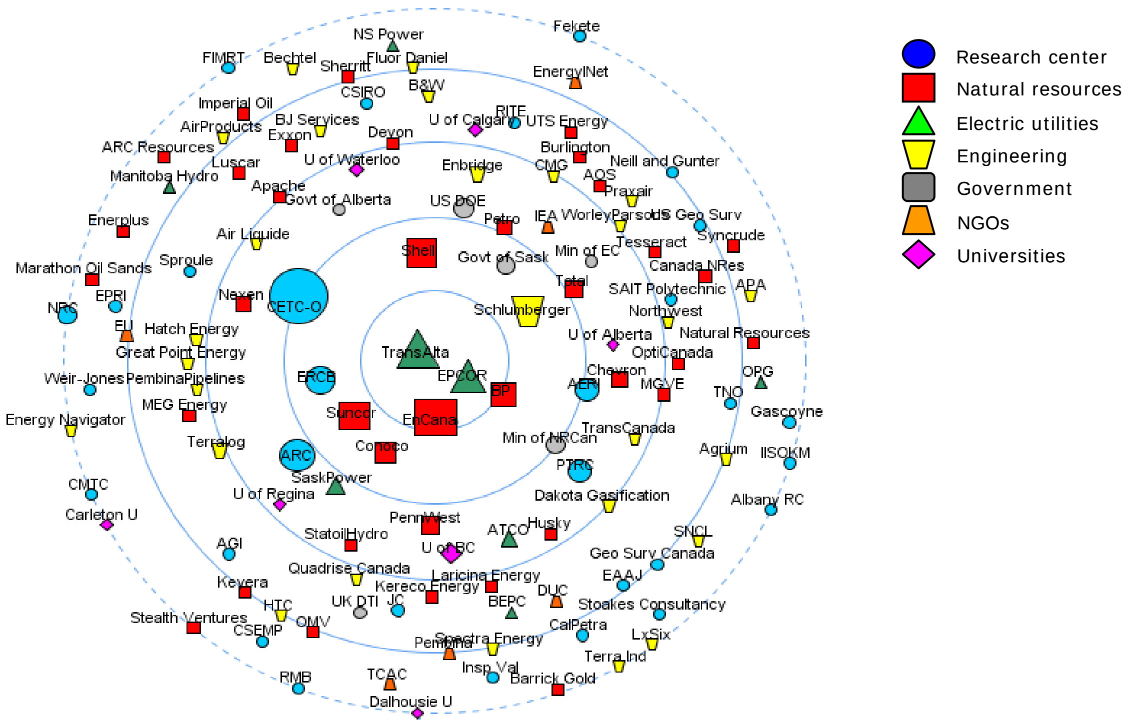


Figure 5-5: Prominence of actors in the Canadian CCS networks between 2005-2008. The prominence of actors is determined by the number of linkages (position) and the betweennes measure (size).

5.3.3.1. Expert evaluation of knowledge diffusion

Considering the growth and increasing connectivity of the Canadian CCS network over the past decade, it is no surprise that the function “knowledge diffusion” is rated highly by the respondents: 3.5 out of 5. The most important drivers for knowledge diffusion are the open knowledge base, conferences, as well as domestic and international CCS partnerships. These partnerships are considered crucial for sharing the relatively high costs (and investment risks) related to CCS project development, but also to solving technological challenges, which require integration of different fields of expertise.

It is very much appreciated by the experts that strong CCS consortia exist in Canada. CCS network organizations like ICO_2N, the Canadian Clean Power Coalition (CCPC), the Canadian CO_2 Capture and Storage Technology Network (CCCSN), and the Petroleum Technology Alliance Canada (PTAC) contribute to the fulfilment of this function by the regular meetings they organize and the newsletters they distribute among their members. Furthermore, it was noted that more consultants are entering the CCS network, who can move relatively freely from one project to another and thereby play an important role for knowledge exchange. Other examples of platforms for knowledge exchange mentioned by the interviewees are the consultancy workshops held by the Canadian-Alberta CCS Taskforce, as well as scientific conferences, like the bi-annual conference series on GHG control technologies coordinated by the IEA GHG R&D programme.

It is recognized by most of the experts that both the amount and the quality of workshops and conferences are increasing. However, there is also concern expressed considering the confidentiality of knowledge. In Canada, private actors carry out a substantial amount of R&D. Since this knowledge can create a competitive advantage, it is typically held confidential or only shared with preferred partners, hampering the diffusion of this information. Interestingly, while some interviewees considered issues around intellectual property as the most important barrier for the performance of this function, others have argued that this is all part of the game, and that competition instead of cooperation is no serious threat to the development of the CCS.

The experts agreed on the need to intensify the exchange of experimental knowledge across borders. Although not depicted in the network visualization, several Canadian organisations are also involved in foreign CCS projects, like the ARC led ECBM pilot project in North China. Furthermore, Canadian actors participate in international CCS partnerships, like the IEA GHG Programme; the Carbon Sequestration Leadership Forum (CSLF) and Asia-Pacific Partnership on Clean Development and Climate. However, some experts argued that current international collaborations are mainly established on a purely scientific or political level and that more should be done to develop a complementary set of CCS demonstration projects around the world, including rapidly growing coal-using countries like China. They 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.

5.3.4. Guidance

For nearly two decades, Canadian scientists have envisioned CCS as a possible solution to solve the twin challenges of reducing GHG emissions, while utilizing indigenous fossil fuels [54]. This is a message that has been embraced in recent years by politicians who started using the promise of CCS in their political rhetoric regarding climate change. “Instead of pumping tons of carbon dioxide into the earth’s atmosphere, we may be able to collect it from our oilsands operations, our coal-fired electrical plants, and other industrial emitters, and pump it deep underground where it will remain for eternity. CCS is a promising technology that could leverage Canada’s expertise and Canada’s geography,” said Prime Minister Harper when he announced the ecoTrust fund and the Canada-Alberta CCS Taskforce [55]. However, it was not before 2008 that CCS started to be seriously considered as part of a comprehensive national emission reduction strategy [56].

Canada has historically relied on a variety of non-compulsory measures to reduce air emissions. However, as emission growth rates show (see Table 5-6), these have not proved sufficient to meet the Kyoto targets, which called for the country to reduce its emissions 6% below 1990 levels by 2012. One explanation for Canada’s limited climate ambitions over the past 10 years is the Unites States’ inaction on climate change, under the Bush administration. Canadian policymakers feared the economic consequences of moving more quickly than the US. The election of President Barack Obama, however, has changed the political landscape regarding climate change. Immediately following the US election in November 2008, the Government of Canada signalled that it intended to pursue a North American approach to climate change and energy security with the US. Therefore, the ambitious climate agenda outlined by the current Obama administration – emissions reduction of 20% below 2005 levels by 2020 and 83% by 2050 [57] - can be seen as an important driver for reaching the climate change targets set by Canada’s federal and provincial governments (Table 5-6).

One major aspects that stands out in both the US and Canadian climate mitigation strategies is the important role for CCS in meeting the emissions reduction targets [58]. For example, in Alberta, the provincial government anticipates that CCS will account for 70% of its intended emissions reductions of 50 Mt by 2020 and by 200 Mt by 2050 [51].

Guidance in the innovations 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 regulatory solutions related to standardization, permitting and liability. In the absence of a sound legal and regulatory frameworks, project developers may assume a legal risk and large-scale deployment of the technology might not occur [59].

Table 5-6: Emission profiles and reduction targets for the main Canadian jurisdictions and the federal government [3].

Jurisdiction	1990 GHG emissions $MtCO_2$-e	2006 GHG emissions $MtCO_2$-e	Relative change 1990-2006	Type of target	GHG reduction Target Level	Timeline
British Columbia	49	62	28%	Absolute	33% below 2007 level	By 2020
					80% below 2007 level	By 2050
Alberta	172	234	37%	Absolute	14% below 2005 level	2050
				Intensity	12% below 2004 level, then 2% per year	By 2007
Saskatchewan	44	72	63%	Absolute	32% below 2004 levels	By 2020
Manitoba	18	21	13%	Absolute	6% below 1990 level	By 2012
Ontario	174	190	9%	Absolute	6% below 1990 level	By 2014
					15% below 1990 level	By 2020
Quebec	83	82	-1%	Absolute	6% below 1990 level	By 2012
New Brunswick	16	18	13%	Absolute	10% below 1990 level	By 2020
Nova Scotia	19	20	3%	Absolute	10% below 1990 level	By 2020
New Found land / Labrador	9	9	0%	Absolute	10% below 1990 level	By 2020
National	591	721	22%	Absolute	20% below 2006 level	By 2020
					65% below 2006 level	By 2050
				Intensity	18% below 2003 level, then 2% per year	By 2010

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 current 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 need to be addressed [59]. 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 among other things is charged 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 [60]. Furthermore, the federal government is also funding several research projects that address regulatory issues. For example, researchers at the University of Calgary are tasked with the development of guidelines and protocols for managing the risks of CO_2 storage operations. In addition, the final phase of the IEA Weyburn-Midale CO_2 Monitoring and Storage Project will deliver a Best Practices Manual, including regulatory guidance for future CO_2 storage projects [61]. Although the experts participating in this study appreciate these initiatives, it is argued that more work is needed to fast track the implementation of clear legal and regulatory frameworks that will provide industry with the certainty needed to make proper investment decisions.

5.3.4.1. Expert evaluation of guidance

Interviewees rated their satisfaction with this function rather low: 2.6 out of 5. They are satisfied with the role of political leaders in advocating the promise of CCS and the recent development of targets and regulations for CCS on state level. The low score, however, can be explained by the variety and inconsistency of existing and proposed GHG reduction targets across Canada and the relatively preliminary status of regulation regarding CCS.

Experts participating in this study argue that current legislation and regulatory frameworks are a good platform to build from, but inadequacies in several areas indicate the need to change part of the current legislation in order to get large-scale CCS projects of the ground. According to the experts the gaps in existing legislation and regulatory frameworks relate to three key areas:

1. Legal issues around subsurface (pore space) ownership and its interaction with mineral rights need to be resolved. This includes uncertainties regarding the acquisition of the rights to store CO_2, third party transfer mechanisms, lease charges and possibly royalties for using the resource.
2. Requirements to cover the operation of CO_2 storage projects, including guidelines for site selection and MMV need to be specified.
3. Timeframes and responsibility for the different liability types (operational, local, and climate) in case of CO_2 leakage from the reservoir need to be articulated and assigned.

Resolving this issue is important, primarily because the liability timeframes for CCS projects extend far beyond other typical liability timeframes that companies are held to today. Regulators should therefore clarify that liability will transfer to relevant government jurisdictions once a project moves to the post-abandonment phase.

Although experts would like to see CCS regulation in place soon, some of them also argue 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. Regulatory agencies should therefore provide approvals on a one-time basis to allow the first projects to move ahead.

5.3.5. Market creation

Within a decade, CCS technologies have advanced from a science-based technology to an option, of which its separate parts are demonstrated by industry. However, it is unlikely that utilities will adopt CCS on a large scale until sound climate policies make CO_2 financially worth capturing. Below we will discuss and evaluate the recent engagement of the Canadian government to develop its own GHG emissions trading scheme (ETS) that could create a market for CCS technologies.

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”[56]. The key concept in this scheme 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. In this regulatory proposal, coal fired power plants and oil sands plants coming into operation in 2012 or later would be required to even meet stricter emissions-intensity targets based by 2018 based on using CCS (though these exact intensity targets were not finalized).

Where a facility improves its emissions intensity by more than the required annual amount it would be issued with emissions credits, which could be traded with other participants in the scheme or could be 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. In 2009, CCS was the only certified investment option that has been identified for this compliance mechanism.

On a provincial level, Alberta enacted a similar ETS as the federal government’s proposed scheme in 2007 to meet its own (much lower) intensity based targets. British Columbia, on the other hand, has introduced an entirely different system built on a carbon tax, to help reach its target of 33% reduction below 2007 levels by 2020. The tax, which has come into effect in July 2008, applies to all fossil fuels and it will be phased in over a five-year period at initial rates of CAD 10 per tonne emitted CO_2 and escalating to CAD 30 per tonne by 2012 [60]. British Columbia's Premier Campbell has also been promoting the development of cross-border emissions trading. Along with Manitoba, Ontario and Quebec, British Columbia is a member of the Western Climate Initiative (WCI). This alliance also includes seven US states including California. The WCI calls for a trading system amongst the members with the intent to reduce absolute GHG emissions by 15% below 1990 levels by 2015 [62]. If and how the various regionally based emissions trading schemes link with the proposed national Canadian scheme (let alone any Federal US ETS) is not clear.

5.3.5.1 Expert evaluation of market creation

It is recognized by most of the experts participating in this study that, at present, CCS is hardly deployed on a commercial scale and no real market exists. It is argued that the main barrier standing in the way of commercial CCS deployment is the absence of comprehensive climate policies that place a significant market value on avoided emissions. Not surprisingly, the satisfaction with this function was low, with 2.0 out of 5; the lowest score of all functions.

Despite the low score, the interviewees are moderately positive about the recent attempts by the federal government to introduce a policy for controlling GHG emissions. They noted that support for dealing with climate change through a regulatory framework built around market mechanisms (rather than a command and control approach) is strong in Canada. Furthermore, the majority of experts participating in this study recognized that an ETS in combination with the increasing stringency of intensity based emission targets for new facilities in the oil sands and power generation sectors could lead to a de facto mandatory use of CCS technologies by 2018 and trigger early investments in “CCS-ready” installations in the short-term.

However, it was suggested by some experts that an intensity based ETS is more complex to administer than the already complex cap and trade schemes based on an absolute limit of GHG emissions. Therefore, standardized accounting methods are needed to ensure the consistent calculation of emissions reductions for crediting purposes. Another disadvantage of the proposed system is that it may be difficult to integrate it with other trading schemes based on a fixed annual GHG emissions limit, such as the EU ETS and several regional North American multi-state cap-and-trade systems. Experts have expressed concern that the growing regulatory patchwork of federal and provincial schemes, if not harmonized, will result in increasing costs, confusion, and decreasing investment.

Finally, most of the experts interviewed in this study stress that additional financial stimuli are needed as the introduction of an ETS is not likely to create enough incentive for private actors to engage in large-scale CCS projects on the short-term. We will further elaborate on this issue in the following section.

5.3.6. Mobilization of Resources

In section 4.1. and 4.2. we already discussed the increasing availability of the financial resources for CCS RD&D, notably in the past three years. Since 2006, the federal government has allocated over a billion CAD in financial support to CCS-related activities, including CAD 125 million under the ecoENERGY Technology Initiative. Furthermore, in 2008, CAD 240 million is allocated to the commercial demonstration of CCS in the coal-fired Boundary Dam power plant in Saskatchewan, which has been matched by the provincial government. In its 2009 budget, the federal government instituted tax breaks for CCS projects and committed an additional CAD 650 million over five years for demonstration of CCS technologies. Moreover, the Alberta government has committed CAD 2 billion to fund a portion of the construction costs of four large-scale CCS projects in its province by 2015 (see also section 3.1.).

Federal and Alberta budgets for the implementation of large-scale CCS projects in the coming years total nearly CAD 3 billion. This budget is expected to leverage at least the same amount of investments from industry. Although this sounds like a lot of money, the Alberta CCS Development Council [63] recommends spending an extra CAD 1-3 billion a year on CCS to ensure that development of the technologies continues after the first demonstration projects in the province have been completed. The council estimates that the costs of CCS projects range from CAD 70 to 150 for each tonne of captured and stored CO_2 and that the financial disadvantage created by CCS needs to be partly compensated by direct subsidies. The Council also argues that there is a business case for public investments in CCS, as these financial contributions to the development of CCS may ultimately lead to increased royalty and tax revenues through EOR [63].

5.3.6.1. Expert evaluation of mobilization of resources

Despite increasing CCS R&D budgets and announcements of billions of dollars to support for CCS demonstration projects, the availability of financial resources was rated relatively low with a 2.8. Interviewees (especially from private firms) argued that the current financial risks are too high for firms to justify CCS investments to shareholders.

In order to provide investor certainty, it is believed that public-private partnerships are the way to go, whereby government agencies fund a substantial part of the billions of dollars necessary to deploy the first integrated CCS projects on a commercial scale. It is argued this approach would offer the most effective 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 comparison to the current budget available for CCS, it was noted by some interviewees that over CAD 150 billion in capital spending in the coming decade has been announced for the oil sands alone. Furthermore, electricity markets across the country require new capacity to meet increasing demand and to replace plants that are at the end of their lifetime. It is argued that if federal and provincial governments fail to demonstrate their seriousness regarding CCS and with no extra funding for CCS on the short term, these facilities will be built with only conventional technology, thus making them costly to retrofit with CCS technologies in the future.

Next to a lack of financial resources, the respondents agree that the increasing scarcity of skilled (technical) personnel in CCS can cause problems. CCS skills are comparable to those of the oil and gas industry; an industry that already competes for qualified personnel. Experts participating in this study see a solution to this problem by introducing educational programs at universities to get future engineers acquainted with specific CCS knowledge. They also stress the need to retrain both current managers and technicians in the industry to preserve experience.

5.3.7. Creation of legitimacy

The legitimacy for CCS in Canada is increasing, as the politicians start to embrace CCS as an important option to reach their climate ambitions; the majority of scientists favour CCS deployment; and the fossil fuel industries see the technology as an opportunity to stay in business in a low-carbon economy. However, in recent years CCS technologies meet increasing opposition from environmental NGO [64].[9] Greenpeace [65] for example portrays CCS as a risky technology, and a lifeline for the continued use of coal and tar sand oil that detracts attention from efforts to shift to a truly sustainable energy system. These vocal public interest groups could have a high impact on the attitudes towards the deployment CCS technologies by the lay-public and thereby on the creation of legitimacy for CCS technologies.

[9] Also note that there is political opposition. The Wildrose Alliance called on the Albertan government to withdraw its CAD 2 billion in funding for CCS, as it is “wasting taxpayer money on an unproven technology to combat a scientifically unproven problem” [63].

Studies show that Canadians are in general increasingly concerned with climate change, but that public awareness about CCS is low. Sharp et al. [66, 67] found a slight public support for CCS in Canada. Furthermore, they 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. 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.

With respect to possible local opposition it should be noted that the world's largest CO_2 EOR project in Weyburn enjoys a good relationship with the local community and that the public permitting processes of the CCS projects that are currently underway has generally been uncontroversial. Furthermore, the 45 acid gas injection sites in Alberta, some quite close to major population centres, have not led to opposition [67]. This should provide confidence to decision-makers that large-scale CCS development will likely be publicly acceptable; an observation that was, however, not shared by all the experts surveyed in this study.

5.3.7.1. Expert evaluation of legitimacy for CCS

Interviewees rated their satisfaction with this function 3.0 out 5, an average score. It is argued that the creation of legitimacy is a somewhat difficult function in the Canadian CCS Innovation System, as the legitimacy for CCS can vary between the stakeholders, ranging from politicians, coal lobby groups and communities that are confronted with sequestration projects under their back yards. Furthermore, it was noted that the legitimacy for CCS has a geographical component as well. In Eastern Canada the public is generally sceptic towards the oil and gas industry, while in Western Canada the public is more used to oil and gas activities and probably less reluctant towards the advancement of CCS.

Many experts participating in this study agree that there are influential coalitions advocating CCS in Canada. Industrial consortia like the Canadian Coal Power Coalition (CCPC) and ICO2N invest heavily in a powerful lobby for CCS in political arenas. It was also noted that oil and gas industry associations have a relatively large influence in Canadian politics, as they are responsible for a large share of the jobs in Western Canada and generate a substantial amount of income for the treasury through the payment of royalties. Furthermore, several major power suppliers, such as SaskPower, are "crown corporations" and fully owned by the (Saskatchewan) Government. Considering the Anglo-Saxon character of the country and taking the financial power of the domestic energy industry into account, this is seen by several experts as a benefit for CCS technologies over renewable alternatives, like wind and solar.

On the other hand, several experts noted that using taxpayers money to support fossil fuel based industries in the development of CCS is one of the reasons that several environmental NGOs as well as politicians oppose CCS. Several interviewees noted that CCS support programs should always be in addition and not at the expensive of support for renewable energy technologies and energy efficiency measures. The latter is not only important to account for public support to CCS, but also because CCS is not the silver bullet to all the problems related to the oil sands. A few experts participating in this study noted that CCS fails to address several non-CO_2 related environmental impacts, like acid rain, destruction of wildlife habitat, and depletion and contamination of fresh water.

The majority of the interviewees argued that even though a vast majority of the Canadian citizens is not familiar with the concept of CCS, the issue of public perception is very important for the future deployment of the technology. The experts participating in this study expect that a public backlash against the technology in general, or opposition towards the siting of a specific project, can stall the development of CCS by many years. The major reasons for public concern are: the potential risks of CO_2 leakage at storage sites; increasing electricity bills due to the extra costs of power generation with CCS; and a slowdown in the development of other low-emission technologies. Several of the experts point out that in order to increase public support these and other legitimate concerns about CCS should be taken into account by project developers, as without public engagement the implementation of CCS projects risks being delayed or even cancelled.

5. 4. System intervention: implications for technology management and policy

Figure 5-6 gives an overview of all the current system drivers and barriers to the development of CCS technologies, derived from the performance assessment of the Canadian CCS Innovation System. To improve the overall performance of the Innovation System and accelerate the deployment of more advanced CCS technologies, it is necessary to direct policy initiatives at the identified weak system functions, i.e. market formation and resources mobilization, as well as (regulatory) guidance and the creation of legitimacy may (see Figure 5-1). Below we will discuss a policy strategy that consists of three interrelated elements targeting the fulfilment of different sets of system functions simultaneously, namely: 1) stimulate technological learning; 2) create financial and market incentives; and 3) improve regulation and legitimization for CCS.

5.4.1. Stimulate technological learning

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, and storage) 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 support these projects, (inter) national CCS networks should be utilized to maximize knowledge sharing and solve issues around intellectual property. To integrate the CCS chain, and take optimal advantage of the available learning potential, improved coordinated among CCS projects action is necessary. Hereby, domestic CCS consortia, as well as international CCS network organizations could play an important role.

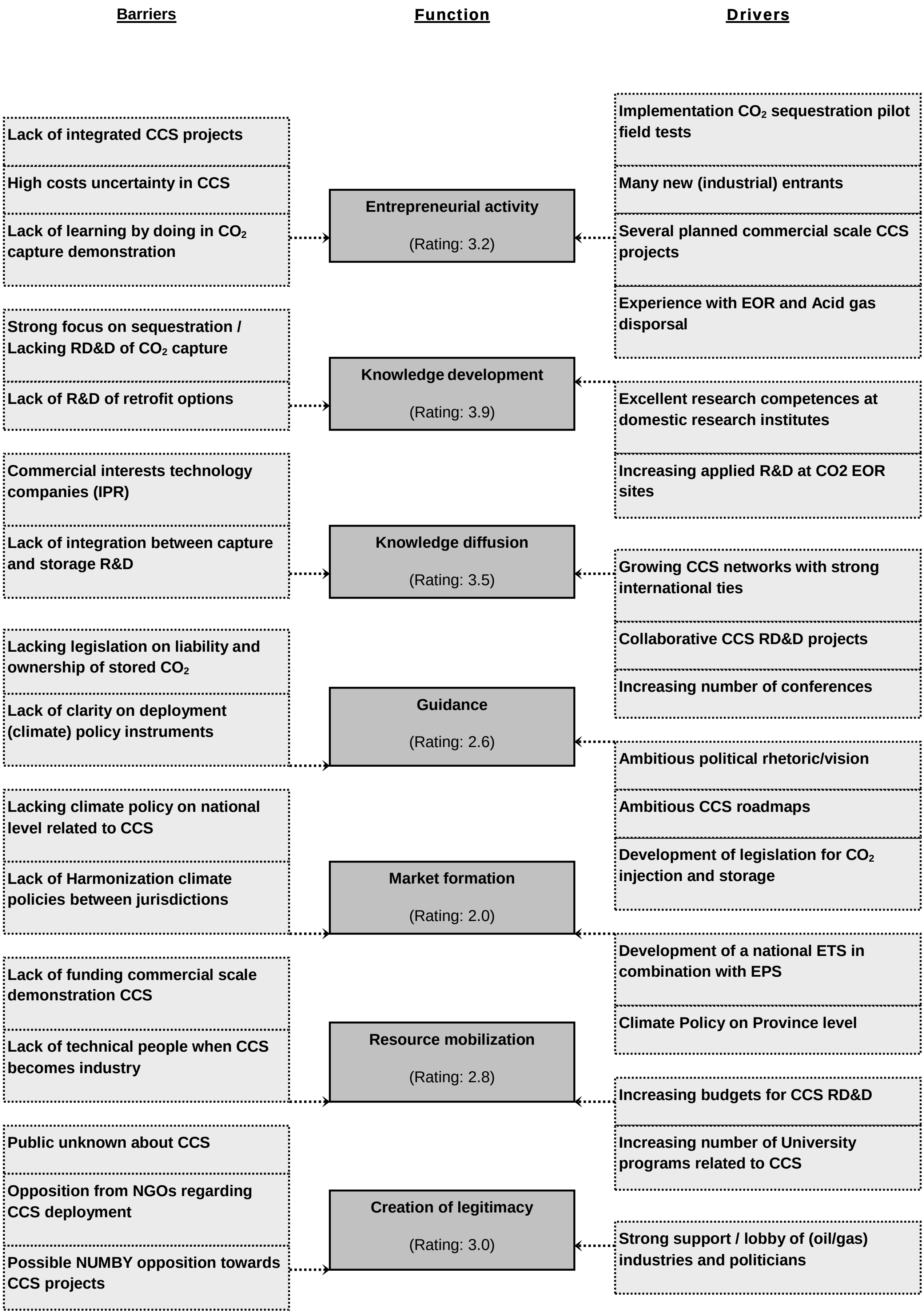


Figure 5-6: Drivers and barriers for CCS development and deployment in Canada as of 2008.

5.4.2. Create financial and market incentives

The implementation of sound climate policies is vital for the development of commercial scale CCS projects, as strong economic drivers for CCS are currently lacking. Industry 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. The proposed nation-wide intensity based ETS is a viable regulatory mechanism to create such market incentives for CCS. Especially in combination with the increasing stringency of emission performance standards for new facilities in the oil sands and power generation sectors, which could lead to a de facto mandatory use of CCS technologies. However, for the proposed national ETS to succeed and generate industry investments it is important to standardize accounting methods. Therefore, it is necessary to harmonize the current regulatory patchwork of federal and provincial cap-and-trade schemes.

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. Public private partnerships are a promising route to take in establishing early commercial-scale CCS demonstration projects. The billions of dollars that have been made available for CCS demonstration in 2009, offer a high incentive to 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 bring CCS technologies down its learning curve and long climate policies that create a clear market for CCS are key for a broad application of CCS in Canada.

5.4.3. Improve regulation and legitimization

Besides implementing sound climate policies, solving the outstanding legal and regulatory issues 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. 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 can be used in the development of these new guidelines and regulations. Therefore we would call for a ‘dynamic’ regulatory framework that is reviewed and updated when more experience with CCS projects has been gained.

Finally, a strong regulatory framework could minimize concerns of CCS being a ‘risky technology’, thereby building public trust in CCS applications. Therefore, such a framework should include mechanisms to approve CCS projects that engage a wide range of stakeholders and incorporate public outreach efforts. It is argued that a two-way communication with stakeholders, including (environmental) interest groups, the media and members of the local community should be an integral part of CCS projects. Thereby it is important to take advantage of successful public outreach strategies applied in other CCS projects.

5.5. Discussion of results and concluding remarks

Before we draw conclusions from our analysis, we will first discuss the main results and reflect on several methodological issues, as well as the proposed policy strategy.

5.5.1. Methodological issues and implications

One of the objectives of this study is to methodologically strengthen the Innovation System Functions approach introducing quantitative methods that stem from other fields of innovation research: social network analysis; bibliometric analysis, and project analysis. Below we will discuss the limitations of the applied methods and the implications for future research.

In order to gain more insight in the amount and focus of CCS R&D (function ‘knowledge development’), as well as entrepreneurial experiments with the technology (function ‘entrepreneurial activity’), a comprehensive project database was constructed. With respect to the completeness of the database it is important to note that data on projects that have already finished are more difficult to acquire compared to projects that are still active. A small part of the increasing amount of funding for CCS RD&D could thus be explained by the more difficult collection of data for earlier years, but is not significant enough to rebut our observation that the number, budgets and variety of CCS projects has increased significantly over the past decade.

A second issue concerning data availability relates to private investments in CCS research. The researchers are aware that CCS R&D projects do take place behind ‘closed doors’ in various industrial labs. Although this could explain part of the difference between the relatively low investments in R&D of CO_2 capture technologies, compared to CO_2 storage projects, it is unlikely that the possible lack of private industry data is the sole reason for this multimillion-dollar difference. We would argue that CO_2 storage facilities have been demonstrated more often in large-scale capital-intensive projects, and that CO_2 capture technologies are still in the R&D phase, which requires fewer resources.

The project database was also used to gain more insight in the configuration and growth of CCS actor networks in Canada. We assumed that organizations that are involved in the same CCS project have the possibility to exchange knowledge among each other. We also assumed that the links among actors are equally strong and bilateral. Thereby this study overlooks the large number of informal links and the variety of interconnected individuals active within such a network. We also did not pay attention to quality of a link; e.g. in terms of research outcomes, or the number of times representatives from the partnering organizations do actually meet. Additional surveys seem an obvious choice for gathering such complementary data and may provide interesting directions for future research. However, such analyses are beyond the scope of this research, as our main interest lies in the possibility of actors to exchange knowledge with other actors in the system in order to gain more insight in the function ‘knowledge diffusion’. It was found that the number of organization involved in CCS projects in Canada, as well as the number of linkages per actor increased significantly over the past decade. Moreover the increasing clustering coefficient - a measure to determine the existence of relative dense clusters in the network - in combination with a relatively short path length between actors indicates that the network suffices the criteria of a ‘small world network’ [68]. As simulations have shown, a small world network is the most efficient structure to achieve knowledge diffusion [38, 69].

Next to the increasing size and connectivity of the actor networks involved in CCS, several important shifts in the composition of the network were found. First of all, we observed a growing share of private industries at the expense of research institutions and universities. The increasing number of new specialized firms entering the system as well as the more central position of private enterprises – mainly oil and gas companies – in the Canadian CCS network point to a change from an R&D based system towards an Innovation System that is conducive to the (commercial) deployment of CCS technologies. However, the observation that the capture clusters in the network consist mainly of research institutions and universities may indicate that the application of CCS in power plants is still in the R&D phase. A notion that is partly confirmed by the bibliometric analysis, which shows an increasing amount of studies into CO_2 capture technologies.

The bibliometric analysis not only points to a shift in focus of scientific publications that describe CO_2 storage research towards publications of CO_2 capture research, but also provides evidence for an increasing amount of studies into non-technical aspects CCS; e.g. public acceptance and regulatory issues. This can be explained by the increasing importance of the social, economic and political aspects of a novel technology when it reaches the implementation phase [70]. In reality the amount of non-technical studies might be even higher, as the used Scopus database has a bias towards natural sciences. Other studies have found that bibliometric analyses that make use of Google Scholar are more beneficial for the fields of business, finance, economics and social sciences in general [36].

The increased attention for non-technical aspects of CCS is in concurrence with the improved fulfilment of functions that relate the build-up of a supportive institutional infrastructure, like the creation of markets and legitimacy for the technology, as well as the provision of (regulatory) guidance in the innovation process. The extensive literature survey that was performed to gain insight in the fulfilment of these ‘soft’ functions shows a slow improvement in the most recent years.[10] Even though CCS has been envisioned as a promising mitigation option for Canada’s fossil fuel based industries since the early nineties, concrete plans to regulate CCS and support its market uptake were proposed in 2008.

In order to further ascertain the fulfilment of Innovation System Functions, we conducted semi-structured interviews with more than 20 CCS experts from industry, research, government and interest groups. The interviewees were asked to verify and complement our results and rate their level of satisfaction with the fulfilment of a particular system function on a 5 point Likert scale. Furthermore, they gave their view on what should be done to improve system functions that are impeding a higher performance of the system. Their evaluations

[10] Note that qualitative indicators and methods are more suitable to gain insight in these ‘soft’ functions.

were mostly in agreement with the results of our historical analysis. For example, we found a sharp increase in CCS RD&D activities, as well as high potential for knowledge diffusion in the fast growing actor networks. These functions received the highest expert rating. In similar fashion the slow development of market incentives for the CCS and the lack of regulatory guidance resulted in low scores on these functions. The main discrepancy related to the function ‘mobilization of resources’. Even though the results show a substantial increase in CCS investments, the majority of experts argue that current budgets are not sufficient to realize large-scale CCS deployment on the short term.

Despite the possible subjectivity of the forward-looking perspective of this study, our historical analysis of the Canadian CCS Innovation System has been corroborated by various data sources. The combination of qualitative and quantitative research methods proved to be very useful for assessing the build-up and performance of Technological Innovation Systems. Thereby providing an important contribution to innovation scholars that wish to extend the application of this approach. Moreover, it provides a solid basis for advice on policy strategies to enhance the development of deployment of CCS in Canada and possibly also in other countries.

5.5.2. Reflection on CCS support strategies

Another key contribution of this study, especially compared to other Innovation System analyses, is the additional focus on policy and technology management issues. By pointing out how strategies of decision makers are likely to affect Innovation System’s performance, this study delivers insights of value to scholars as well as practitioners.

The proposed strategy targets a variety of aspects that are decisive for successful CCS deployment, including technological learning; alteration of short term financial stimuli and long-term market incentives; the improvement of a supportive regulations; and sound communication on CCS. 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 et al. [71] on policies related to the creation of a market for CCS in Europe; Pollak and Wilson [72] on providing regulatory guidance in the US and Canada; Wade and Greenberg [73] regarding the creation of legitimacy and public acceptance of CCS; or de Coninck et al. [7] on knowledge diffusion and global technological learning. We would argue that these detailed insights could help to fill in the general deployment strategy outlined in this study.

Furthermore, a policy maker at the national level should be aware of the increasing importance of these global innovation processes for local activities. Whether to buy foreign technology, or rely on ‘home-grown’ CCS solutions and expertise is at the heart of this policy decision. In order to analyze these global trends in the development of CCS technologies, it is desirable to apply the analytical framework presented in this study to other countries as well. These analyses would not only allow for cross-national comparison on a function level – e.g. differences between R&D expenditures, technological focus, and regulatory frameworks –, but would also provide an opportunity for technology managers to learn from a broad range experiences regarding the development of CCS technologies in other countries [see e.g. 74].

5.5.3. Summary and conclusions

In this study we have described the early build-up of a CCS Innovation System in Canada. The results show that converging perspectives on the importance of CCS in the energy system by researchers, (industrial) entrepreneurs, and governments have resulted in a steady growth of the CCS Innovation System as a whole. This is visible through the entry of new actors in the system; extension of the knowledge base; increasing connectivity in CCS networks; successful entrepreneurial projects; increasing availability of public and private funding for CCS; changes in legislation; the creation of strong advocacy coalitions; and a guiding government fostering the development of CCS.

However, the performance evaluation of the system also point out that the rapid build-up of an Innovation System around CCS technologies in Canada has entered a critical phase, as entrepreneurs have not yet utilized the extensive knowledge base and knowledge networks, which have accumulated over the past years, to explore the market for power generation with CCS. It is realized by the experts participating in the study that in order to move the CCS Innovation System through this present difficult episode and accelerate the deployment of large-scale CCS projects, it is necessary to direct policy initiatives at the identified weak system functions: market creation, the mobilization of resources, (regulatory) guidance, and the creation of legitimacy.

In order to remedy malfunctioning of the Canadian CCS Innovation System and improve its performance, 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 direct subsidies for a variety of commercial scale integrated CCS projects. It is believed that the creation of such partnerships could offer a high incentive to projects in an early phase 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, (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 technology 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 on both federal and provincial level, 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 therefore be an integral part of every CCS project plan.
- Finally, we would argue that abovementioned efforts would only be successful if overarching long-term climate policies are developed. Governments need to change ‘the rules of the game’ by implementing e.g. an emissions trading scheme in combination with performance standards 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
We would like to gratefully acknowledge David Keith, for his cooperation with Christian Eveleens during his internship at the Energy and Environmental Systems Group, University of Calgary. The authors are especially grateful to the interviewees for their willingness to participate in this study and for their valuable contributions. This research is part of the CATO program, the Dutch national research program on CCS.

References

1. van Alphen, K., C. Eveleens, M.P. Hekkert, R.E.H.M. Smits, and W.C. Turkenburg (Under review). *Evaluating the build-up of a carbon capture and storage innovation system in Canada.* Energy policy.
2. EIA (2009). *International Energy Outlook 2009*, Energy Information Administration: Washington D.C. (USA).
3. Environment Canada (2009). *2007 Greenhouse Gas Inventory - A Summary of Trends*: Gatineau Quebeck (Canada).
4. IPCC (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*, ed. B. Metz, et al. Cambridge (UK).
5. Bachu, S. (2003). *Screening and Ranking of Sedimentary Basins for Sequestration of CO2 in Geological Media in Response to Climate Change.* Environmental Geology 44: p. 277-289.
6. G8 (2008). *Joint Statement by G8 Energy Ministers*: Aomori (Japan).
7. de Coninck, H., J.C. Stephens, and B. Metz (2009). *Global learning on carbon capture and storage: A call for strong international cooperation on CCS demonstration.* Energy Policy. 37(6): p. 2161-2165.
8. Murphy, L.M. and P.L. Edwards (2003). *Bridging the Valley of Death: Transitioning from Public to Private Finance*, National Renewable Energy Laboratory (NREL): Colorado (USA).
9. Klein Woolthuis, R., M. Lankhuizen, and V. Gilsing (2005). *A system failure framework for innovation policy design.* Technovation. 25(6): p. 609-619.
10. Kline, S.J. and N.R. Rosenberg (1986). *An overview of innovation*, in *The Positive Sum Strategy Harnessing Technology for Economic Growth*, R. Landau and N. Rosenberg, ed. National Academy Press: Washington D.C. (USA). p. 275-306.
11. Carlsson, B. and R. Stankiewicz (1991). *On the nature, function and composition of technological systems.* Journal of Evolutionary Economics. 1(2): p. 1432-1386.
12. Hekkert, M.P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann, and R.E.H.M. Smits (2007). *Functions of innovation systems: A new approach for analysing technological change.* Technological Forecasting and Social Change. 74(4): p. 413-432.
13. Foxon, T.J., R. Gross, A. Chase, J. Howes, A. Arnall, and D. Anderson (2005). *UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures.* Energy Policy. 33(16): p. 2123-2137.
14. Hekkert, M.P., R. Harmsen, and A. de Jong (2007). *Explaining the rapid diffusion of Dutch cogeneration by innovation system functioning.* Energy Policy. 35(9): p. 4677-4687.
15. Jacobsson, S. (2008). *The emergence and troubled growth of a 'biopower' innovation system in Sweden.* Energy Policy. 36: p. 1491–1508.
16. Jacobsson, S. and A. Bergek (2004). *Transforming the energy sector: the evolution of technological systems in renewable energy technology.* Industrial and Corporate Change 13(5): p. 815–849.
17. Negro, S.O., M.P. Hekkert, and R.E.H.M. Smits (2007). *Explaining the failure of the Dutch innovation system for biomass digestion--A functional analysis.* Energy Policy. 35(2): p. 925-938.
18. Suurs, R.A.A. and M.P. Hekkert (2009). *Competition between first and second generation technologies: Lessons from the formation of a biofuels innovation system in the Netherlands.* Energy. 34(5): p. 669-679.
19. van Alphen, K., M.P. Hekkert, and W.G.J.H.M. van Sark (2008). *Renewable energy technologies in the Maldives--Realizing the potential.* Renewable and Sustainable Energy Reviews. 12(1): p. 162-180.
20. Edquist, C. (1997). *Systems of innovation - Technologies, institutions and organizations*. Pinter Publishers. London (UK).
21. Freeman, C. (1995). *The 'National System of Innovation' in historical perspective.* Cambridge Journal of Economics. 19(1): p. 524.

22. Lundvall, B.Å. (1992). *National Systems of innovation: Towards a theory of innovation and interactive learning* Pinter Publishers. London (UK).
23. Nelson, R.R. and S.G. Winter (1977). *In search of useful theory of innovation.* Research Policy. 6(1): p. 36-76.
24. Hekkert, M.P. and S.O. Negro (2009). *Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims.* Technological Forecasting and Social Change. 76(4): p. 584-594.
25. Bergek, A., S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne (2008). *Analyzing the functional dynamics of technological innovation systems: A scheme of analysis.* Research Policy. 37(3): p. 407-429.
26. Carlsson, B., S. Jacobsson, M. Holmén, and A. Rickne (2002). *Innovation systems: analytical and methodological issues.* Research Policy. 31(2): p. 233-245.
27. Markard, J. and B. Truffer (2008). *Technological innovation systems and the multi-level perspective: Towards an integrated framework.* Research Policy. 37: p. 596–615.
28. Jacobsson, S. and A. Johnson (2000). *The diffusion of renewable energy technology: an analytical framework and key issues for research.* Energy Policy. 28(9): p. 625-640.
29. Rickne, A. (2001). *Assessing the Functionality of an Innovation System*, Presented at the Nelson and Winter Conference: Aalborg (Denmark).
30. Liu, X. and S. White (2001). *Comparing Innovation Systems: a framework and application to China's transitional context.* Research Policy. 30(7): p. 1091-1114.
31. Edquist, C. (2004). *Systems of innovation: perspectives and challenges*, in *The Oxford Handbook of Innovation*, J. Fagerberg, D.C. Mowery, and R.R. Nelson, ed. Oxford University Press: Oxford (UK).
32. Suurs, R.A.A. and M.P. Hekkert (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): p. 1003-1020.
33. van Alphen, K., J. van Ruijven, S. Kasa, M. Hekkert, and W. Turkenburg (2009). *The performance of the Norwegian carbon dioxide, capture and storage innovation system.* Energy Policy. 37(1): p. 43-55.
34. Legg, J.F. and F.R. Campbell (2006). *Carbon Dioxide Capture and Storage: A Compendium of Canada's Participation*, Prepared under NRCan Office of Energy Research and Development Ottawa: Ontario (Canada).
35. IEA GHG (2009). *CO2 Capture and Storage RD&D Projects Database*, IEA Greenhouse Gas R&D Programme: Cheltanhan (UK).
36. Bornmann, L., W. Marx, H. Schier, E. Rahm, A. Thor, and H.D. Daniel (2009). *Convergent validity of bibliometric Google Scholar data in the field of chemistry--Citation counts for papers that were accepted by Angewandte Chemie International Edition or rejected but published elsewhere, using Google Scholar, Science Citation Index, Scopus, and Chemical Abstracts.* Journal of Informetrics. 3(1): p. 27-35.
37. Deroïan, F. (2002). *Formation of social networks and diffusion of innovations.* Research Policy. 31(5): p. 835-846.
38. Kim, H. and Y. Park (2009). *Structural effects of R&D collaboration network on knowledge diffusion performance.* Expert Systems with Applications. 36(5): p. 8986-8992.
39. Cantner, U. and H. Graf (2006). *The network of innovators in Jena: An application of social network analysis.* Research Policy. 35(4): p. 463-480.
40. Baur, M. (2009). *Thesis: Visone: software for the analysis and visualization of social networks*, University of Karlsruhe: Karlsruhe (Germany).
41. Borgatti, S.P., M.G. Everett, and L.C. Freeman (2009). *Ucinet for Windows: software for social network analysis*, Analytic Technologies: Lexington (USA).
42. Bachu, S., W.D. Gunter, E.S. Rubin, D.W. Keith, C.F. Gilboy, M. Wilson, T. Morris, J. Gale, and K. Thambimuthu (2005). *Overview of acid-gas injection operations in Western Canada*. Greenhouse Gas Control Technologies 7. Oxford (UK): Elsevier Science Ltd.
43. Wassermann, F. and K. Faust (1994). *Social network analysis: methods and applications*. Cambridge University Press. Cambridge (UK).

44. MacPherson, J. (2003). *Alberta's New Royalty Initiatives for CO2 Enhanced Oil and Gas Recovery Projects*, Presented at the PTAC Forum CO2 From Industrial Sources to Commercial Enhanced Oil & Gas Recovery: Calgary (Canada).
45. CGPC (1997). *Natural gas potential in Canada: A Report by the Canadian Gas Potential Committee*, Canadian Gas Potential Committee (CGPC): University of Calgary (Canada).
46. Lakeman, B. (2005). *Alberta Research Council Enhanced Coalbed Methane Recovery Project in Alberta Canada*, Presented at the Carbon Sequestration Leadership Forum, 1st International Workshop on CSLF projects: Potsdam (Germany).
47. Deng, X., M. Mavor, D. Macdonald, B. Gunter, S. Wong, J. Faltinson, and H. Li (2008). *ECBM Technology Development at Alberta Research Council*, Presented at the Coal-Seq VI Forum: Houston (US).
48. Steadman, E. (2008). *The Plains CO2 Reduction (PCOR) Partnership: Phase III Overview*, Presented at the Regional Carbon Sequestration Partnership Annual Peer Review Meeting: Pittsburgh (USA).
49. Gunter, W.D., S. Bachu, D. Palombi, B. Lakeman, W. Sawchuk, and D. Bonner (2009). *Heartland Area Redwater reef saline aquifer CO2 storage project*. Energy Procedia. 1(1): p. 3943-3950.
50. NrCan (2009). *EcoENERGY Technology Initiative*. Available from: http://www.nrcan.gc.ca/eneene/science/etiiet-eng.php.
51. Government of Alberta (2009). *Government moves forward on carbon capture projects*, Government of Alberta Information Bulletin.
52. Enhance Energy Inc (2009). *The most carbon stored in the world. The greatest benefits in store for Albertans*, Enhance Energy Inc: Calgary (Canada).
53. Shell Canada (2009). *Shell Quest Carbon Capture and Storage - The Quest Public Disclosure Document.*, Shell Canada: Calgary (Canada).
54. Legg, J.F. (1992). *Overview of carbon dioxide removal and disposal in Canada*. Energy Conversion and Management. 33(5-8): p. 787-794.
55. Harper, S. (2007). *Prime Minister announces ecoTrust fund and carbon capture taskforce in Alberta*. Available from: http://www.pm.gc.ca/eng/media.asp?id=1567.
56. Government of Canada (2008). *Turning the corner: Regulatory Framework for Industrial Greenhouse Gas Emissions*: Ottowah (Canada).
57. Waxman, H.A. and E.J. Markey (2009). *Summary of H.R. 2454, the American Clean Energy and Security Act of 2009*, Pew Centre on Global Climate Change: Arlington (USA).
58. Forbes, S. (2009). *Carbon Capture and Storage and The American Clean Energy and Security Act*, World Resources Institute: Washington D.C. (USA).
59. Bachu, S. (2008). *Legal and regulatory challenges in the implementation of CO2 geological storage: An Alberta and Canadian perspective*. International Journal of Greenhouse Gas Control. 2(2): p. 259-273.
60. IEA (2008). *CO2 Capture and Storage: A Key Carbon Abatement Option*. IEA/OECD. Paris (France).
61. Preston, C., S. Whittaker, B. Rostron, R. Chalaturnyk, D. White, C. Hawkes, J.W. Johnson, A. Wilkinson, and N. Sacuta (2009). *IEA GHG Weyburn-Midale CO2 monitoring and storage project-moving forward with the Final Phase*. Energy Procedia. 1(1): p. 1743-1750.
62. WCI (2009). *Design Recommendations for the WCI Regional Cap-and-Trade Program*, Western Climate Initiative (WCI). p. 122.
63. Alberta CCS Development Council (2009). *Accelerating Carbon Capture and Storage Implementation in Alberta, final report*, Alberta Carbon Capture and Storage Development Council Edmonton (Canada).
64. D'aliesio, R. (2009). *Home power bills may triple Alberta green plan to cost up to $24B over eight years*, *Carbon capture and storage*, Calgary Herald: Calgary (Canada).
65. Greenpeace International (2008). *False Hope, why carbon capture and storage won't save the climate*, E. Rochon, et al., ed. Greenpeace International: Amsterdam (The Netherlands). p. 44.
66. Sharp, J., M. Jaccard, and D. Keith (2006). *Public attitudes toward geological disposal of carbon dioxide in Canada*, Presented at the Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8): Trondheim (Norway).

67. Sharp, J.D., M.K. Jaccard, and D.W. Keith (2009). *Anticipating public attitudes toward underground CO2 storage.* International Journal of Greenhouse Gas Control. 3(5): p. 641-651.
68. Albert, R. and A.L. Barabási (2002). *Statistical mechanics of complex networks.* Reviews of Modern Physics. 74: p. 47–97.
69. Cowan, R. and N. Jonard (2004). *Network structure and the diffusion of knowledge.* Journal of Economic Dynamics and Control. 28(8): p. 1557-1575.
70. Alkemade, F. and M. Hekkert (2008). *Development paths for emerging innovation systems: implications for environmental innovations,* Working paper series Innovation studies group (ISU), Utrecht University: Utrecht (The Netherlands).
71. Groenenberg, H. and H. de Coninck (2008). *Effective EU and Member State policies for stimulating CCS.* International Journal of Greenhouse Gas Control. 2(4): p. 653-664.
72. Pollak, M.F. and W.J. Wilson (2009). *Regulating geologic sequestration in the united states: early rules take divergent approaches.* Environmental Science and Technology 43: p. 3035–3041.
73. Wade, S. and S. Greenberg (2009). *Afraid to Start Because the Outcome is Uncertain?: Social Site Characterization as a Tool for Informing Public Engagement Efforts.* Energy Procedia. 1(1): p. 4641-4647.
74. van Alphen, K., M.P. Hekkert, and W.C. Turkenburg (2009). *Comparing the development and deployment of carbon capture and storage technologies in Norway, the Netherlands, Australia, Canada and the United States-An innovation system perspective.* Energy Procedia. 1(1): p. 4591-4599.

Interlude E

The following chapter builds on the results presented in the previous chapter, but broadens the perspective on TIS performance by comparing the developments in the Dutch, Norwegian, American, and Canadian[1] TISs around CCS technologies. Furthermore and additional case is added to the comparison, namely the performance assessment of a TIS around CCS technologies in Australia. The analysis presented in the following chapter 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.

The research presented in this chapter was executed in the period 2007 – June 2008 and was originally published as [1]: van Alphen, K., Hekkert, M. P., Turkenburg, W.C. (2010). Accelerating the deployment of carbon capture and storage technologies by strengthening the Innovation System. *International Journal of Greenhouse Gas* Control 4(2): p. 396-409.

[1] The performance assessment of the Australian CCS TIS will only be presented as part of this comparative analysis and is not presented in a separate Chapter.

6. Accelerating the deployment of carbon capture and storage technologies by strengthening the Innovation System

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 Innovation System Functions 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.

6.1. Introduction

Most 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 main blueprints for reducing GHG emissions until 2050 [2, 3]. As well as being supported by the scientific community, CSS has attracted great interest from world leaders [4], particularly those whose countries depend heavily on fossil fuels for secure (coal based) electricity generation and export income, notably Europe, Australia, Canada and the US.

Despite the acknowledged urgency to demonstrate CCS technologies [see e.g. 4] and the increasing amount of funding, no fully integrated power plants with CCS have yet been built at commercial scale[5]. 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)[6].

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 [7]. 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 [8], Kline and Rosenberg [9], Lundvall [10], Freeman [11], 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 or opposing the technology and by an institutional infrastructure that legitimizes, regulates and standardizes the new technology [12]. A well performing Innovation System accelerates technological development, while a poorly functioning Innovation System hampers technological innovation [13].

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. 14, 15]. These system functions are decisive processes that foster the shaping and development of a technology [16]. 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. 17, 18-22].

This study applies the Innovation System Functions 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.

6.2. 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. 10, 11], 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 [23]. 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 [24].

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 [12]. 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 [14]. 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 6-1 for definitions).

Table 6-1: Innovation System Functions [14].

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 favourable 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.

To some extent, system functions need to be realized simultaneously, since they can complement, or reinforce each other [17], but an Innovation System may very well collapse due to the absence of a single system function. For example, Kamp [25] 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 research organisations 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.

6.2.1. Methods

In order to ascertain to what extent the Innovation System Functions 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 6-2). The results of the interviews were verified and complemented by additional literature review of scientific as well as “grey literature” (e.g. professional journals, financial yearbooks, roadmaps and policy papers).

Table 6-2: Indicative questions that reflect the extent to which each function in the Innovation System is fulfilled by the components of the system [see also 14, 15].

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 total, about hundred interviews have been conducted with senior representatives from industry, research, government and environmental groups within the five the different countries under study. 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 national CCS TIS the interviewee is most familiar with. The interviewees have been asked to rate their level of satisfaction with the fulfilment of a particular system function in a particular country on a 5-point Likert scale [26] 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 in a particular country. This provides the basis for advice on policy strategies to enhance the development of deployment of CCS.

6.3. 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.

6.3.1. Entrepreneurial activity

In 2009, Canada and Norway are hosting three of the four complete, end-to-end commercial CCS facilities in the world today [27].[2] 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 [28]. 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 [29]. 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 a coal gasification plant, located 325 km south of Weyburn, in North Dakota (US) [30]. 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, in 2009 CCS projects of similar scale as Weyburn, Sleipner and Snøhvit, only exist in project plans (see Table 6-3).

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[3], 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.

[2] 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 [38].
[3] The average score is based on the average scores for each of the five countries under study.

Table 6-3: Major active and planned large-scale CCS projects in 2009 commencing before 2015 in Norway, the Netherlands, United States, Canada and Australia [sources: 31, 32-36].

Country	*Name (location)*	*Project Leader*	*Reservoir type*	*CO_2 Source*	*Size Mt/yr*	*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

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.

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 [6], 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.

Table 6-4 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 [37]. At present there are over 70 CO_2 EOR sites in North America [38]. 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 [39]. 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".

Table 6-4: 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

6.3.2. 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 6-5). 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.

Table 6-5: 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

6.3.2.1. 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 million over 80 R&D projects in 2008 [34]. 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 behaviour, and validating the findings against the results from the field projects such as the work conducted in the Allison Unit [40, 41].

▪ 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 [41, 42].

▪ The Frio project was the first injection of CO_2 into a saline aquifer to demonstrate the feasibility of injection into high-permeability sandstone [43]. 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[41].

▪ 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% [41, 44].

▪ 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 [45]. 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 [46]. 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 [47, 48].

6.3.2.2. Canada

In 2008, approximately 200 organizations were active in over 75 CCS R&D projects in Canada [49]. 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 [30, 50]. More applied research regarding EOR has been carried at the Zama and Pembina EOR Projects in Alberta [51, 52]. 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 [53], and the Alberta Saline Aquifer Project identified the top three suitable deep saline formations in the province[41]. 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 [54]. In terms of capture research there are two major Canadian test centres 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 [41].

▪ 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 [55].

6.3.2.3. 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 [56]. CATO-1 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% [57, 58]. In order to achieve this, a wide portfolio of future capture technologies is being investigated. Furthermore, E.ON and the Netherlands Organisation for Applied Scientific Research (TNO) 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 [59]. In the coming CATO-2 programme the budget is expected to triple to €75 million. In this programme the focus will be applied research to support planned CCS pilot projects in the Netherlands [60]. These may 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 [61].

6.3.2.4. 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 [62]. 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 [63]. In addition to this program, the Mongstad European test centre was established in June 2007 in conjunction with the future Mongstad CCS 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 [64]. 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 [65].

6.3.2.5. 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 [66]. 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 [41]. 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 should commence in 2010 and involves the injection and storage of up to 0.5 Mt of captured CO_2 [66].

▪ 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 [41, 67].

▪ 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 [41].

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 of 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.

6.3.3. 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 6-6).

Table 6-6: Expert evaluation of "knowledge diffusion" on a scale of 1–5.

Netherlands	Norway	US	Canada	Australia	Average
3.7	4.0	4.0	3.2	3.5	3.7

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 [39]. Public private CCS consortia in Canada include, the Integrated CO_2 Network (ICO2N) 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.

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 [68, 69], and the organization of the bi-annual International Greenhouse Gas Control Technologies (GHGT) conference series. The largest GHGT conference until 2009 was held in Washington DC, in November 2008 and hosted 1460 participants from 42 different countries [70]. 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 [71].[4] 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 [72].

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

[4] 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 [71].

knowledge can create a competitive advantage. It is argued by experts in all countries that commercial interest and 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.

6.3.4. 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 6-7). The latter is formally illustrated in several white papers [e.g. 73, 74, 75] and technology roadmaps [e.g. 76, 77], 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” [78]. 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”[79].

Table 6-7: Mid-term GHG emission reduction targets in the Netherlands, Norway, US, Canada and Australia; the status in 2009 [74-76, 80, 81]

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

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 [82]. 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 [83].

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 [84] 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 [85]. 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 [85]. 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 [86]. 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 [87].

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 [88]. 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 [41]. 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 [41]. 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 6-8).

Table 6-8: Expert evaluation of "guidance" on a scale of 1–5.

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

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:

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 provide – after a thorough site selection procedure – approvals on a one-time basis to allow the first projects to move ahead.

6.3.5. Market creation

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 [27]. 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 6-9); the lowest score of all functions.

Table 6-9: Expert evaluation of "market creation" on a scale of 1–5.

Netherlands	Norway	US	Canada	Australia	Average
2.0	2.9	2.2	2.0	2.1	2.2

The fact that Norwegian experts rated the fulfilment 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 [62]. 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.

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 [89]. 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-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 [87]. 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.[5] Under these caps, GHG emissions must be reduced by 17% by 2020 and over 80% by 2050 compared to 2005 levels [90]. 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 [91]. 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 [92], 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 [74]. Australia's ETS will be established at the earliest in 2010 and recognizes CCS as an 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 [93]. 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 [41], and the carbon price on the market, varying between €10 and €16/tCO_2 in the first half of 2009 [94]. 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 [95]. Therefore, the European Commission has outlined the possibility of a "CO_2 emissions fade out" [96], 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 [33].

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

[5] 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 [87].

public investments are needed. We will further elaborate on this issue in the following section.

6.3.6. 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 6-10). 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.

Table 6-10: 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

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.

The majority of Australia's AUD 500 million Low Emissions Technology Demonstration Fund has been allocated for CCS deployment in public private partnerships [66]. 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 [97]. 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 6-3, Section 3.1 for the planned commercial scale CCS projects in Australia) [98].

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 [32]. 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 the provincial government [99]. 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 [100]. 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 [101]. 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 [102]. 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 [47, 48, 103]. 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 [104, 105]. 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 [104]. 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 [87, 91].

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 fulfilment of this function in these countries (see Table 6-10). However the Norwegian and Dutch projects should be implemented before 2013, while the budgets mentioned above stretch over a longer period of time [61, 64]. 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 [106]. 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 [107]. 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 [33].

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 [108]. 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.

6.3.7. Creation of legitimacy

The current fulfilment 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 favoured 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 [62]. 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 favour 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 ICO2N 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. 109]. 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 fulfilment 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 [110] and Sharp et al. [111] for their research on informed public opinions in the Netherlands and Canada; Curry [112] and Reiner et al. [113] for their survey studies in the US; and Ashworth et al. [114] 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 [115]. 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 [111]. 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 [110, 111]. 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 [115]. 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 [116].

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 [62]. This was confirmed by Shackley et al. [117] in their survey of opinion regarding the role of CCS in Europe's energy future among 500 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 6-11).

Table 6-11: Expert evaluation of “creation of legitimacy” on a scale of 1–5.

Netherlands	Norway	US	Canada	Australia	Average
3.0	4.0	2.9	2.9	2.8	3.1

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 [118] and the Otway Basin storage project [119]. 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 as an alternative to renewables.

6.4. 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 Figure 6-1). Below we will discuss a general policy strategy that would help alleviate the current barriers to the technology's future deployment.

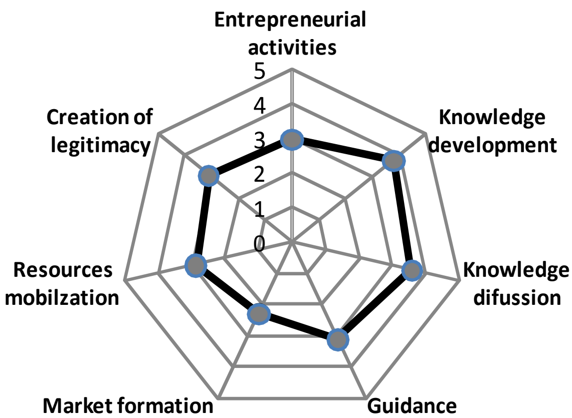


Figure 6-1: Radar diagram depicting the overall score on the Innovation System Functions by a hundred experts in Norway, Netherlands, United States, Canada and Australia, interviewed in the period 2007-2009.

While continuing basic research, there is great need to implement 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.

Taking into account that the carbon price in the early years will probably not be high or stable enough to trigger the required CCS investments, additional incentives are 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) 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 another important action 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. In the United States, where - unlike in most other jurisdictions in the world - the sub-surface geology is not necessarily owned by the state. In jurisdictions where the government does own the pore space, the government will be responsible for determining property access and allocation. A particular challenge for governments in this area is how competing uses of the sub-surface are managed (for example, how CO_2 storage interacts with existing or potential oil and gas production activities or geothermal energy production).

Second, timeframes and responsibility for the different liability types (operational, local, and climate) need to be articulated and assigned. Resolving this issue is important, primarily because the liability timeframes for CCS projects extend far beyond other typical liability timeframes that companies are held to today. Regulators should therefore clarify if and in what timeframe liability will transfer to relevant government jurisdictions once a project moves to the post-abandonment phase. 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. Clear regulations regarding site selection, MMV and risk mitigation strategies could help inform the public about the risks and uncertainties associated with a CCS project and the reason for siting the project in their backyard. 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 part 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.

6.5. 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 investigated 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 need for in depth studies that focus on single aspects of technology development. See for example, Groenenberg and de Coninck [95] on policies related to the creation of a market for CCS in Europe; Pollak and Wilson [86] on providing regulatory guidance for CCS in the US; Wade and Greenberg [120] regarding the creation of legitimacy and public acceptance of CCS; or de Coninck et al. [5] on knowledge diffusion and global technological learning. Moreover, there is vast body of literature that investigates technical issues regarding the risk, costs and environmental performance of CCS technologies, like studies into the behaviour of CO_2 in geologic reservoirs [28, 121]. 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 about 100 experts in five different countries and an extensive literature review.

It is realized by the majority of the experts participating 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 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 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 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

1. van Alphen, K., M.P. Hekkert, and W.C. Turkenburg (2010). *Accelerating the deployment of carbon capture and storage technologies by strengthening the innovation system.* International Journal of Greenhouse Gas Control. 4(2): p. 396-409.
2. IEA (2008). *World Energy Outlook 2008*, IEA/OECD: Paris (France).
3. IPCC (2007). *Climate Change 2007: Mitigation of climate change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. B. Metz, et al. Cambridge University Press. Cambridge (UK), New York (USA).
4. G8 (2008). *Joint Statement by G8 Energy Ministers*: Aomori (Japan).
5. de Coninck, H., J.C. Stephens, and B. Metz (2009). *Global learning on carbon capture and storage: A call for strong international cooperation on CCS demonstration.* Energy Policy. 37(6): p. 2161-2165.
6. Hawkins, D., G. Peridas, and J. Steelman (2009). *Twelve years after Sleipner: Moving CCS from hype to pipe.* Energy Procedia. 1(1): p. 4403-4410.
7. Murphy, L.M. and P.L. Edwards (2003). *Bridging the Valley of Death: Transitioning from Public to Private Finance*, National Renewable Energy Laboratory (NREL): Colorado (USA).
8. Nelson, R.R. and S.G. Winter (1977). *In search of useful theory of innovation.* Research Policy. 6(1): p. 36-76.
9. Kline, S.J. and N.R. Rosenberg (1986). *An overview of innovation*, in *The Positive Sum Strategy Harnessing Technology for Economic Growth*, R. Landau and N. Rosenberg, ed. National Academy Press: Washington D.C. (USA). p. 275-306.
10. Lundvall, B.Å. (1992). *National Systems of innovation: Towards a theory of innovation and interactive learning* Pinter Publishers. London (UK).
11. Freeman, C. (1995). *The 'National System of Innovation' in historical perspective.* Cambridge Journal of Economics. 19(1): p. 524.
12. Carlsson, B. and R. Stankiewicz (1991). *On the nature, function and composition of technological systems.* Journal of Evolutionary Economics. 1(2): p. 1432-1386.
13. Hekkert, M.P. and S.O. Negro (2009). *Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims.* Technological Forecasting and Social Change. 76(4): p. 584-594.
14. Hekkert, M.P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann, and R.E.H.M. Smits (2007). *Functions of innovation systems: A new approach for analysing technological change.* Technological Forecasting and Social Change. 74(4): p. 413-432.
15. Bergek, A., S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne (2008). *Analyzing the functional dynamics of technological innovation systems: A scheme of analysis.* Research Policy. 37(3): p. 407-429.
16. Edquist, C. (2004). *Reflections on the systems of innovation approach.* Science and Public Policy. 31(6): p. 485-489.
17. Suurs, R.A.A. and M.P. Hekkert (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): p. 1003-1020.
18. Negro, S.O., M.P. Hekkert, and R.E.H.M. Smits (2007). *Explaining the failure of the Dutch innovation system for biomass digestion--A functional analysis.* Energy Policy. 35(2): p. 925-938.
19. Jacobsson, S. and A. Bergek (2004). *Transforming the energy sector: the evolution of technological systems in renewable energy technology.* Industrial and Corporate Change 13(5): p. 815–849.
20. Foxon, T.J., R. Gross, A. Chase, J. Howes, A. Arnall, and D. Anderson (2005). *UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures.* Energy Policy. 33(16): p. 2123-2137.
21. van Alphen, K., M.P. Hekkert, and W.G.J.H.M. van Sark (2008). *Renewable energy technologies in the Maldives--Realizing the potential.* Renewable and Sustainable Energy Reviews. 12(1): p. 162-180.

22. Jacobsson, S. (2008). *The emergence and troubled growth of a 'biopower' innovation system in Sweden.* Energy Policy. 36: p. 1491–1508.
23. Smits, R.E.H.M. (2002). *Innovation studies in the 21st century;: Questions from a user's perspective.* Technological Forecasting and Social Change. 69(9): p. 861-883.
24. Klein Woolthuis, R., M. Lankhuizen, and V. Gilsing (2005). *A system failure framework for innovation policy design.* Technovation. 25(6): p. 609-619.
25. Kamp, L.M. (2002). *Thesis: Learning in wind turbine development : a comparison between the Netherlands and Denmark*, Faculty of Geosciences Utrecht University: Utrecht (The Netherlands).
26. Likert, R. (1932). *A Technique for the Measurement of Attitudes.* Archives of Psychology 140: p. 1-55.
27. Dooley, J.J., C.L. Davidson, and R.T. Dahowski (2009). *An Assessment of the Commercial Availability of Carbon Dioxide Capture and Storage Technologies as of June 2009*, United Stated Department of Energy (DOE): Richland (USA). p. 33.
28. Torp, T.A. and J. Gale (2004). *Demonstrating storage of CO2 in geological reservoirs: The Sleipner and SACS projects.* Energy. 29(9-10): p. 1361-1369.
29. Estublier, A. and A.S. Lackner (2009). *Long-term simulation of the Snøhvit CO2 storage.* Energy Procedia. 1(1): p. 3221-3228.
30. Preston, C., M. Monea, W. Jazrawi, K. Brown, S. Whittaker, D. White, D. Law, R. Chalaturnyk, and B. Rostron (2005). *IEA GHG Weyburn CO2 monitoring and storage project.* Fuel Processing Technology. 86(14-15): p. 1547-1568.
31. MIT (2009). *Carbon Dioxide Capture and Storage Project Database*, The Massachusettes Institute of Technology (MIT): Cambridge, Massachusettes (USA).
32. NrCan (2009). *EcoENERGY Technology Initiative*. Available from: http://www.nrcan.gc.ca/eneene/science/etiiet-eng.php.
33. ETP ZEP (2008). *EU Demonstration Programme for CO2 Capture and Storage (CCS) – ZEP's proposal*, European Technology Platform for Zero Emission Fossil Fuel Power Plants: Brussels (Belgium).
34. NETL (2008). *Carbon Sequestration Project Portfolio 2008*. Available from: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2008/index.html.
35. CO2CRC (2009). *CCS activity in Australia*, Cooperative Research Centre for Greenhouse Gas Technologies (CO2CR2): Canberra (Australia).
36. IEA GHG (2009). *CO2 Capture and Storage RD&D Projects Database*, IEA Greenhouse Gas R&D Programme: Cheltanhan (UK).
37. Bachu, S., W.D. Gunter, E.S. Rubin, D.W. Keith, C.F. Gilboy, M. Wilson, T. Morris, J. Gale, and K. Thambimuthu (2005). *Overview of acid-gas injection operations in Western Canada*. Greenhouse Gas Control Technologies 7. Oxford (UK): Elsevier Science Ltd.
38. IPCC (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*, ed. B. Metz, et al. Cambridge (UK).
39. Litynski, J.T., S. Plasynski, H.G. McIlvried, C. Mahoney, and R.D. Srivastava (2008). *The United States Department of Energy's Regional Carbon Sequestration Partnerships Program Validation Phase.* Environment International. 34(1): p. 127-138.
40. Reeves, S., R. Gonzalez, S. Harpalani, and K. Gasem (2009). *Results, status and future activities of the coal-seq consortium.* Energy Procedia. 1(1): p. 1719-1726.
41. IEA (2008). *CO2 Capture and Storage: A Key Carbon Abatement Option*. IEA/OECD. Paris (France).
42. ZERT (2009). *A national resource for geologic sequestration science*. Available from: http://www.montana.edu/zert/index.html.
43. Ghomian, Y., G.A. Pope, and K. Sepehrnoori (2008). *Reservoir simulation of CO2 sequestration pilot in Frio brine formation, USA Gulf Coast.* Energy. 33(7): p. 1055-1067.
44. Miracca, I., K. Ingvar Asen, J. Assink, C. Coulter, L. Curran, C. Lowe, G. Torres Moure, and S. Schlasner (2009). *The CO2 Capture Project (CCP): Results from Phase II (2004-2009).* Energy Procedia. 1(1): p. 55-62.

45. FutureGen Alliance (2007). *Final Site Selection Report*, FutureGen Alliance Inc: Washington D.C. (USA).
46. US DOE (2008). *Fossil Energy Techline: DOE Announces Restructured FutureGen Approach to Demonstrate CCS Technology at Multiple Clean Coal Plants*. Available from: http://www.fossil.energy.gov/news/techlines/2008/08003-DOE_Announces_Restructured_FutureG.html.
47. FutureGen Alliance (2009). *FutureGen Cooperative Agreement with the U.S. Department of Energy*, FutureGen Fact Sheets & Presentations FutureGen Alliance: Washington D.C. (USA).
48. FutureGen Alliance (2009). *FutureGen Initial Conceptual Design Report*, FutureGen Alliance: Washington D.C. (USA).
49. Legg, J.F. and F.R. Campbell (2006). *Carbon Dioxide Capture and Storage: A Compendium of Canada's Participation*, Prepared under NRCan Office of Energy Research and Development Ottawa: Ontario (Canada).
50. Preston, C., S. Whittaker, B. Rostron, R. Chalaturnyk, D. White, C. Hawkes, J.W. Johnson, A. Wilkinson, and N. Sacuta (2009). *IEA GHG Weyburn-Midale CO2 monitoring and storage project-moving forward with the Final Phase.* Energy Procedia. 1(1): p. 1743-1750.
51. Lakeman, B., W.D. Gunter, S. Bachu, R. Chalaturnyk, D. Lawton, D. van Everdingena, G. Lim, and E. Perkins (2009). *Advancing the deployment of CO2 monitoring technologies through the Pembina Cardium CO2 Monitoring Project.* Energy Procedia. 1(1): p. 2293-2300.
52. Smith, S.A., J.A. Sorensen, E.N. Steadman, and J.A. Harju (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): p. 1981-1988.
53. Deng, X., M. Mavor, D. Macdonald, B. Gunter, S. Wong, J. Faltinson, and H. Li (2008). *ECBM Technology Development at Alberta Research Council*, Presented at the Coal-Seq VI Forum: Houston (US).
54. Keith, D. and R. Lavoie (2009). *An overview of the Wabamun Area CO2 Sequestration Project (WASP).* Energy Procedia. 1(1): p. 2817-2824.
55. Wilson, M., P. Tontiwachwuthikul, A. Chakma, R. Idem, A. Veawab, A. Aroonwilas, D. Gelowitz, J. Barrie, and C. Mariz (2004). *Test results from a CO2 extraction pilot plant at boundary dam coal-fired power station.* Energy. 29(9-10): p. 1259-1267.
56. Lysen, E., A. Faaij, and C. Hendriks (2005). *The CATO programme in the Netherlands on CO2 capture, transport and storage*, Presented at the 7th International Conference on Greenhouse Gas Control Technologies: Vancouver (Canada).
57. Jansen, D. and S. van Egmond (2009). *Recent developments in the Dutch CAPTECH programme.* Energy Procedia. 1(1): p. 1451-1456.
58. Meerman, H., T. Kuramochi, and S. van Egmond (2008). *CO2 Capture Research in the Netherlands*, R. Stuart, ed. CATO, Utrecht University: Utrecht (The Netherlands).
59. Nell, L. (2008). *CATO CO2 catcher pilot plant factsheet*. TNO Science and Industry. Delft (The Netherlands).
60. Pagnier, H. (2009). *The National CCS knowledge and innovation program 2009–2014*, Presented at the 4th Dutch CCS symposium: Driebergen (The Netherlands).
61. 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).
62. van Alphen, K., J. van Ruijven, S. Kasa, M. Hekkert, and W. Turkenburg (2009). *The performance of the Norwegian carbon dioxide, capture and storage innovation system.* Energy Policy. 37(1): p. 43-55.
63. Gassnova (2006). *Norwegian Gas Power Technology RD&D Program CLIMIT: Work Programme 2006*, Gassnova and the Research Council Norway: Oslo (Norway).
64. de Koeijer, G., Y.O. Enge, C. Thebault, S. Berg, J. Lindland, and S.J. Overå (2009). *European CO2 test centre mongstad-Testing, verification and demonstration of post-combustion technologies.* Energy Procedia. 1(1): p. 1321-1326.
65. Chadwick, A., R. Arts, C. Bernstone, F. May, S. Thibeau, and P. Zweigel (2008). *Best Practice for the Storage of CO2 in Saline Aquifers - Observations and Guidelines from the SACS and CO2STORE projects.* Vol. 14. British Geological Survey Occasional Publication. Nottingham (UK): p. 267.

66. Cook, P.J. (2009). *Demonstration and Deployment of Carbon Dioxide Capture and Storage in Australia.* Energy Procedia. 1(1): p. 3859-3866.
67. Cottrell, A.J., J.M. McGregor, J. Jansen, Y. Artanto, N. Dave, S. Morgan, P. Pearson, M.I. Attalla, L. Wardhaugh, H. Yu, A. Allport, and P.H.M. Feron (2009). *Post-combustion capture R&D and pilot plant operation in Australia.* Energy Procedia. 1(1): p. 1003-1010.
68. Beck, B. and T. Aiken (2009). *An Introduction to the IEA GHG International Research Network on Monitoring.* Energy Procedia. 1(1): p. 2383-2387.
69. Beck, B. and T. Aiken (2009). *An Introduction to the IEA GHG International Research Network on Risk Assessment.* Energy Procedia. 1(1): p. 2581-2586.
70. MIT (2008). *The GHGT 9 Conference Summary*, 9th International Conference on Greenhouse Gas Control Technologies (GHGT 9): Washington D.C. (USA)
71. CSLF (2008). *Carbon Sequestration Leadership Forum Recognized Projects*. Available from: www.cslforum.org.
72. GCCSI (2009). *Global CCS Institute Overview Booklet*, Global Carbon Capture and Storage Institute: Canberra (Australia).
73. Australian Government (2004). *Securing Australia's Energy Future. Australian Government*, Department of the Prime Minister and Cabinet: Canberra (Australia). p. 192.
74. Australian Government (2008). *Carbon Pollution Reduction Scheme: Australia's low pollution future*, Department of Climate Change: Canberra (Australia). p. 385.
75. VROM (2007). *Clean and Efficient: New energy for climate policy*, Ministry of Housing Special Planning and the Environment (VROM): The Hague (The Netherlands).
76. Environment Canada (2009). *2007 Greenhouse Gas Inventory - A Summary of Trends*: Gatineau Quebeck (Canada).
77. NETL (2007). *Carbon Sequestration Technology Roadmap and Program Plan*, National Energy Technology Laboratory, United States Department of Energy (DOE): Pittsburgh (USA).
78. Tjernshaugen, A. (2007). *Gasskraft. Tjue års klimakamp*. Pax forlag Oslo.
79. Obama, B. (2008). *Barack Obama and Joe Biden: New Energy for America*, Obama for America.
80. US EPA (2009). *EPA Analysis of the American Clean Energy and Security Act of 2009 H.R. 2454 in the 111th Congress*, Environmental Protection Agency: Washington D.C. (USA).
81. NME (2007). *Norwegian climate policy*, Summary in English: Report No. 34 (2006–2007) to the Storting. Norwegian Ministry of the Environment: Oslo (Norway). p. 43.
82. MCMPR (2005). *Carbon Dioxide Capture and Geological Storage: Australian Regulatory Guiding Principles*, Ministerial Council on Mineral and Petroleum Resources: Canberra (Australia).
83. Australian Government (2009). *Initial Release of Offshore Areas for Assessment of GHG storage sites-Guidance notes for applicants*: Canberra (Australia). p. 52.
84. European Commission (2008). *Proposal for a directive of the European Parliament and of the council on the geological storage of carbon dioxide and amending Council Directives*, European Commission: Brussels (Belgium).
85. US EPA (2008). *Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO2) Geologic Sequestration (GS) Wells: Proposed Rule*, Federal Register p. 43492–43541.
86. Pollak, M.F. and W.J. Wilson (2009). *Regulating geologic sequestration in the united states: early rules take divergent approaches.* Environmental Science and Technology 43: p. 3035–3041.
87. Waxman, H.A. and E.J. Markey (2009). *Summary of H.R. 2454, the American Clean Energy and Security Act of 2009*, Pew Centre on Global Climate Change: Arlington (USA).
88. Bachu, S. (2008). *Legal and regulatory challenges in the implementation of CO2 geological storage: An Alberta and Canadian perspective.* International Journal of Greenhouse Gas Control. 2(2): p. 259-273.
89. Government of Canada (2008b). *Turning the corner: Regulatory Framework for Industrial Greenhouse Gas Emissions.*

90. EIA (2009). *Energy Market and Economic Impacts of H.R. 2454, the American Clean Energy and Security Act of 2009*, Energy Information Administration, United States Department of Energy (DOE): Washington D.C. (USA). p. 82.
91. Forbes, S. (2009). *Carbon Capture and Storage and The American Clean Energy and Security Act*, World Resources Institute: Washington D.C. (USA).
92. Rubin, E.S. (2009). *A Performance Standards Approach to Reducing CO2 Emissions from Electric Power Plants*, Coal Initiative Reports, White Paper Series, Pew Centre on Global Climate Change, Carnegie Mellon University: Arlington (USA).
93. Garnaut, R. (2008). *The Garnaut Climate Change Review*, Garnaut Climate Change Review, Cambridge University press.
94. ECX (2009). *EUA Daily Futures (Spot) Contract: Historic Data*. Available from: http://www.ecx.eu/.
95. Groenenberg, H. and H. de Coninck (2008). *Effective EU and Member State policies for stimulating CCS.* International Journal of Greenhouse Gas Control. 2(4): p. 653-664.
96. Bellona Foundation (2009). *ZEP General Assembly 2009 calls for action on CCS*. Available from: www.bellona.org/articles/articles_2009/zep_2009.
97. State of Queensland (2007). *Clean Coal Technology Special Agreement Act 2007 – Act No. 30*: Queensland (Australia).
98. Australian Government (2009). *$4.5 billion clean energy initiative*, Ministry for Resources and Energy, Ministry for Tourism, Ministry for the Environment, Heritage & the Arts, Ministry for Climate Change and Water, Ministry for Innovation, Industry, Science and Research, Ministry of Finance and Tressury: Canberra (Australia).
99. Campbell, K. (2008). *Canada's Saskatchewan investing in carbon capture and storage demo plant*, Mining weekly.
100. Government of Canada (2009). *Canada's Economic Action Plan: Budget 2009*, Department of Finance: Ottawah (Canada).
101. Government of Alberta (2009). *Government moves forward on carbon capture projects*, Government of Alberta Information Bulletin.
102. Litynski, J., S. Plasynski, L. Spangler, R. Finley, E. Steadman, D. Ball, K.J. Nemeth, B. McPherson, and L. Myer (2009). *U.S. Department of Energy's Regional Carbon Sequestration Partnership Program: Overview.* Energy Procedia. 1(1): p. 3959-3967.
103. US DOE (2009). *Secretary Chu Announces Two New Projects to Reduce Emissions from Coal Plants*. Available from: http://www.energy.gov/news2009/7559.htm.
104. Charles, D. (2009). *Stimulus gives DOE billions for carbon-capture projects.* Science. 323(5918): p. 1158.
105. CRS (2009). *Energy Provisions in the American Recovery and Reinvestment Act of 2009 (P.L. 111-5)*, Congressional Research Reports for the People (CRS): Washington D.C. (USA). p. 23.
106. European Commission (2009). *Call for proposals concerning a program to aid economic recovery by granting community financial assistance to projects in the field of energy*, Directorate-General for Energy and Transport: Brussels (Belgium).
107. 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*, European Parliament: Brussels (Belgium).
108. Bryant, S. and J. Olson (2009). *Training carbon management engineers: why new educational capacity is the single biggest hurdle for geologic CO2 storage.* Energy Procedia. 1(1): p. 4741-4748.
109. Greenpeace International (2008). *False Hope, why carbon capture and storage won't save the climate*, E. Rochon, et al., ed. Greenpeace International: Amsterdam (The Netherlands). p. 44.
110. de Best-Waldhober, M., D. Daamen, and A. Faaij (2006). *Informed public opinions on CO2-capture and storage technologies*, Presented at the Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8): Trondheim (Norway).
111. Sharp, J.D., M.K. Jaccard, and D.W. Keith (2009). *Anticipating public attitudes toward underground CO2 storage.* International Journal of Greenhouse Gas Control. 3(5): p. 641-651.

112. Curry, T.E. (2004). *Public awareness of carbon capture and storage : a survey of attitudes toward climate change mitigation*, Cambridge MIT: Cambridge Massachusetts (USA).

113. Reiner, D., T. Curry, M. de Figueiredo, H. Herzog, S. Ansolabehere, K. Itaoka, K. Akai, F. Johnsson, and M. Odenberger (2006). *An international comparison of public attitudes towards carbon capture and storage technologies*, Presented at the Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8): Trondheim (Norway).

114. Ashworth, P., S. Wade, D. Reiner, D. Daamen, and K. Itaoka (2009). *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 Copenhagen (Denmark).

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

116. Chazan, G. (2009). *Shell's plan to lead in storage of carbon dioxide hits a snag*, Wallstreet journal.

117. Shackley, S., D. Reiner, P. Upham, H. de Coninck, G. Sigurthorsson, and J. Anderson (2009). *The acceptability of CO2 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 Greenhouse Gas Control. 3(3): p. 344-356.

118. Hund, G. and K. Judd (2008). *Stakeholder Acceptance Issues Concerning CCS*, Presented at the Ninth International Conference on Greenhouse Gas Control Technologies — Lessons Learned from FutureGen: Washington D.C. (USA).

119. Anderson, C. (2007). *Social research Otway CCS project*, Presented at the CO2CRC CCSA Seminar: Melbourne (Australia).

120. Wade, S. and S. Greenberg (2009). *Afraid to Start Because the Outcome is Uncertain?: Social Site Characterization as a Tool for Informing Public Engagement Efforts.* Energy Procedia. 1(1): p. 4641-4647.

121. Mathieson, A., I. Wright, D. Roberts, and P.S. Ringrose *Satellite Imaging to Monitor CO2 Movement at Krechba, Algeria,* GHGT-9 Greenhouse Gas Technologies: Washington D.C. (USA)

Interlude F

The introduction of new technologies often leads to resistance from established actors, or society. Previous chapters have shown that opposition has been encountered in the development of CCS technologies in various countries. The following chapter zooms in on the fulfilment of one particular system function in the Dutch CCS Innovation System that relates to this issue, namely “Creation of Legitimacy”. The study presented in this chapter aims to gain insight into the societal acceptance of CCS in the Netherlands, and to analyze whether and how this can influence further development and implementation of this technology. This extensive study has been separated into two parts. The main objective of the first part is to determine the stakeholders’ attitudes towards the technology and to pose conditions for the deployment of CCS in the Netherlands. In the second part, we explore one of the determining factors in the creation of legitimacy of CCS for the lay public, i.e. the way the Dutch press perceives and portrays CCS.

This chapter was originally published as [1]: van Alphen, K., van Voorst tot Voorst, Q., Hekkert, M. P., Smits, R.E. H. M. (2007). Societal acceptance of carbon capture and storage Technologies. *Energy Policy*, 35 (8), 4368-4380.

However, media articles related to CCS have been collected and systematically filed also for the period after 2007 [see 2]. Because this additional material also covers the media portrayal of the Barendrecht project, which is considered very important for the creation of “local” legitimacy for CCS technologies, the original published article in Energy Policy has been updated with recent results (where deemed appropriate).

7. Societal acceptance of carbon capture and storage Technologies in the Netherlands

Abstract

For the actual implementation of carbon capture and storage (CCS) technologies, societal support is a crucial precondition. This paper describes an extensive study on the legitimacy of CCS by stakeholders in the Netherlands and explores one of the determining factors in the acceptance of CCS by the lay public, i.e. the way the Dutch press perceives and portrays CCS. The stakeholder analysis, executed in 2006, shows that there is in principle a positive attitude towards CCS by industry, government, and environmental NGOs, provided that the conditions they pose on the deployment of CCS are met. The content analysis of Dutch news articles in the period 1991-2009 conveys that the media portrayal of CCS is —to a certain extent— a balanced reflection of the way CCS is perceived by the stakeholders. Both analyses show that the concerns about CCS have not overshadowed the main promise that CCS is part of the solution to climate change. However, the critical attitudes towards CCS found in the stakeholder- and media analysis will remain unchanged if no action is taken to address public concerns regarding the implementation CCS. Therefore, the conditions posed on the use of CCS by the stakeholders participating in this study, as well as the actions required to meet these conditions, could function as a proxy for the 'societal voice', articulating the most important issues concerning the future acceptance of CCS technology.

7.1. Introduction

Despite the fact that many countries strive for the stabilization of greenhouse gas concentrations in the atmosphere at a level that prevents dangerous interference with the climate system [3], most scenarios portray a substantial increase in the anthropogenic emissions of carbon dioxide for the decades to come. The world's primary energy supply will most probably continue to be dominated by fossil fuels until at least the middle of this century, and a portfolio of mitigation measures is required to provide the emission reductions needed to achieve stabilization [4, 5]. This notion has led to a growing interest among policy makers around the world in the technology of carbon dioxide capture and storage (CCS) as a means of reducing carbon dioxide emissions, while continuing to make use of (domestic) fossil fuel resources and infrastructure [6].

CCS is a technology that comprises the separation of carbon dioxide from industrial and energy related sources, transport to a storage location (e.g. saline aquifers and depleted hydrocarbon fields), and long-term isolation from the atmosphere. Some characteristics of this technology may cause societal resistance upon actual implementation, like the possible leakage of carbon dioxide from the storage reservoirs and its impact on the local environment [7].

Societal acceptance is widely recognized as an important factor influencing the successful development and diffusion of new technologies [8, 9]. Illustrative examples of societal opposition hindering or even stopping the actual implementation of planned projects involving energy technology can be found in relation to nuclear power [10-13]and, more recently, in wind energy programs [14-16].

Many decision makers now realize that a better understanding of potential societal responses preceding the implementation of CCS projects is desirable to effectively design public policy for this technology [17, 18]. Consequently, it is useful to study these possible response strategies in the early development stages of CCS technology, in order to overcome possible impediments created by various societal groups [19, 20].

Societal acceptance of CCS includes the response of both the lay public and stakeholders. We define stakeholders as agents with a professional interest in CCS. Hence, stakeholders can include industry, non-governmental organizations (NGOs), governments and research institutions. The issues concerning CCS are quite different for the lay public compared to the stakeholders. One of the reasons for this is that the latter nearly always have a defined agenda or set of preferred policy objectives in mind when evaluating CCS, whereas the lay public does not have an a priori viewpoint [21].

In fact, the few studies on public perceptions of CCS indicate that this technology is largely unknown to the general public [19, 22-27]. Moreover, a study by [28] shows that the current public opinion on CCS options, assessed by traditional questionnaires, is unstable and affected by small amounts of information given to the respondent. These uninformed opinions are weak indicators for predicting future public acceptance of CCS technology and by this a source of uncertainty for policy makers. Instead, marketing efforts of stakeholders and information given by the media[1] have a major influence on how CCS will be perceived by the general public [29, 30].

Therefore, we argue that stakeholders can play a double role in the development of CCS technology. On the one hand, they have a direct influence on the implementation of CCS projects, because of their professional interest in the technology. On the other hand, they can indirectly influence this process because of their ability to shape the public opinion by the way they proclaim their perception on CCS technology into society [31]. Despite this important (double) role of stakeholders, they (especially environmental NGOs) are hardly involved in CCS programs, nor are they subject of scientific studies on the societal acceptance of CCS [21, 32].

The relation between the attitudes of stakeholders and the opinion of the general public is far from simple, as the media to a large extend control what kind of communication goes out to the public [33-35], thus influencing the public debate by the way they interpret and present the information they receive from their sources [36, 37]. Proponents of a technology are often anxious that the media will amplify the technology's possible risks, altering their message in a negative way [32, 38, 39]. Vice versa, opponents of a technology may fear a ‘hosanna atmosphere’ created by the media. This implies that the understanding of complex technological issues by the lay public (whether or not that understanding is ‘correct’) relies heavily on the media, even if merely in terms of information diffusion [40]. Therefore, we argue that media portrayals of CCS can provide heuristics for the understanding and assessment of the lay public's opinion on CCS technology.

The aim of this paper is to gain insight into the societal acceptance of CCS in the Netherlands, and to analyze whether and how this can influence further development and implementation of this technology. We have separated this extensive study into two parts. The main objective of the first part is to determine the stakeholders’ attitudes and to pose conditions for the use of CCS technology in the Netherlands, as well as actions required to meet these conditions that have to be satisfied to increase stakeholder support for CCS. In the second part, we explore one of the determining factors in the public acceptance of CCS, i.e. the way the Dutch press perceives and portrays CCS.

The results of both parts are presented in this paper. In the following discussion, we will compare the stakeholders’ attitudes with the portrayal of CCS by the media; in order to assess the extent to which the attributes of CCS are subject to a process of amplification by the way the media portray the technology. Subsequently, we will elaborate on the implications of these results for the deployment of CCS, which allows us to advice on how public policy on CCS may be improved.

[1] Although people receive information concerning the aspects of complex technologies from many channels of communication, e.g. the internet, informal networks or the specialist press, the mass media is arguably the most important of these channels [32].

7.2. Design of stakeholder analysis

The selection of stakeholders participating in this study was guided by the importance of their support for the implementation of CCS technology in the Netherlands, as well as their influence on the Dutch public opinion. The organizations that were chosen represent government, industry (associations), and environmental NGOs. With this selection, a balanced representation of the different stakeholder groups was pursued (see Table 7-1). Note that no research institutes participated in this study. The reason for this is that research institutes have been involved in earlier similar discussions and the minutes of those studies explicitly indicate that the discussion drifted to the technical side, so that acceptance as such was not adequately addressed [41].

Table 7-1: Stakeholder groups that participated in our study and their role in the development of CCS.

	Stakeholder	Role
Government	Ministry of Economic Affairs	This ministry is responsible for energy policy and, thus, for the national policy on CCS
	Ministry of Housing, Spatial planning and Environment	Climate change policy is one of the main responsibilities of this ministry
	Provincial governance (Drenthe and Limburg)	These two provinces offer possibilities for CO_2 storage in depleted gas fields (Drenthe) and coal beds (Limburg)
Industry	Confederation of Dutch Industry and Employers Federation of Energy Companies (EnergieNed)	These umbrella organizations represent the interests of their member companies, thus showing the acceptance of CCS by companies in general and by energy companies in particular
	Nederlandse Aardolie Maatschappij BV and Shell BV	These companies are the largest oil and gas producers in the Netherlands and own most of the (depleted) oil and gas fields
Environmental NGOs	World Wide Fund for Nature, The Dutch Society for Nature & Environment and Greenpeace	These environmental NGOs are all engaged in the Dutch CCS debate. In this debate, Greenpeace operates through confrontation and action, while the other two are proponents of partnerships and open dialogues with other stakeholders

In total 12 representatives of the selected organizations were interviewed and invited for a workshop. The purpose of the in-depth interviews was to get a first impression of the attitudes of stakeholders towards CCS. Attitudes can be defined as evaluative and affective reactions to a particular subject, such as the deployment of CCS technology [42]. The output of the interviews and the results of comparable projects [43] were used to design a workshop around the questions whether CCS should be used to mitigate climate change and, if indeed this technology is to be used, what conditions would have to be satisfied to increase stakeholder support for CCS. With these two questions, insight is obtained into the acceptance of CCS by different stakeholder groups. To further deepen this insight, an additional step was made in the workshop in order to determine what actions and information are desired to meet the conditions for societal support of CCS.

The workshop took place early 2006 in an Electronic Board Room (hardware) with a Group Decision Support System (software). This interactive, computer-based system facilitates participants to communicate simultaneously and anonymously on unstructured and semi-structured problems by brainstorming, giving comments, and voting on statements [44]. Generally speaking, a Group Decision Support System may positively affect the following aspects of problem analysis [45, 46]:

- The system increases insight into the complexity of a problem: the involvement of different stakeholders can lead to a clustering of information and insights that, together, have a surplus value.
- It enables testing and evaluating: compared with individuals, a group of stakeholders can better assess the reality of results or solutions for a problem.
- It increases acceptance: involvement of a variety of interests may broaden the insight into the needs and points of view of different participants, which may contribute to the acceptance of solutions.
- It stimulates synergy and creativity: the involvement of different interests in the analysis of a problem can stimulate creativity when participants build on others' ideas, using insights and knowledge from different angles.

In our study, we used the characteristics of a Group Decision Support System to encourage open discussions between the stakeholders on different aspects of CCS; e.g. (long-term) risks and the role of CCS in the future energy supply system. These discussions elucidated the general attitude of several (groups of) stakeholders towards CCS. Furthermore, the system was used to discuss the conditions for increased stakeholder support in the process of realizing CCS in the Netherlands, and to vote on statements on the importance of these conditions. Finally, the stakeholders brainstormed on the actions required to meet these conditions for acceptance, and discussed the most promising ones.

7.3. Results of stakeholder analysis

All parties consider climate change a serious and urgent problem lacking a simple solution. Government, industry, and environmental NGOs agree that CCS technology should be used to mitigate climate change. They argue that, in order to achieve substantial emission reductions, better energy efficiency, renewable energy, and CCS will all be needed simultaneously. Although most environmental NGOs see CCS technology as a necessary option to achieve the required carbon dioxide reductions, it is not their first choice. Their viewpoints range from 'not the favourite option' to an 'option of last resort'. According to the stakeholders participating in this study the role of CCS within this total package of climate measures should be focused on achieving large amounts of carbon dioxide reductions in a relatively fast and easy way. CCS can be used to 'buy time' for the development and large-scale application of a more sustainable energy supply system.

Additionally, all parties emphasize that the climate problem calls for a global approach and they consider CCS as a global mitigation option with considerable potential. Particularly for countries such as China and India, where large coal reserves are being utilized to meet the rapidly increasing energy demands of their growing economies.

Despite the positive attitude towards CCS, the government, industry, and environmental NGOs pose several conditions on their support for the actual implementation of this technology, namely: safety, temporality & partiality, financial stimuli, simplicity, cooperation & commitment, and open communication. This set of conditions is detailed below. The description of each condition is followed by possible actions required to meet the condition. Only few references to particular stakeholder groups are made, because of a broad consensus among the stakeholders. In the cases where such specifications are absent, all stakeholders agreed on the condition and/or action offered.

7.3.1. Safety

A first condition for the acceptance of CCS is safety. CCS should be safe on the short term as well as on the long term, both for humans as well as for the environment in general. The understanding among all stakeholders is that the short-term (operational) risks can be adequately managed, because of industrial analogues such as acid gas injection, enhanced oil recovery, natural gas storage, and carbon dioxide pipeline transportation. Contrary to these short-term risks, the long-term risks are less well known. Leakage of carbon dioxide from the reservoirs is generally considered the largest risk. The consequences of carbon dioxide leakage are mainly of environmental nature, although the efficacy of CCS will also be reduced by leakage. The safety risks for human beings, on the other hand, are expected to be minimal.

The concerns about carbon dioxide leakage differ among the parties. In general, the industry trusts the technology and considers the risk of leakage small and well manageable. The government expects the risks to be small as well, but emphasizes that additional research is required. The environmental NGOs are most concerned about the leakage risks. Their concerns are mainly based on uncertainties, caused by a lack of knowledge of (the quantification of) possible leakage pathways, the behaviour of carbon dioxide in the underground, and the appropriate materials to seal abandoned injection wells.

These uncertainties regarding the CCS risks will have to be reduced in order to stimulate the acceptance of CCS by the various stakeholder groups, especially environmental NGOs. To accomplish this, the attendants of the workshop agreed that pilot projects will have to be initiated, taking into account the experiences of other (foreign) projects. Research on, for example, natural and industrial analogues will also be necessary. In order to optimally learn from demonstration projects, skilled monitoring will be necessary, which may require new monitoring techniques. To assure safety for longer periods of time, rules and standards will have to be developed for these monitoring techniques. This legislative framework should also contain requirements for storage site selection, operation and storage, and reporting (e.g. pressure, amounts of sequestered carbon dioxide). Finally, both government and environmental NGO representatives suggested creating a fund to be used for the compensation of unexpected consequences on the long term.

7.3.2. Temporality & partiality

The second condition for the acceptance of CCS is that it should be used only temporarily and as a partial solution to the climate change problem. In this case, temporarily means for the duration of several decades. Since most stakeholders consider CCS an unsustainable ‘end-of-pipe solution’, it should not be used if more sustainable solutions become widely available, as can be expected on the longer term. At the same time though, the application term should not be shorter than 25 years, as various investments will have to be made and the industry is not willing to make those investment if the time period is too short to recover the costs.

Although most environmental NGOs consider CCS a necessary option to achieve the required carbon dioxide reductions, it is not their first choice. According to the NGOs, it should only be used as an addition to measures stimulating energy efficiency and the use of renewable energy. Furthermore, they emphasize that carbon dioxide emissions are not the only (unsustainable) problem of fossil fuels; there are for example the human casualties in coal mining and other harmful emissions than carbon dioxide. These problems will remain if CCS displaces learning and cost reductions in renewable energy technology.

The opinions differ as to whether action is required to assure the temporality of CCS. According to both government and industry, CCS will phase out over time due to market mechanisms. No specific action is required to assure temporality, as the potential of (cheap and safe) storage sites—which will be used first—is limited. Furthermore, new technologies will develop, making CCS superfluous or relatively too expensive in the long term. However, the environmental NGOs do not fully concur in this standpoint. CCS may phase out by itself, but whether this will indeed happen and, if so, when it will occur is not certain. For this reason, in the medium term, action might be required to assure the CCS’ temporality. This action will have to be in the form of severe requirements for CCS (sites) e.g. more stringent licensing procedures and the stimulation of renewable energy technologies.

To guarantee that efforts for CCS are not made at the expense of efforts for energy efficiency and renewable energy, the environmental NGOs propose a policy that links CCS support to increased funding for renewable energy and efficiency, e.g. by ‘double matching’: for each (government) Euro spent on CCS, at least two Euros should go to energy efficiency and sustainable energy. Other stakeholders did not share this requirement, because of the cost differences in measures to support energy efficiency and CCS technologies. However, they did not provide other clear actions that would satisfy the condition of partiality.

7.3.3. Financial stimuli

In order to make investments in CCS technologies attractive and acceptable for the industry, financial stimuli will be necessary. CCS is rather expensive, without yielding direct benefits for the investing company. Under the current circumstances, there are very few incentives for companies to invest in CCS: the capture and preparation of carbon dioxide reduces the energy efficiency of power plants. This ‘energy penalty’ also has its repercussions on the electricity price, which could lower the acceptance of CCS by the general public.

A first step towards financial stimuli for CCS is its inclusion in the European Union's Greenhouse Gas Emission Trading Scheme (EU ETS). By including CCS in the EU ETS, it will be part of a generic mechanism for carbon dioxide mitigation options. Specific measures for CCS are not desired, for they limit the freedom of companies and are less cost-effective. A second step is setting ambitious emission reduction targets for the post-Kyoto period. This will lead to lower emission ceilings for national industries, which will increase the price for carbon dioxide to a level that exceeds the costs of CCS and, thus, create a financial stimulus for its application. Furthermore, by setting targets, the financial uncertainty will be reduced resulting in a greater willingness of the industry to invest in carbon dioxide mitigation measures. According to the stakeholders attending the workshop, this will make CCS commercially attractive in due time after the first Kyoto period (2012). Ambitious emission reduction targets will also improve the acceptance of CCS by the environmental NGOs, as the chances that renewable energy and energy efficiency suffer from CCS efforts are reduced, since all of these options will be needed to achieve the targets.

7.3.4. Simplicity

A fourth condition is that CCS should not be made more complex than necessary. This means it should not be linked obligatorily to other possible advantages, such as hydrogen or coal bed methane production. The rationale is that CCS is complex enough in itself. Despite this complexity, it can be implemented relatively soon and in a relatively easy and cheap way. However, these advantages could disperse if CCS is combined obligatorily with other, possibly more complex, purposes. Additionally, the climate change might have such far-reaching effects, that no additional reason is needed to justify the deployment of CCS. A government representative added that obligatory links could also incur risks: if the anticipated additional advantages turn out to be disappointing, the public support for CCS might decline.

The participants of the workshop considered the origin of the carbon dioxide for sequestration irrelevant: the purpose of CCS is to keep carbon dioxide out of the atmosphere and not to facilitate a hydrogen economy. The way the carbon dioxide is captured is not relevant for this purpose, nor for the acceptance of this technology. The process is only relevant for the costs of carbon dioxide.

No action is required to fulfil this condition. The combination of CCS with hydrogen production or other additional advantages should not be made obligatory. If this combination occurs, it should be in the hands of the market instead of the legislator.

7.3.5. Cooperation & Commitment

A fifth condition for acceptance is commitment of and cooperation between different sectors. The Netherlands has competitive advantages in the field of CCS because of the presence of (nearly) depleted natural gas reservoirs as well as other storage options and the considerable knowledge of CCS within a number of companies and research institutes. In order to take advantage of this strategic position, cooperation between and commitment of various parties as well as a long-term vision will be necessary. Both industry and government raised this point. Coordination can bring existing knowledge and expertise together, and promote the best options to be identified and used. Additionally, a proper coordination of activities will stimulate learning and prevent double work and unnecessary investments. Representatives of both industry and government gave the example that cooperation between parties may prevent production wells of depleted gas fields from being sealed, so that no new wells will have to be drilled when the decision is made to inject carbon dioxide into those fields.

The action required for the fulfilment of this condition is to collectively draw up a plan for the implementation and application of CCS. This plan will have to be based on the strategic positions of the parties involved as well as their responsibilities. Furthermore, it should present what needs to be done at what moment. In other words, a roadmap for the implementation of CCS should be drawn up. This will reduce the uncertainties regarding investment decisions for CCS and improve the commitment and, thus, the reliability of the different parties involved. Additionally, as an industry representative noted, if the parties are able to cooperate and coordinate efficiently, there will be substantial business opportunities for this option to export the gained knowledge and experience.

7.3.6. Open communication

The sixth condition is open communication about CCS to the public. To create and maintain public acceptance, appropriate communication is essential. Without public acceptance, the stakeholder groups—particularly the industry—will not contribute to the implementation and use of CCS, for they will consider it too risky. If CCS is to be implemented on a larger scale, communication to the public will have to be intensified and organized in such a way that it creates public awareness and understanding. Therefore, the conditions mentioned above will have to be met and communicated properly to the public at large. However, the stakeholders did note that the conditions that have to be satisfied to increase their support for CCS might be quite different from the concrete acceptance of storage at a specific site by local communities.

This ‘not in my backyard principle’ (NIMBY) can be reduced by giving local communities the opportunity to voice their concerns, and by providing additional benefits. In order to create societal acceptance at large, open, clear, two-way and well-timed communication of information will be necessary, putting CCS in the broader perspective of climate change. According to all stakeholders, the public should become aware of the fact that climate change is a serious and urgent problem, and that CCS is needed to solve this problem. Furthermore, the risks of climate change will need to be communicated in a clear and—for the public—understandable language. The ‘CCS message’ should be based on experience, knowledge, and facts as much as possible, and refer to current projects and analogues. Communication to society is a joint responsibility of all organizations involved and includes consultation of the public.

7.4. Design of media analysis

The stakeholder analyses showed that government, industry, and environmental NGOs do not expect the acceptance of CCS technology by the general public to be a major problem, provided that the conditions discussed in the previous section are met and communicated to society in an open and understandable way. Besides consultation, this communication should include the stakeholders' consensus view, that climate change is a serious global problem, that rigorous emission reductions are needed to reduce this threat, and that CCS is an effective means to accomplish this. However, the established mass communication media, such as newspapers, influence this communication to the public by the way they interpret and 'frame' information on CCS [32].

This part of our study focuses on the role of the print media in framing CCS technology in their communication to the public. Therefore, all documents related to CCS in the main Dutch daily newspapers were retrieved in the period 1991-June 2006, as well as July 2006-April 2009 from the LexisNexis® Academic database. The terminology for CCS used in the press releases of the Intergovernmental Panel for Climate Change (IPCC) was taken as a starting point. These terms were translated for the Dutch language and used in the database to obtain a sample of 30 newspaper articles. These articles were analyzed to find various translations of 'carbon capture and storage'. Search terminology comprised: 'Schoon Fossiel' OR 'CO_2' OR 'kooldioxide' OR 'Koolstofdioxide' AND 'opslag' OR 'afvang' OR 'sequestratie'; these terms were used to obtain the final set of articles to be used for this report. This set contained several irrelevant articles, for example describing carbon storage in forests. These articles were removed and the remaining set comprised 887 articles, covering a time period from 1991—when the first article appeared—until April 2009 [1, 2].[2]

In the content analysis of the Dutch news articles on CCS, first of all, we focused on the events that triggered the publication of these articles, such as policy announcements, or the release of scientific reports. We explored the extent to which external events stimulate media coverage and influence the way the press perceives and portrays CCS. For example, an increase in these 'trigger events' could change the way the media interpret and, subsequently, presents CCS to the public. Furthermore, it gives an indication of the recognition of CCS in the media (as more CCS related issues are being published) and it presents the background for the media portrayals of CCS technology. This helps to understand the articulation of key issues related to CCS in the Dutch media.

This articulation process is depicted by the distribution of positive, negative, and neutral articles over time. Articles were classified 'positive' if the majority of statements used in the article were in favour of CCS, 'neutral' if the number of negative and positive statements was balanced, and 'negative' if the majority of statements and the overall impression of the article were negative towards CCS. A fourth category was introduced, indicating whether CCS is mentioned in an article but not discussed as such. A second researcher checked this

[2] Please note that the results of the content analysis of the articles that appeared in the time period from 1991 until June 2006 were published in van Alphen et al. [1] and the content analysis of the remainder of the articles was presented in the thesis of Kliest [2].

classification, after which differences were discussed to harmonize the classification procedure. In cases of doubt, more attention was paid to the title and the first few lines of the article.

Finally, the main arguments in favour or against CCS were distilled from each article, as well as the type of actors linked to these arguments if they were cited in the article. This enables a comparison between the statements that stakeholders made during the workshop and the ones depicted by the media. This will be done in the discussion of this paper, wherein the results of the stakeholder analysis and this study on the portrayal of CCS by the print media will be discussed and compared.

7.5. Results of media analysis

CCS received considerably more attention by the media from 2005 onwards. Partly, the increasing number of articles discussing CCS is a consequence of the fact that there were an increasing number of events to report. Figure 7-1 presents the annual distribution of CCS articles related to key ‘trigger events’ that occurred between 1991 and June 2006, such as the release of scientific reports, and the launch of specific commercial projects. It shows that the increasing number of CCS projects, together with a more intense climate change debate in recent years, not only have led to increased media attention for CCS, but also to a more positive portrayal of CCS in the press. From 2007, the media attention for CCS started to grow even faster when the first plans to store CO_2 in a depleted gas field under the town of Barendrecht were announced. This event had a drastic impact on the way CCS was portrayed in the media, which we will further outline in Sections 7.5.5. and 7.5.6..

7.5.1. 1991–1996

Figure 7-1 shows that in the early nineties, CCS did not get much press attention. The possibility to store carbon dioxide underground was first reported in relation to a demonstration coal gasification plant in Buggenum. A year later, CCS was mentioned in relation to the Earth Summit in Rio de Janeiro, the Dutch Energy Outlook 1990–2015 [47] and the First International Conference on Carbon Dioxide Removal held in Amsterdam [48]. This did not lead to any pilot projects, because of the disapproval of such projects by the Dutch Energy Council and a reserved stance of the ministries of economic and financial affairs [49]. Even though the style of discourse used in relation to CCS was rather cautious in the mid-nineties, media attention started to grow with the publication of the IPCC Second Assessment Report on Climate Change [50] and subsequent Dutch reports on this matter by the Centre for Energy Conservation [51] and the Dutch Organization for Applied Scientific Research [52].

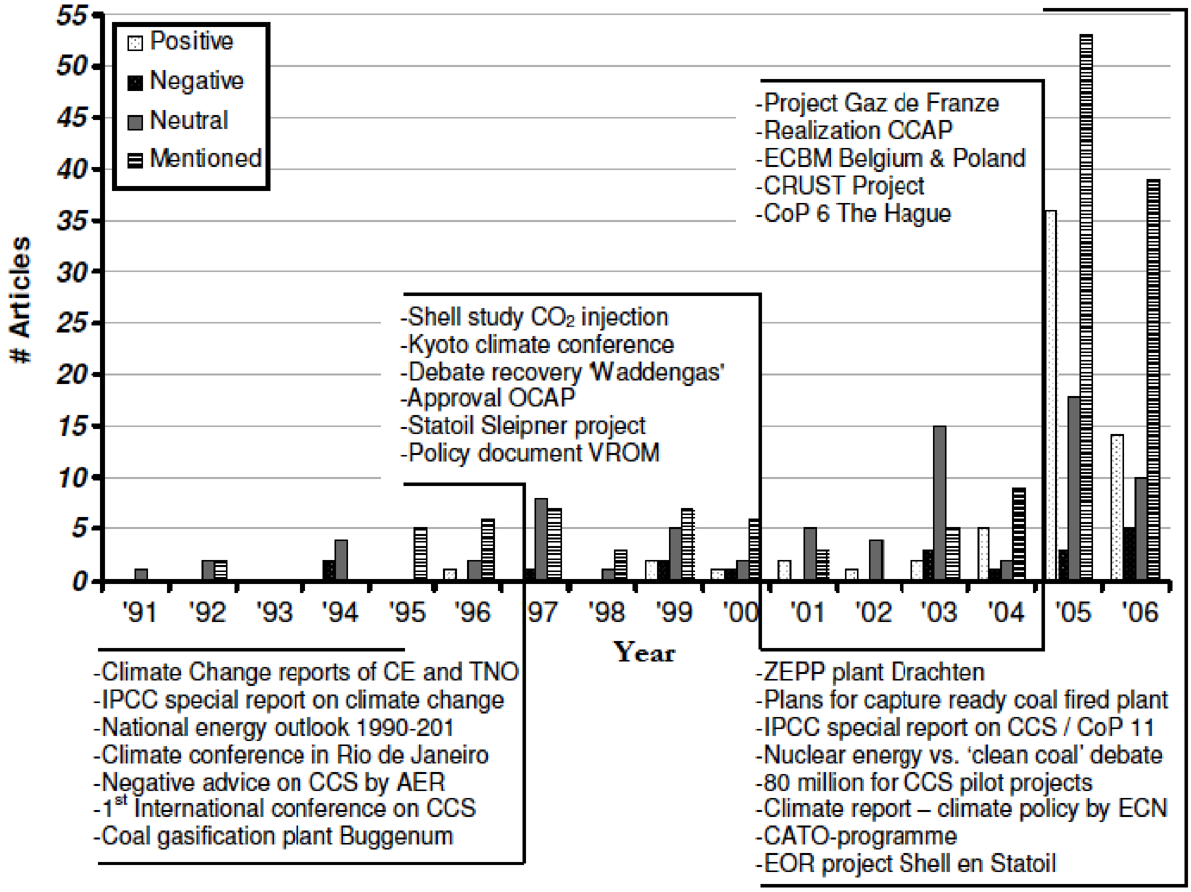


Figure 7-1: The number of articles on CCS published in Dutch newspapers in the period 1991–2006; subdivided in positive, negative, neutral and 'only mentioned' articles and related to key 'trigger events'.

7.5.2. 1997–2000

Following the example of Statoil—the company that started the storage of carbon dioxide in an aquifer underneath the Norwegian North Sea—Shell announced their plans to store a CO_2 stream from the Shell Pernis refinery. This announcement triggered fair media attention in 1997, especially after the Conference of Parties (CoP) III in Kyoto. Eventually, part of the carbon dioxide from Shell Pernis was not stored underground, but transported to greenhouse horticulture in order to meet the carbon dioxide requirement. This plan was approved in 1999 and realized by OCAP [53]. In that same year, media attention for CCS was related to the Dutch debate on the limited allowance of natural gas drilling in the 'Waddenzee' ('Storage of carbon dioxide is an option to prevent subsidence of depleted gas fields'). Furthermore, a policy document on climate change by the Ministry of Housing, Spatial planning, and Environment [54], referred to CCS as the most important back-up option for the Netherlands to reach its emission reduction targets as formulated in the Kyoto protocol. At the end of the millennium, the way CCS was covered by the press shifted slightly from 'neutral' to 'positive'.

7.5.3. 2001–2004

This trend continued with the press coverage of the CoP-6 in The Hague, which was an important stimulus for the realization of the CO_2 Re-use through Underground Storage

(CRUST) project [41]. This project was covered quite extensively in the media in 2002. In 2003 and 2004, the news articles on CCS were dominated by several CCS projects in both the Netherlands and abroad. The project receiving most media coverage (mostly positively) was the domestic carbon dioxide storage experiment in the North Sea (field K12-B), carried out by Gaz de France and monitored by the Dutch Organization for Applied Scientific Research (TNO-NITG). Furthermore, there was some media attention for the RECOPOL project in Poland, a research project to investigate the use of CO_2 for enhanced coal bed methane production (ECBM), and for research performed by the Flemish Institute for Technological Research on the possibility to store carbon dioxide in Flemish coalmines.

7.5.4. 2005–2006

As shown in Figure 7-1, the amount of news articles on CCS in 2005 and 2006 is quite high compared to the previous years. This can be explained by the increasing number of CCS related events in this period, and by the fact that the projects and plans for CCS implementation have become more concrete. In the beginning of 2005, three possible locations for zero emission power plants (ZEPP) are discussed in the media. Most of the attention is focused on SEQ B.V., planning to build a ZEPP in cooperation with the ‘Nederlandse Aardolie Maatschappij’ in the North of the Netherlands (city of Drachten). Apart from this project, CCS is mentioned in several articles related to the realization of new coal plants on the ‘Maasvlakte’ (near the city of Rotterdam) and the ‘Sloegebied’ (province of Zeeland). The newspapers report on the possibility to equip these new power plants with capture technology, as an alternative to expand the nuclear energy capacity as a greenhouse gas mitigation strategy. This discussion on the possible role of CCS in the future energy supply system of the Netherlands was partly initiated by the realization of national research program on CCS (CATO). Other primary trigger events for this debate were the release of the IPCC Special Report on CCS [7], the CoP 11 in Montreal, and the first National Conference on CCS in the Netherlands; both held in 2005.

The debate on nuclear versus ‘clean coal’ was extensively covered by the media and one of its outcomes in 2006 was that the current nuclear plant (Borssele) in the Netherlands will be kept open for a longer period of time, i.e. until 2033, instead of 2013, and that part of the revenues (80 million Euros) are reserved for CCS demonstration projects. This corresponded with an influential report presented by the Energy Research Centre of the Netherlands (ECN) and the Dutch Environmental Planning Bureau [55], proclaiming nuclear energy and CCS to be the most affordable options when it comes to achieving the emission reduction targets on the short term. Other news articles in 2005-2006 on CCS cover the agreement between Shell and Statoil to work towards developing the world's largest project using carbon dioxide for enhanced oil recovery offshore[3] and importance of CCS in relation to Al Gore’s climate change movie “An inconvenient Truth”.

[3] As described in Chapter 2, this prestigious Halten CO_2 Value Chain project was cancelled 2 years later.

7.5.5. 2007 – April 2009[4]

Media attention for CCS started to grow further in the second quarter of 2007 when the Dutch Government officially announced its financial support of €80 million for some CCS pilot projects. At the same time a large number of CCS related reports were released and discussed by the Dutch writing press (see Table 7-2 for an overview). Towards the end of 2007, the first plans to store CO_2 in a depleted natural gas field under the town of Barendrecht were made public.[5] Nevertheless, the big media hype around the project, did not start until a year later. In the meantime media attention focussed on the launch of the "CO_2 Catcher", a CO_2 capture pilot project at the Maasvlakte (Rotterdam) operated by E.ON-Benelux and the Dutch Institute for Applied Scientific Research. The second peak of media attention for CCS occurred in the last quarter of 2008, when €60 was made available by the Government for the development of two CO_2 storage projects at Barendrecht and Geleen.[6] It is worth noting that the CO_2 storage project at Geleen has 'only' been mentioned twenty times in the total number of 582 articles that have been filed for this time-period, compared to 97 articles that were related to the Barendrecht project. Besides interest into funding from the National Government a fare bit of media attention was paid to the announcement of the EU to possibly fund a CCS project in the Netherlands with €180 million from its economic stimulus package. In the first trimester of 2009, 129 articles on CCS appeared in the Dutch newspapers. In the months before the Commission responsible for Environmental Impact Assessment of the Barendrecht project had to come to a decision (April 2010), the Dutch national newspapers took the opportunity to publish a large number of articles on CCS with the Barendrecht project as the main topic. In total 40% of the news coverage on CCS was related to the Barendrecht project and most of these articles portrayed a negative picture of CCS.

[4] This Section is largely based on Kliest, 2010 [2].

[5] The Barendrecht depleted gas field is only 18 km from a source of pure CO_2: Shell's hydrogen production plant in Pernis. The location is attractive because existing natural gas infrastructure can be re-used and the small reservoir can be filled rapidly so that the entire transport and storage cycle down to the permanent sealing of the injection wells can be demonstrated within a timeframe of several years.

[6] At the Chemelot site in Geleen Orascom (former DSM Agro) operates two ammonia factories whereby relatively pure CO2 is released. This CO2 is used partly in other chemical production processes and partly delivered to the soft drink industry. The excess amount of pure CO2 can be can be injected in a chalk-sandstone layer below coal layers located under the site.

Table 7-2 : CCS events reported in the Dutch writing press between January 2007 and April 2009 [2]. Note that in this Table, events that were picked up by only one press article, were not included.

CCS R&D, Pilots and Demonstration projects	2007	2008	2009	Total
CO_2 Storage Barendrecht (Shell NAM OCAP)	4	41	52	97
E.ON centrale Maasvlakte (CO_2-catcher TNO)	4	20	1	25
NUON Magnum CCS project - Eemshaven	9	9	2	20
DSM Chemelot CO_2 Storage Project Geleen (GTI)	0	10	10	20
Rotterdam Climate Initiative (RCI)	5	11	3	19
Nuon demonstration coal gasification plant Buggenum	8	5	2	15
CATO-1	2	7	2	11
E.ON MPP3 Maasvlakte - ROAD Project	0	7	2	9
ZEPP by SEQ International (Drachten and Corus Ijmuiden)	5	2	0	7
North of the Netherlands CCS Region- Energy Valley	0	4	1	5
RWE and Gasunie CCS Project - Eemshaven	0	5	0	5
CATO-2	0	5	0	5
Vattenfall CO_2-capture Schwarze Pumpe (Germany)	1	2	1	4
CO_2 Storage Project Ketzin (Germany)	4	0	0	4
FutureGen CCS Project (US)	1	1	0	2
Clinton Climate Initiative	0	2	0	2
Statoil Sleipner CCS project (Norway)	1	1	0	2
Total Lacq Basin CCS project (France)	2	0	0	2
Rotterdam Climate Initiative (RCI)	0	2	0	2
K12-B storage project (GDF Suez & TNO)	2	0	0	2
Investments and Policy	**2007**	**2008**	**2009**	**Total**
CO_2 Emission Trading (EU ETS)	8	24	2	34
60 million for storage projects in Barendrecht and Geleen	0	15	9	24
5/6 Billion for CCS by EU - 250/180 million for Dutch projects	0	5	14	19
80 million for CCS projects	10	0	0	10
Coalition Accord New Dutch Government	8	0	0	8
Transposition EU CCS Directive into Dutch Mining Law	0	6	1	7
European Parliament: "CCS compulsary for new build power plants"	0	2	0	2
Reports and Conferences	**2007**	**2008**	**2009**	**Total**
Energy Report 2008 (National Government's Energy Vision)	0	8	0	8
Advisory report on Barendrecht by EIA commission	0	0	7	7
UN Climate Conference Bali December 2007	6	1	0	7
Report: CCS in the Rijnmond region 2007 (DCMR)	5	0	0	5
Advice Taskforce Energietransition 2007 (Agenda Energy 2007-2020)	5	0	0	5
Netherlands and Saudi Arabia CCS conference in The Hague	0	5	0	5
Energy Vision 2050 Report (Netherlands Centre for Energy Reserch-ECN)	5	0	0	5
Climate Summit EU March 2007	4	0	0	4
Assessment Report work program: "Clean and Efficient"	0	4	0	4
IPCC Fourth Assessment report	4	0	0	4
Copenhagen Climate Summit (lead up)	0	1	2	3
UN Summit: Poznan (Poland)	0	1	2	3
Environmental Assessment 2007 (Environmental Assessment Agency)	3	0	0	3
International Energy Forum (conference, Rome)	0	2	0	2
Climate Summit Bangkok May 2007	2	0	0	2

7.5.6. Media Portrayal of CCS

What is striking in the augmenting media attention for CCS is not only the considerable increase in the absolute number of news articles, but also the rise and fall in the relative amount of 'positive' articles (see Figure 7-2). If we leave out the articles in which CCS is only being mentioned briefly and the ones in which it is referred to as an item in the discussion of another topic, the relative share of positive articles has risen from approximately 10% in the nineties to 60% in 2006. On average, the share of negative articles per year has decreased from 17% in the first two time periods to 11% in 2006 onwards. However from 2007 onwards negative publicity around CCS started to grow, reaching its peak in the first trimester of 2009, wherein almost 50% of the articles related to CCS portrayed the technology in a negative way. This was mainly caused by the negative portrayal of the Barendrecht project in the most recent period of the analysis.

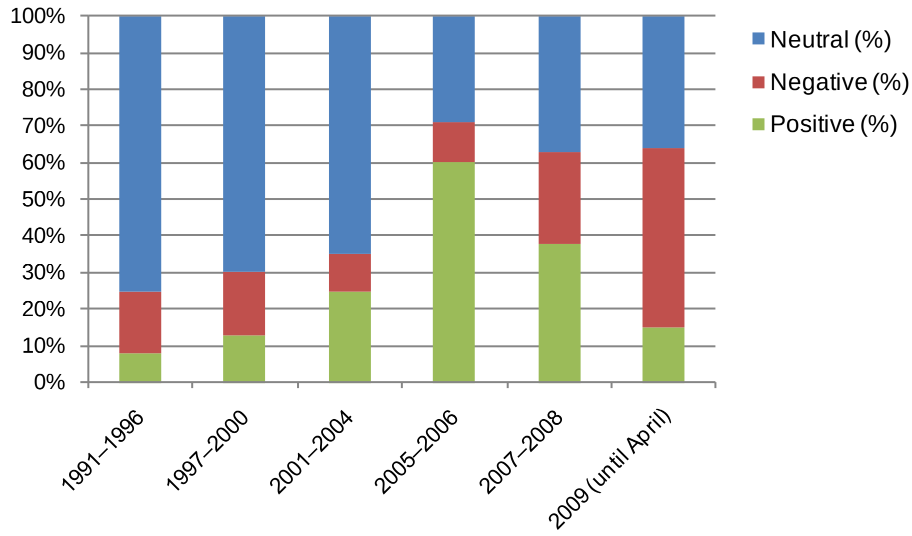


Figure 7-2: Overall portrayal of CCS in Dutch print media in six different time periods.

Table 7-3 shows that in 79 articles in between 2007 and April 2009 CCS has been described as unreliable and not safe. This line of argumentation was mainly used in the press coverage of the Barendrecht project. Furthermore, the national newspapers wrote 33 times about the lack of public support for CCS and mainly referred to the citizens of Barendrecht. According to the press, the citizens of Barendrecht were concerned about the public health risk of the projects and afraid that the value of their houses would devaluate as a consequence of the CO_2 storage project. Without Barendrecht the number of negative arguments would be substantially lower. Between January and April 2009 29 negative CCS articles were released, which represents 49% of the articles that contain an opinion on CCS. Table 7-3 also shows that in the most recent years there has been more talk about the lack of supportive legal and regulatory frameworks for CCS.

Table 7-3: Overview of the rank and number of negative arguments between 2007-April 2009 compared to the period 1991-2006 [2].

Negative Statements	2007 - April 2009		1991 - 2006	
	Rank	Frequency	Rank	Frequency
Technology not reliable (safety not proven)	1	79	6	13
High costs (electricity production + CO_2 capture)	2	60	1	34
Lack of public support for CCS	3	51	9	5
Government support needed (dependent on subsidies - no market)	4	47	5	13
Risks (general)	5	33	3	15
Threat for renewable energy/energy efficiency	6	32	4	14
Lack of legal and regulatory frameworks	7	31	-	-
Energy penalty (lower efficiency of power plants with CO_2 capture)	8	31	7	10
Public health risks	9	26	14	3
Liability issues in case of leakage	10	22	11	4
Lack of (a common) CO_2 transport and storage infrastructure	11	20	19	1
Devaluation of house prices	12	19	-	-
Stimulation of fossil fuel use (indirect support for 'dirty' coal)	13	13	13	4
Uncertainty about CO_2 behaviour in reservoir	14	11	12	4
Seismic effects (subsidence)	15	11	17	2
End-of-pipe solution (no solution to the problem)	16	8	2	22
Ecological risks through leakage	17	8	8	9
Lock-in (sub-optimal) fossil fuel based energy system	18	7	16	3
Against principle 'polluter pays'	19	5	15	3
Continuing fossil fuel dependency	20	4	10	5
Groundwater contamination risk	21	4	-	-
CCS does not reduce emissions	22	4	-	-
Uncertainty around climate benefits in case of leakage	23	3	12	4
Explosion risk	24	1	-	-
Problems with spatial planning	-	-	18	2

A negative argument that has been used frequently in both time periods is the lack of a market for CCS and the subsequent implication that government support (including public money) is needed to support its development. Even though CCS is considered to be cost-effective compared with other carbon dioxide mitigation strategies, there are high costs involved in the deployment of CCS. At this moment CCS substantially reduces the energy efficiency of coal or gas fired plants. Therefore, large RD&D investments are needed to lower this energy penalty and, thus, a substantial part of the costs involved in CCS. Given the fact that, in some articles, CCS is considered an end-of-pipe solution, it is proclaimed in the media that when government funding is provided to CCS this should not come at the expense of the support of other mitigation technologies, like renewables.

Table 7-4 clearly shows that one of the major themes in the news articles, namely the 'promise' that CCS could help accomplish a significant reduction in carbon dioxide emissions into the atmosphere, has been dominant throughout the whole time period. Various other positive arguments listed in Table 7-4 relate to this promise, e.g. the large geological potential for CCS, the existing expertise on this technology, and the realization of successful pilot projects. Furthermore, economic arguments contribute to a positive portrayal of CCS in the Dutch media, i.e. its cost-effectiveness compared to other carbon dioxide mitigation options, the possibility for enhanced oil and gas recovery, and business opportunities for Dutch companies. This argument has been used more frequently in the most recent period; partly in relation to the press coverage of the Rotterdam Climate Initiative (RCI).[7] As part of this initiative, the city of Rotterdam (responsible for 20% of all emissions in the Netherlands) aims to reduce the city's emissions by 50% in 2025, of which half should be realized by the application of CCS, i.e. 20 Mt CO_2 captured and stored or reused by 2025. New positive statements in press coverage of CCS compared to the period before 2007 include the possibility of "negative CO_2 emissions", when CCS is applied to biomass based power plants.

Table 7-4: Overview of the rank and number of positive arguments between 2007-April 2009 compared to the period 1991-2006 [2].

Positive Statements	2007 - April 2009		1991 - 2006	
	Rank	Frequency	Rank	Frequency
CO_2 emission reduction (while using fossil fuels)	1	205	1	99
Large mitigation potential	2	65	2	34
Safe and reliable CCS technologies available	3	62	7	17
Business opportunities for Dutch companies	4	33	9	14
Part of broad energy supply portfolio against climate change	5	32	5	18
Bridging technology "buys time for renewables"	6	32	17	1
Answer to growing global fossil fuel demand (India, China)	8	23	15	2
Enhanced oil/gas recovery	9	21	6	17
Cost-effectiveness (compared to renewable energy technologies)	10	21	3	24
Short term option (quick implementation possible)	11	17	10	10
Successful pilot and demonstration projects	12	8	4	22
Compatible with current energy system	13	6	16	2
Less dependent on fossil fuel imports (energy security)	14	6	14	4
Alternative for nuclear	15	6	12	9
Bridge to hydrogen economy (options for transport sector)	16	3	13	8
Potential for negative emissions (in combination with biomass)	17	3	-	-
Help against subsidence	18	1	11	10
Use CO_2 in case of a new ice age	19	1	-	-
CO_2 mineralization option (olefin)[8]	20	1	-	-

[7] The Rotterdam Climate Initiative (RCI) is a collaboration between the City of Rotterdam, the Port of Rotterdam, the Environmental Protection Agency Rijnmond (DCMR), and the industry organization Deltalinqs.
[8] This could also be considered a negative article, as in scientific debates, olefin is also refered to as an alternative to CCS.

Table 7-3 and Table 7-4 show that apart from the increasing number of events reported by the media in the last time period, there are more arguments used per article in the portrayal of CCS, both of which indicate that the discussion on CCS is becoming a regular and grounded part of the discourse. Figure 7-3 shows the attitudes of the main stakeholders towards CCS in the CCS debate as portrayed in the media. It shows that the environmental NGOs, as well as the local community and government of Barendrecht in particular express their concerns about the development of CCS technology. It also clearly shows that the Dutch research bodies are quite balanced in their views of CCS when referred to in the newspapers. The government, having been rather neutral about CCS for many years, started shifting towards a more positive attitude since 2007, seemingly influenced by the opinion of the industry, where the benefits of CCS have been proclaimed for a longer period of time. Another explanation for a more positive attitude by the Goverment towards CCS is that in 2007 the new Dutch government's 'Clean and Efficient' programme calls for a 30% reduction in Dutch greenhouse gas emissions by 2020 and recognizes CCS as a key component to meet these targets [56].

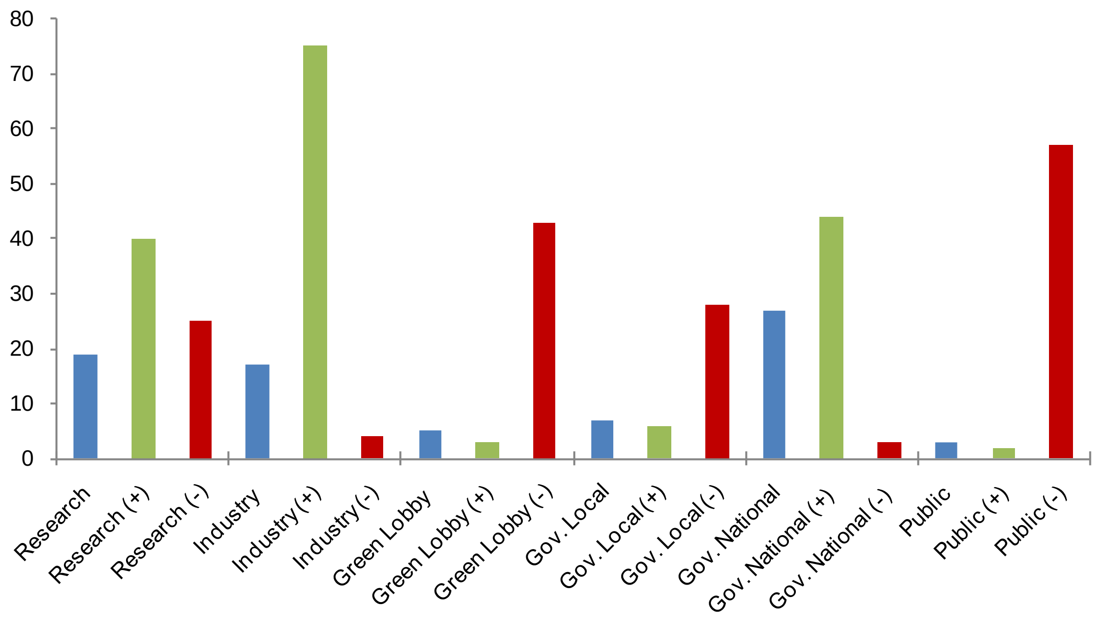


Figure 7-3: Attitudes of main stakeholders towards CCS; expressed (cited) in the Dutch print media between 2007 and April 2009 [2].

7.6. Discussion of main results and conclusions

The stakeholder analysis shows that, as far as the government, industry, and environmental NGOs are concerned, there has been a positive attitude towards CCS technologies in the Netherlands till at least 2008. Although most environmental NGOs see CCS technology as an effective option to achieve the required carbon dioxide reductions, it is not their first choice. Their acceptance of CCS can be characterized as 'reluctant' rather than 'enthusiastic'. Despite the positive attitude towards CCS, stakeholders pose several conditions for their support of the actual implementation of CCS. A broad consensus exists as to what these conditions should be. The first condition is that CCS should be safe, on the short term as well as on the long term, and for human beings as well as for the environment. The second condition is that CCS should be deployed temporarily and partially. It should only be used for a few decades and efforts for CCS should not be made at the expense of more sustainable options. The third condition is simplicity, meaning it should not be made more complex than necessary by obliging a link with other purposes. Fourth, financial stimuli are necessary in order to make investments in CCS acceptable for the industry. Furthermore, commitment of and cooperation between different stakeholders is considered a crucial condition for the successful implementation of CCS. The sixth condition is an open communication on CCS to the public; this communication should be based on experience, knowledge, and facts as much as possible. The latter is a responsibility of both stakeholders and media, as the way in which the media portray this new technology can radically affect the success of its implementation.

The results of our analysis on the portrayal of CCS in the Dutch media show that, up till 2007, the information on CCS is neither dramatized, nor hyped by the media. Instead, the technology was presented in a balanced to positive way, with great emphasis on the benefits of allowing continued fossil fuel use, while addressing climate change concerns. The same trend has been found in other countries. This was shown by Gough and Mander [57], who studied the impact of the publication of the IPCC Special Report on CCS on the portrayal of CCS in the print media of five English speaking countries: the United Kingdom, the United States, Australia, Canada, and New Zealand. Similar results were found for Germany, France, Italy, and Spain by the Institute for Innovation and Learning [58]. In all of the countries surveyed in these studies, more articles about CCS technology were neutral to positive than negative.

Despite the fact that the concerns about CCS have not overshadowed the main promise that CCS is part of the solution to climate change until the end of 2008, in the first trimester of 2009 the media did pay more attention to the possible weaknesses of this technology, than on its advantages. This was mainly caused by the negative portrayal of the Barendrecht project in the most recent period of the analysis. The negative statements that were expressed in the print media most often are quite similar to the concerns raised in the stakeholder analysis, as depicted in Table 7-5. This similarity between stakeholders' conditions for the deployment of CCS technologies and media portrayals of CCS in the Dutch press provides some evidence that the way the media present CCS is —to a certain extent— a balanced reflection of the way the stakeholders perceive CCS.

The current negative aspects of CCS as raised by different stakeholders and the media will remain if no action is taken. It is reasonable to assume that the stakeholders who raised these concerns—NGOs and local communities in particular—will find the media again to express them. Earlier research by Shackley et al. [26] and Terwel et al. [31] showed that levels of trust in key institutions, like NGOs, and the information given by the media have a major influence on how CCS will be perceived by the general public. Therefore, the conditions posed on the use of CCS, as well as the actions required to meet these conditions (see Table 7-5) articulate important issues concerning the creation of (public) legitimacy for CCS in the Netherlands. These insights in the potential societal responses are useful to overcome possible impediments created by various societal groups and effectively design public policy for this technology. The (policy) strategies proposed by the stakeholders to deal with their most critical concerns and those of expressed by the media are discussed below.

Table 7-5: Overview of concerns towards CCS raised by media; conditions posed by stakeholders on the deployment of CCS, and the actions required to meet them.

Concerns raised by media	Conditions	Actions proposed by stakeholders
Ecological and human health risks through leakage; and uncertainty about reservoir behaviour/seismic effects	Safety	Initiation of (pilot) projects, more scientific research; and development of rules and standards for storage site selection, storage and monitoring
Threat for renewable energy; continuing fossil fuel dependency (lock in suboptimal technology); and 'end of pipe' solution	Temporality and partiality	Develop a legislative framework on reservoir requirements; and make support for CCS contingent on increased funding for renewable energy; e.g. by 'double matching'
High costs of technology (energy penalty) and the need for government support	Financial stimuli	Stimulate extra RD&D efforts. Use generic mechanisms; e.g. the inclusion in EU ETS, complemented by ambitious post Kyoto targets
Technology not proven and limited potential	Simplicity	Prevention of obligatory links to other technologies and 'Goldplate' first projects
Responsibility / Liability issues and lack of common CO_2 infrastructure	Cooperation and commitment	Drawing up a roadmap and create public private partnerships with articulation of responsibilities.
Risk of NIMBYism and uncertain public acceptance	Open communication	Establish an open, two-way communication and present CCS in a broader context of climate change, as part of broad portfolio of options. Develop local value proposition.

The uncertainties regarding the safety and environmental risks involved in CCS will have to be reduced in order to stimulate acceptance. To achieve this, first of all, pilot projects for underground storage will have to be initiated and complemented with scientific research. It is important that these first projects will be sited in low or unpopulated areas and preferably offshore. Second, rules and standards will have to be developed for new monitoring techniques, to assure safety for longer periods of time. This legislative framework should also contain requirements for storage site selection, operation and storage. Such a stringent storage framework could help actuate the phase-out of CCS on the longer term and stimulate more sustainable technological options. To guarantee that CCS efforts are not made at the expense of energy efficiency and renewable energy, the environmental NGOs propose a policy that makes support for CCS contingent on increased funding for renewable energy and energy efficiency.

There is an urgent need for a legislative framework that provides the necessary financial stimuli to allow investments in CCS technology. This could be achieved by the inclusion of CCS in the EU ETS, thus making it part of a generic mechanism for carbon dioxide mitigation options. However, in order to establish a carbon price that makes CCS investments worthwhile, ambitious emission reduction targets for the post-Kyoto period will need to be set. Therefore, most probably other governmental policy instruments, like emission performance standards for power plants, need to investigated and implemented too.

In order to make CCS investments attractive for Industry, CCS should not be linked obligatory with other possible advantages. Adding obligatory links might incur risks: if the anticipated additional advantages turn out to be disappointing, public support of CCS might decline. Especially in the early development phases of CCS, a single failure may lead to societal opposition. To facilitate the implementation of CCS projects, partnerships between the government, environmental NGOs, public research institutes, and the energy industry need to be established. Such partnerships should include a collective plan for the implementation and application of CCS, including the development of common user infrastructure. In other words, a roadmap for the use of CCS should be drawn up.

The communication of such an implementation plan to society is a joint responsibility of all stakeholders involved. A distinction should be made between communications to the general public and to citizens burdened by a single CCS project. The support of the latter group could be achieved by giving these local communities the opportunity to voice their concerns at an early stage and by providing additional benefits.[9] To create societal acceptance at large, open, clear, two-way and well-timed communication is needed, clearly putting CCS in the broader context of climate change and the range of possible solutions for a more sustainable future. A greater understanding of the urgency and severity of the climate change problem will make CCS more acceptable.

Acknowledgements

We would like to gratefully acknowledge Gert Jan Kramer (Shell Global Solutions), for his cooperation with and supervision of Quirine van Voorst tot Voorst during her internship at Shell Global Solutions International BV, and Jan Paul van Soest (Former Chairman of the CRUSTproject) for his advice during the preparation of the stakeholders workshop. We would also like to thank Wim Turkenburg (Utrecht University) and Dancker Daamen (Leiden University) for their inspiring and helpful comments on earlier versions of this paper, as well as the anonymous reviewers of this journal who put in a lot of effort to improve the quality of this paper. Finally we are grateful to Marjan Ossebaard (I2L) for her valuable contribution to the media analysis. This research is part of the CATO program, the Dutch national research program on Carbon dioxide Capture and Storage. The Dutch Ministry of Economic Affairs (EZ) and the consortium partners financially support CATO.

[9] As became clear from the media analysis this did not happen in the case of Barendrecht.

References

1. van Alphen, K., Q. van Voorst tot Voorst, M.P. Hekkert, and R.E.H.M. Smits (2007). *Societal acceptance of carbon capture and storage technologies.* Energy Policy. 35(8): p. 4368-4380.
2. Kliest, A. (2010). *MSc Thesis: Beeldvorming over CO2 afvang en opslag. Analyse van de berichtgeving in Nederlandse landelijke dagbladen*, Utrecht University: Utrecht (The Netherlands).
3. UN (1998). *Kyoto Protocol to the United Nations Framework Convention on Climate Change*, United Nations: New York (US).
4. EEA (2004). *Impacts of Europe's changing climate, an indicator-based assessment*, European Environmental Agency (EEA): Copenhagen (Denmark).
5. IPCC (2001). *Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, ed. R.T. Watson and the Core Writing Team. Cambridge University Press. Cambridge (UK), New York (USA): p. 398.
6. Gough, C. and S. Shackley (2006). *Towards a multi-criteria methodology for assessment of geological carbon storage options.* Climate Change. 74(1-3): p. 141–174.
7. IPCC (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*, ed. B. Metz, et al. Cambridge (UK).
8. IEA (2003). *Technology Innovation, Development and Diffusion*, IEA/OECD: Paris (France).
9. Reiner, D., T. Curry, M. de Figueiredo, H. Herzog, S. Ansolabehere, K. Itaoka, K. Akai, F. Johnsson, and M. Odenberger (2006). *An international comparison of public attitudes towards carbon capture and storage technologies*, Presented at the Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8): Trondheim (Norway).
10. IEA (2001). *Nuclear Power in the OECD*, IEA/OECD: Paris (France).
11. Pickett, S.E. (2002). *Japan's nuclear energy policy: from firm commitment to difficult dilemma addressing growing stocks of plutonium, program delays, domestic opposition and international pressure.* Energy Policy. 30(15): p. 1337-1355.
12. Surrey, J. and C. Huggett (1976). *Opposition to nuclear power : A review of international experience.* Energy Policy. 4(4): p. 286-307.
13. van der Pligt, J. (1992). *Nuclear energy and the public*. Blackwell Publishers. Oxford (England).
14. Devine-Wright, P. (2005). *Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy.* Wind Energy 22(2): p. 125–139.
15. Devlin, E. (2005). *Factors affecting public acceptance of wind turbines in Sweden.* Wind Energy. 29(6): p. 503–511.
16. Kaldellis, J.K. (2005). *Social attitude towards wind energy applications in Greece.* Energy Policy. 33(5): p. 595-602.
17. Dietrich, H. and R. Schibeci (2003). *Beyond public perceptions of gene technology: community participation in public policy in Australia.* Public Understanding of Science. 12: p. 381-401
18. Shackley, S., S. Mander, and A. Reiche (2006). *Public perceptions of underground coal gasification in the United Kingdom.* Energy Policy. 34(18): p. 3423-3433.
19. de Best-Waldhober, M., D. Daamen, and A. Faaij (2006). *Informed public opinions on CO2-capture and storage technologies*, Presented at the Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8): Trondheim (Norway).
20. Itaoka, K., A. Saito, and M. Akai (2006). *A path analysis for public survey data on social acceptance of CO2 capture and storage technology*, Presented at the Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8): Trondheim (Norway).
21. de Coninck, H., J. Anderson, P. Curnow, T. Flach, O. Flagstad, H. Groenenberg, C. Norton, D. Reiner, and S. Shackley (2006). *Acceptability of CO2 capture and storage—a review of legal, regulatory, economic and social aspects of CO2 capture and storage*, Energy Research Centre of the Netherlands (ECN): Petten (The Netherlands).

22. Ashworth, P., A. Littleboy, A. Pisarski, A. Beath, and K. Thambimuthu (2006). *Understanding and incorporating stakeholder perspectives to low emission technologies in Australia*, Presented at the Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8): Trontheim (Norway).
23. Curry, T., D.M. Reiner, S. Ansolabehere, and H.J. Herzog, 2004 (2004). *How aware is the public of carbon capture and storage?*, Presented at the Seventh International Conference on Greenhouse Gas Control Technologies (GHGT-7): Vancouver (Canada).
24. Itaoka, K., A. Saito, and M. Akai (2004). *Public acceptance of CO2 capture and storage technology: a survey of public opinion to explore influential factors*, Presented at the Seventh International Conference on Greenhouse Gas Control Technologies (GHGT-7): Vancouver (Canada).
25. Palmgren, C.R., M.G. Morgan, W. BruinedeBruin, and D.W. Keith (2004). *Initial public perceptions of deep geological and oceanic disposal of carbon dioxide.* Environmental Science & Technology 38(24): p. 6441–6450.
26. Shackley, S., C. McLachlan, and C. Gough (2004). *The Public Perceptions of Carbon Capture and Storage*, Tyndall Centre for Climate Change Research: Manchester (UK).
27. Sharp, J., M. Jaccard, and D. Keith (2006). *Public attitudes toward geological disposal of carbon dioxide in Canada*, Presented at the Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8): Trondheim (Norway).
28. Daamen, D., M. de Best-Waldhober, K. Damen, and A. Faaij (2006). *Pseudo-opinions on CCS technologies*, Presented at the International Conference on Greenhouse Gas Control Technologies (GHGT-8): Trondheim (Norway).
29. Huijts, N.M.A. (2003). *Public Perception of Carbon Dioxide Capture and Storage, The role of Trust and Affect in Attitude Formation*, Eindhoven University of Technology Eindhoven University of Technology: Eindhoven (The Netherlands).
30. Zaller, J. (1992). *The Nature and Origins of Mass Opinion*. Cambridge University Press. Cambridge (UK)
31. Terwel, B., F. Harinck, E. N., and D. Daamen (2006). *Just say what they expect you to say: the influence of argumentation on trust in organizations*, Presented at the Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8): Trondheim (Norway).
32. Mander, S. and C. Gough (2006). *Media framing of new technology: the case of carbon capture and storage*, Presented at the Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8): Trondheim (Norway).
33. Nisbet, M.C. and D.A. Scheufele (2002). *Knowledge, reservations, or promise? A media effects model for public perceptions of science and technology.* Communication Research 29(5): p. 584–608.
34. Scheufele, D.A. and B.V. Lewenstein (2005). *The public and nanotechnology: how citizens make sense of emerging technologies.* Journal of Nanoparticle Research. 7: p. 659–667.
35. Wynne, B. (1996). *May the sheep safely graze? A reflexive view of the expert-lay knowledge divide*, in *Risk, Environment and Modernity: Towards a New Ecology*, S. Lash, B. Szerszynski, and B. Wynne, ed. Sage Publishers: London (UK). p. 165–198.
36. Hornig, S. (1993). *Reading risk: public response to print media accounts of technological risk.* Public Understanding of Science 2: p. 95–109.
37. Siegrist, M. (2000). *The influence of trust and perceptions of risks and benefits on the acceptance of gene technology.* Risk Analysis 20: p. 195–204.
38. Bradbury, J. and J. Dooley (2004). *Who's talking? What are the issues? The media portrayal of carbon dioxide capture and sequestration in the United States*, Presented at the Seventh International Conference on Greenhouse Gas Control Technologies (GHGT-7): Vancouver (Canada).
39. Ryan, C. (1991). *Prime Time Activism: Media Strategies for Grassroots Organizing*. South End Press. Boston (USA).
40. Ten Eyck, T.A. (2005). *The media and public opinion on genetics and biotechnology: mirrors, windows, or walls?* Public Understanding of Science 14: p. 305–316.

41. Dijk, J.W. and P.J. Stollwerk (2002). *CO2 reuse through underground storage (CRUST)—the start-up: an inventory of market opportunities, technology and policy requirements*, CO2 Reduction Plan Project Office: Zwolle (The Netherlands).
42. Eagly, A.H. and S. Chaiken (1993). *The Psychology of Attitudes*. Harcourt Brace Jovanovich College Publishers. Forth Worth (USA).
43. PWC (2001). *Eindrapportage 'Schoon Fossiel', 'Laten we samen de eerste stapjes zetten'*, PricewaterhouseCoopers NV, Dick Swart Consultancy, Ecofys: Utrecht (The Netherlands).
44. Agterbosch, S., P. Glasbergen, and W.J.V. Vermeulen (2007). *Social barriers in wind power implementation in The Netherlands: Perceptions of wind power entrepreneurs and local civil servants of institutional and social conditions in realizing wind power projects.* Renewable and Sustainable Energy Reviews. 11(6): p. 1025-1055.
45. Bongers, F.J. (2000). *Thesis: Participatory Policy Analysis and Group Support Systems*, Katholieke Universiteit Brabant: Tilburg (The Netherlands).
46. van de Herik, C.W. (1998). *Groups Support for Policy Making*, Delft University of Technology Delft University of Technology: Delft (The Netherlands).
47. Boonekamp, P.G.M., O. van Hilten, R. Kroon, and M.N.E.V. Rouw (1992). *Nationale Energie Verkenningen (Dutch Energy Outlook) 1990-2015*, Netherlands Energy Research Foundation (ECN): Petten (The Netherlands).
48. Turkenburg, W.C. (1992). *CO_2 removal; Some conclusions.* Energy Conversion and Management 33(5-8): p. 819-823.
49. AER (1994). *Advies AER over de Vervolgnota Energiebesparing*, Algemene Energieraad: The Hague (The Netherlands).
50. IPCC (1995). *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific–Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, ed. R.T. Watson, M.C. Zinyowera, and R.H. Moss. Cambridge University Press. Cambridge (UK): p. 889.
51. CE (1996). *Nationale themadag waterstof*, Centre for Energy Conservation and Environmental Technology: Delft (The Netherlands).
52. TNO and RGD (1996). *Inventarisatie van mogelijkheden voor CO2-opslag in de Nederlandse ondergrond*, TNO/RGD: Haarlem (The Netherlands).
53. OCAP (2004). *Milieuwinst in de glastuinbouw*, , Organic Carbon dioxide for Assimilation of Plants VOF: Westland (The Netherlands).
54. VROM (1999). *Uitvoeringsnota Klimaatbeleid*, Ministry of Housing, Spatial planning, and Environment (VROM): The Hague (The Netherlands).
55. ECN and NMP (2006). *Optiedocument Energie en Emissies 2010/2020*, B.W. Daniels and J.W.M. Farla, ed. Energy Research Centre of the Netherlands, Dutch Environmental Planning Bureau: Petten (The Netherlands).
56. VROM (2007). *Clean and Efficient: New energy for climate policy*, Ministry of Housing Special Planning and the Environment (VROM): The Hague (The Netherlands).
57. Gough, C. and S. Mander (2006). *Carbon Dioxide Capture and Storage in the Media*, I. G. G. Programme. Tyndall Centre for Climate Change Research: Norwich (UK).
58. I2L (2006). *The impact of the 'IPCC Special Report on Caron Capture and Storage' on written news reports*, I2L-Institute for Innovation and Learning: Utrecht (The Netherlands).

8. Summary, conclusions and recommendations

First the background, objectives and scope of this thesis will be reiterated in this chapter. Then the answers to the research questions of this thesis are provided and the main outcomes from the analyses presented in the previous chapters will be highlighted. Finally, future research avenues will be indicated.

8.1. Background, objectives and scope

Global warming is a problem that requires urgent action. The increasing anthropogenic emissions of greenhouse gases (GHG) into the atmosphere are expected to result in global climate change with potentially severe consequences for ecosystems and mankind. The most dominant source of GHG contributing to the rise in atmospheric concentrations since the industrial revolution is the combustion of fossil fuels. Despite the increase of non-fossil energy generation, the share of fossil sources in overall energy production remains relatively constant at about 80% due to a strong rise in energy demand. At present, carbon dioxide capture and storage (CCS) is the only technological solution that has the potential to substantially reduce carbon emissions from fossil fuel fired power plants and other large-scale industrial processes such as iron and steel production, cement making, natural gas processing and petroleum refining. The ultimate goal of CCS is to store the otherwise emitted CO_2 for geological times in the deep underground. By reaching its goal CCS can significantly cut back CO_2 emissions from burning carbon-containing fuels which may dominate the primary energy supply until at least the middle of the 21st century.

After being supported by research since about 1990, CCS has attracted great interest from world leaders since about 2005, particularly those whose countries depend heavily on fossil fuels for secure electricity generation and export income, notably Western Europe (including Norway), Australia, Canada and the US. Despite the acknowledged urgency to demonstrate CCS technologies and the increasing amount of funding available, no fully integrated power plants with CCS have yet been built at commercial scale. The pattern of difficulty at the demonstration phase, whereby new technologies fail to negotiate the various market and institutional barriers that confront them, is often manifested in multifaceted, capital-intensive technologies, like CCS. Innovation scholars have argued that this development pathway between basic R&D and commercialization is very complex and characterized by high technological uncertainty, high investment requirements and many social and political forces that interact and influence the final outcome of this phase. If this part of the innovation process is not well managed, either by policy makers or industries, this might lead to the development of technologies that do not match market demands or the absence of technological innovation altogether. On the other hand if the innovation process is well understood, it may allow for shaping and accelerating the development and deployment of emerging technologies.

This thesis is centred around the question of how to accelerate the development and deployment of CCS technologies, using a multi-disciplinary research focus. After all, the innovation process is not only influenced by technological characteristics. The social-economic environment in which a technology is developed and deployed – called the 'Technological Innovation System (TIS)' - is of great importance. A well performing Innovation System accelerates technological development, while a poorly functioning Innovation System hampers technological innovation. Given the prominent role that CCS is now taking in global attempts to attain climate mitigation goals and the existing lack of knowledge regarding the CCS innovation process, the first objective of this thesis is to provide insight into the build-up process of Technological Innovation Systems around CCS technologies in a number of leading countries with regard to the development of CCS, i.e. the United States, Canada, Australia, Norway and the Netherlands. This is done by applying the Innovation System Functions approach. System Functions are key processes required for an Innovation System to develop and grow and, thereby, to increase the commercial chances of the new technology. In recent scientific articles published by the Innovation Studies Group of the Utrecht University, seven functions are discerned, each covering a critical aspect of technology development, namely entrepreneurial activities, knowledge development, knowledge diffusion, guidance, market creation, resources mobilization and the creation of legitimacy.

To some extent, system functions need to be realized simultaneously, since they can complement, or reinforce each other, but an Innovation System may also very well collapse due to the absence of a single system function. 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 and comparison of emerging CCS Innovation Systems in the US, Canada, Australia, the Netherlands and Norway. Such a comparison offers the possibility to learn from each other's experiences regarding the development of CCS. This leads to the second objective of this research, namely to demonstrate how the obtained insights in the performance of CCS Innovation Systems in industrialized countries can be useful to technology managers that wish to accelerate the future (commercial) deployment of CCS. The third and final goal of this thesis relates to its contribution to the Innovation Systems Functions literature by applying several quantitative methods for performance assessment that stem from other research fields.

8.2. Summary of main results and conclusions

In this section, answers to the research questions of this thesis are provided and lessons learned from the case studies will be highlighted.

8.2.1. Research question 1

How did the Innovation System around CCS technologies build-up over time in the United States, Canada, Norway, the Netherlands and Australia and what are the main drivers and barriers encountered for further growth?

In this thesis the build-up of national CCS Innovation Systems has been described for Norway, The Netherlands, The United States, Canada and Australia. The results show that converging perspectives, by researchers, (industrial) entrepreneurs, and governments on the importance of CCS in taking up the twin challenge of reducing carbon dioxide emissions, while meeting a growing energy demand, have resulted in a rapid growth of CCS Innovation Systems in the countries under study. This has become visible through, for example, the entry of new actors in the system; extension of the knowledge base; increasing connectivity in CCS knowledge networks; successful entrepreneurial projects; increasing availability of public and private funding for CCS; changes in legislation; the creation of strong advocacy coalitions; a guiding government fostering the development of CCS; but also a growing opposition against CO_2 storage from local communities and a part of the environmental NGOs.

Despite the growing complexity due to an increased amount of activity regarding all system functions, the evolution of the CCS Innovation Systems in all countries show a similar kind of positive interaction pattern between the system functions. As a consequence of guiding emission reduction targets (*Function 4: Guidance*) and an increasing legitimacy to support CCS technologies by politicians and interest groups till at least 2009 (*Function 7: Creation of Legitimacy*), the government provided either financial resources (*Function 6: Mobilization of Resources*) or market incentives (*Function 5: Market Creation*). This resulted in a rising number of RD&D programs (*Function 2: Knowledge Developments*) and subsequently triggered entrepreneurial activities with the technology (*F1: Entrepreneurial Activity*). These research and commercial CCS projects were often done in strong partnerships to share knowledge and complement skills (*F3: Knowledge Diffusion*). The researchers and companies involved in these projects generated higher expectations regarding the promise of CCS (*Function 4)* and subsequently lobbied for more financial resources (*Function 7*). Thereby reinforcing this virtuous cycle.

As shown in Chapter 2 of this thesis, one of the earliest virtuous cycles between functions (or "Motors of Innovation", as Suurs (2009) calls them) has been observed in Norway. In 1987, the UN report 'Our Common Future'; written by the Brundtland Commission, about the growing tension between economic growth and ecological deterioration was published (*Function 4: Guidance*). After chairing this commission, Brundtland was re-elected as Norway's prime minister in 1990 and one year later she introduced a carbon tax *(Function 5: Market Creation)*. The introduction of a carbon tax for offshore activities triggered Statoil – Norway's largest oil and gas company- to investigate options for cost-effective CO_2 handling at their offshore Sleipner West gas field and in 1992, Statoil opted to inject the CO_2 in the Utsira formation, a large aquifer southwest of Norway. In order to realise its plans, Statoil started several R&D projects wherein they aligned with Norwegian research organisations SINTEF and NTNU, as well as with Kværner; one of Norway's largest technology vendors *(Function 2 & 3: Knowledge development & Diffusion)*. Subsequently, Statoil invested €94 million in a separation unit at Sleipner West and started operations in 1996 *(F1: Entrepreneurial Activities)*; sequestering 1 $MtCO_2$ each year ever since. The successful execution of this project and the involvement of many national and international research groups triggered a range of other activities, thereby reinforcing the further growth of the system.

The CCS Innovation Systems in the other countries under study really started to take off in the new millennium when CCS became part of national climate policies and funding was made available to start large CCS RD&D programs. Despite the relatively late start compared to Norway, the CCS Innovation Systems in the Netherlands, Australia and North America showed a rapid build-up and caught up quickly with Norway. The major difference between Norway and the other countries with regard to the general function interaction pattern described above is the lack of clear market incentives in the latter *(Function 5: Market Creation)*. The general functional pattern initiating system growth in these countries indicate that Guidance *(Function 4)* in the form of climate policies and, directly linked to it, the Mobilization of Resources (*Function 6*) have resulted in a boost to Knowledge Development programs *(Function 2)*, an increasing amount of entrepreneurial experiments (*Function 1*) and also conferences and collaborative CCS efforts that are conducive to Knowledge Diffusion (*Function 3*). The other observation, which is similar to the general pattern described above, is a recurring lobby (to the government) for resources and regulations by (regional) industries (*Function 7*). Thereby providing a basis for positive expectations *(Function 4: Guidance)* and lobbies for more resources *(Function 7)*; thereby setting of a new "short circuit" virtuous cycle. These short effective virtuous cycles based on lobbying, resource mobilization, and project development, in combination with the overarching need to reduce greenhouse gas emissions from fossil fuel use ensured that over the last decade the amount of funding available for the development of CCS has changed from several millions to billions of Euros.

However, observed positive functional patterns or the increase in the fulfilment of individual system functions do not guarantee a thriving development of CCS in the future. The CCS Innovation Systems may have to face new challenges that obstruct a further expansion of the system. For example, in the Netherlands the lack of public support (legitimacy) for a project, whereby CO_2 would be stored in a deleted gas field under the town of Barendrecht, may result in a vicious cycle, as companies might not want to invest in similar CCS technologies because of reputational risk. Similarly politicians (as representatives of the public) may stop public financing of CCS demonstration. In this sense, technological innovation is a complex outcome which is determined by its weakest element(s). There is no standard yet for appraising the performance of each individual system function in terms of some kind of threshold that needs to be surpassed. Evaluative studies therefore typically point out the relative strengths and weaknesses of particular Technological Innovation Systems, usually on the basis of comparison between countries.

Furthermore, success or failure can be determined on the basis of expert opinions. Several indicators or so-called diagnostic questions for different system sub-functions have been developed for performance assessment and applied in this study to determine the performance of CCS Innovation Systems in Norway, The Netherlands, The United States, Canada and Australia. In total over a hundred interviews have been carried out with key CCS stakeholders in the countries under study.[1] In this way, the performance assessment emerges as a socially constructed judgement that arises from within a TIS. Based on these expert

[1] The results of the interviews were verified and complemented by additional literature review of scientific as well as "grey literature" (e.g. professional journals, financial yearbooks, roadmaps and policy papers). Furthermore, quantitative methods from other fields of innovation studies have been applied to complement these qualitative research methods. The applicability of these methods for the analysis of a TIS will be further detailed in Section 8.2.3.

judgments, mechanisms that are currently driving, or blocking the future deployment of CCS in the countries under study have been identified and thereby the last part of the first research question will be answered. The main results of the performance assessment of the five CCS Innovation Systems that have been analysed are discussed below.

Entrepreneurial Activity

Canada and Norway are hosting three of the four complete, end-to-end commercial CCS facilities in the world today (November 2010). Twelve years after Statoil started its CO_2 storage operations at the Sleipner West gas field on the Norwegian continental shelf, Norway's largest oil company 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. In Canada 2.8 $MtCO_2$ is injected annually to enhance oil recovery (EOR) from the Weyburn field, since 2000. The CO_2 that is used in this project is a by-product from a coal gasification plant, located 325 km south of Weyburn, in North Dakota (US). Since Sleipner, many smaller CCS projects have commenced in the countries that are the focus of this thesis. 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. In the world there are approximately 85 large-scale demonstrations planned, of which the majority is located in North America, Australia, and Europe (of which a relatively large number in the Netherlands and Norway).

The increasing project development activity is verified by the increasing number of industrial actors that have entered the CCS Innovation Systems over the past decade. The project analysis showed, for example, a growing share of enterprises at the expense of research institutions and universities in the United States, indicating that the prominence of technology developers and energy companies is increasing over time. This change is mainly caused by an increasing involvement of oil, gas and coal companies (from 3% to 20%). Also the relative amount of utilities has risen substantially, indicating an increased attention for capture technologies in recent years. The total amount of organisations involved in Canadian CCS projects nearly doubled from 62 in 2000 to 120 in 2009. With their involvement in CCS pilot and demonstration projects they have contributed to a considerable amount of entrepreneurial activities regarding CCS in Canada.

Most CCS experts who evaluated the performance of this function recognized 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 confirmed the rapidly increasing amount of (industrial) organizations involved in these CCS projects. However, they valued the fulfilment of this function as moderate (i.e. 2.9 on a scale of 1 to 5) and relatively to some of 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, it has become time CCS projects related to power production will become a reality.

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 found that it 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, more efforts should be made to deploy retrofit options for existing power plants.

In relation to power production with CCS, there seems to be 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. It's argued that 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 found in all countries under study that a "common carrier", CO_2 infrastructure in industrial areas, like the Rotterdam Port Area in the Netherlands, or the Industrial Heartland in Alberta Canada, likely hampers the implementation of more entrepreneurial experiments with the technology. It is argued that the existence of such an infrastructure, which includes transportation and storage, could significantly lower the financial risk for companies willing to invest in CCS. Furthermore, it would simplify the current complex commercial structures that are related to CCS projects.

Overall the performance of this function is evaluated higher in North America then in the other three CCS Innovation Systems. 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. At present there are over 70 CO_2 EOR sites in North America. Several planned CCS capture projects will therefore feed their CO_2 into existing EOR pipeline networks, like the Permian Basin. EOR also generates a revenue stream, which makes such projects more attractive for business. 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. Finally, more uncertainty was observed 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.

Knowledge Development

The 100 experts that evaluated the performance of CCS Innovation Systems in Norway, The Netherlands, The United States, Canada and Australia were satisfied with the knowledge base that has been accumulated over the past decade. On average they scored this function with a

3.9 on a scale of 1 to 5, which is the highest of all functions. Despite this, it is argued to continue R&D of all components of the CCS chain.

R&D activity (and funding for R&D) increased rapidly over the past decade in all countries under study. In 2008 Canada counted 70 ongoing R&D projects, compared to 7 in the year 2000. A similar amount of R&D projects were funded by the US Department of Energy (DoE) through its USD 100 million Carbon Sequestration Program. In the Netherlands, CCS R&D is concentrated around one large heterogeneous national CCS consortium. This CATO (CO_2 Capture, Transport and Storage) program included over 40 research organisations and industry partners in 2009 which conducted R&D into all aspects of the CCS chain. 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). 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. 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. It is found that Norway is the only country of the five countries analysed in this thesis that has specific focus of CO2 capture at gas fired power stations, as capture R&D efforts in the other countries focus mainly on CCS related to coal based power generation. In terms of storage R&D, the results show that in North America R&D is much more on EOR, while in the two European countries and Australia more research is done with respect to Saline Aquifers and Depleted gas fields.

In general, the knowledge developed regarding CO_2 storage is considered by the 100 experts surveyed for the performance assessment of CCS Innovation Systems, as being of high quality. This is the result of a rich history of oil and gas activities as well as of the scientific excellence of research institutes in all countries under study. In order to advance the current knowledge regarding CO_2 storage, several research priorities have been identified 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 can be done by drilling more wells for pilot injections, which would give a more reliable overview of the most suitable storage sites in a particular country or region. It is argued that such a pre-competitive storage assessment is not only beneficial from a scientific perspective, but more so for project developers in search for a suitable site. From the first CCS projects it was found that securing a suitable storage location can be very expensive and time consuming.

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 pipeline transportation of CO_2 when applied in a network context like Rotterdam whereby the quality of CO_2 (i.e. level of impurities) provided by the different emitters connected to pipeline might differ, which has implications for balancing the system. From an economic and commercial perspective more research is needed as the high upfront costs of oversized pipelines, creates a different investment risk profile. The participation of multiple stakeholders, both current and future, complicates commercial structures, terms and contracting, especially due to the need for early users and operators to bear disproportionate amounts of risk.

In order to improve the quality and diversity of CO_2 capture R&D, it's argued that more basic research into new solvents, sorbents and membranes is needed to identify innovative cost-effective capture technologies. Some countries may need to consider diversification of capture R&D efforts. In Norway, for example, the possibility to increase R&D efforts into capture technologies for coal-fired power plants may need to be considered, as these technologies would have a large world market potential. While in the US and Canada it was recognized that R&D efforts should diversify towards CO_2 capture from gas-fired generators and retrofit options for existing power plants. Finally, it was found 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 of power plants with pre-combustion CO_2 capture technologies.

Despite the above, it was found in the evaluation 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 to improve public outreach strategies.

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 (on a scale of 1 to 5).

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 Regional Carbon Sequestration Partnerships are also government-industry collaborative networks that involved, in 2008, more than 350 organizations covering 42 American states and four Canadian provinces. Public private CCS consortia in Canada include, the Integrated CO_2 Network (ICO2N) and the Canadian CO_2 Capture and Storage Technology Network (CCCSTN); both tasked with coordination of R&D and demonstration efforts with the aim to establish large-scale integrated CCS systems. Furthermore, the major Norwegian R&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.

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.

It was found that the value of international CCS consortia is highly regarded by most of the organisations involved in CCS. It’s argued that best practices should be made available in order to optimize technological learning, as no single company or nation can develop CCS in isolation. The IEA GHG R&D programme fulfils an important role for international knowledge diffusion in the field of CCS. This is done by the research networks of its sponsors, and the organization of the bi-annual International Greenhouse Gas Control Technologies (GHGT) conference series. The largest GHGT conference until now (November 2010) was held in Amsterdam, in September 2010 and hosted approximately 1500 participants from 60 different countries. However, it is also recognized 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. 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 project knowledge and expertise. The institute has obtained the support of more than 40 national governments and over 150 leading corporations, non-governmental organizations (NGOs) and research organizations to facilitate knowledge sharing around CCS across the globe.

Despite the recognition that the increasing amount of (inter)national CCS platforms and conferences, as well as the increasing attention for CCS in scientific journals (e.g. the Journal of GHG Control Technologies) have contributed significantly to the optimization of CCS knowledge networks, it was also observed that this is not always the case for knowledge networks around capture technologies. It’s argued that R&D on capture technologies often occurs behind “closed doors, since this knowledge can create a competitive advantage for businesses. The protection of intellectual property is often considered by companies as the sole base of survival in a competitive market. However, strong protection of IP hinders an optimal flow of information between the actors involved in CCS R&D and therefore the creation of that very same market for CCS technologies.

It was found that knowledge sharing for companies can therefore be considered as a difficult balancing act, whereby on the one hand companies are willing to share knowledge to benefit from the creation of a market from which they could profit. On the longer term and on the other hand they would like to keep IP for themselves, so they can position themselves as a market leader when CCS becomes a global industry. Despite these difficulties the results show that more information could be shared by companies without compromising their competitive advantages in any future market for CCS. The results also indicated that the current lack of knowledge sharing as the most important barrier for the performance of this function.

Guidance

On average, the 100 experts participating in the performance assessment of the CCS TISs in the countries covered in this thesis rated their satisfaction of this function with a moderate score of 3.0. They were 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. The latter is formally illustrated in several white papers and technology roadmaps, 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”. 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”.

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 will be discussed further under the next function: “market creation”), but also legislative and regulatory solutions related to standardization, permitting and liability. It was found that in most countries under study permitting capture and transportation facilities is 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. Although, the results presented in this thesis show that significant progress has been made regarding the development of supportive CCS regulations in the countries under study, it was also found that there are still major outstanding legislative and regulatory issues that need to be addressed in order to enable large-scale CCS deployment. In general it can be concluded that current regulatory frameworks, and recently proposed directives in case of the EU, are a good platform to build from, but inadequacies in several areas indicate the need to change part of the current legislation. These gaps in existing regulatory frameworks relate to four main areas:

1. Legal issues around pore space ownership and its interaction with mineral rights, especially in North America.
2. Cross boarder transportation still needs to be allowed under international treaties like the London Protocol (offshore transportation) and is particularly relevant in the context of the European countries.

3. Specification of requirements to cover the operation of CO_2 storage projects, including guidelines for MMV.
4. 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.

Resolving the fourth issue is considered most important, primarily because the liability timeframes for CCS projects extend far beyond other typical liability timeframes that companies are held to today, which increases the risk profiles of project investors. Regulators therefore need to clarify if and when liability will transfer to relevant government bodies once a project moves to the post-abandonment phase. Although it's argued that CCS regulation needs to be in place soon, one could also argue 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 regulatory agencies could provide – after a thorough site selection procedure – approvals on a one-time basis to allow the first projects to move ahead.

Market Creation

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 CCS with EOR, whereby relative pure CO_2 from industrial operations is utilized to gain extra oil revenues, but also in other entrepreneurial experiments, like the OCAP project in the Netherlands whereby the CO_2 from a Shell refinery is not stored underground, but transported to greenhouse horticulture in order to meet the CO_2 requirement. 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. 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 was rated with an average 2.2 (whereby 5 is maximum); the lowest score of all functions.

The fact that the performance of this function was better evaluated in Norway than in the other countries can be explained by the introduction of a carbon tax in the early nineties, which has proved to be an effective incentive to encourage CO_2 storage operations underneath the North Sea. Additionally, it triggered the development of capture solutions for initially offshore and later onshore gas-fired power plants. However, it also 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 considering their climate policies.

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. 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. 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. 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. However for all these three countries it is still uncertain when such an ETS will be implemented, if implemented at all.

The Netherlands and to a lesser extend Norway, both rely on the European Union 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, and the carbon price, varying between €10 and €20/tCO_2 in 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. 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. Note that similar policies around a phased approach to more stringent Emission Performance Standards for power plants have been proposed in the US ACES Act and in 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.

The importance of financing the first large-scale CCS demonstration projects that have not yet benefited from scale economies and technological learning was recognized in all the case studies presented in this thesis. It was 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.

Mobilization of Resources

Although investments in CCS RD&D have grown substantially over the past years, the 100 experts surveyed for the purpose of evaluation the performance of this particular function rate their satisfaction on the availability resources with an average score of 2.8. The most widely shared opinion is that the current availability of financial resources is not sufficient to realize commercial-scale integrated CCS demonstration projects. Argued that financial risks are too high to obtain private equity and 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 be needed to demonstrate the technology at commercial scale.

To provide investor certainty, it is believed 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. 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.

The majority of Australia's AUD 500 million Low Emissions Technology Demonstration Fund has been allocated for CCS deployment in public private partnerships. 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. 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.

Since 2006, the federal government of Canada has allocated CAD 375 million in financial support to CCS-related activities, including CAD 125 million under the ecoENERGY Technology Initiative. 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 the provincial government. 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. Moreover, the Alberta government has committed CAD 2 billion to fund a portion of the construction costs of four large-scale CCS projects in its province by 2015. In Canada public funding for CCS is nearly CAD 3 billion, which is expected to leverage 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. 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. 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.

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. Although it should be noted that over the past 6 years a similar amount of money has been provided by government and industry for basic R&D programs, like CATO, CAPTECH and CRUST. 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 lower rating on the fulfilment of this function in these countries. However the Norwegian and Dutch projects will be implemented before 2013, while the budgets mentioned above stretch over a longer period of time. 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 6 CCS projects as part of their European Economic Recovery Plan, of which the ROAD Project in Rotterdam received €180 million. Subsequently the Dutch Government has made available €150 million to co-finance the project. 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. 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.

Next to the current lack of financial resources, the case study results also show 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. The solution for this potential problem is to introduce educational programs at universities to get future engineers and project managers acquainted with specific CCS knowledge. They also stress the need to retrain current managers and technicians in the industry.

Creation of Legitimacy

The current fulfilment of this function is scored 3.1. by the 100 CCS experts that have been asked to evaluate the performance of this function for their respective country. 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 in their back yards. Below the legitimacy for CCS will be discussed as seen by different stakeholder groups.

In all countries considered in this study, CCS is favoured 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. 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 favour of deploying CCS technologies in order to stay in business in a low-carbon economy. Furthermore, the majority of Canadian experts surveyed agree that there are influential coalitions advocating CCS in Canada. They noted that industrial consortia like the Canadian Coal Power Coalition (CCPC) and ICO2N 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 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 a 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. Furthermore, it was recognized 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. Due to the energy penalty of CCS, it may even enhance these problems.

It was found that in all of the countries that are the focus of this thesis, one of the major bottlenecks in the fulfilment of this function lies in possible public resistance towards CCS because of similar reasons as currently given by some environmental interest groups (see above), but also because of the opposition to large-scale infrastructural works like CO_2 pipelines, and potential health and safety risks. 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.

Despite the moderate support for CCS found in social science literature, 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. 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 the Dutch Parliament.

It was found 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. This partly explains the relatively high rating of 4.0 in the average of 3.0.

In order to create legitimacy for the CCS technologies under the lay public, 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, it’s argued that experts should engage more often in open dialogue with the public about benefits, risks and other legitimate concerns about CCS. Finally it was recognized that in any communication on CCS. CCS needs to be portrayed as part of a wider portfolio of climate mitigation options and not as an alternative to renewables.

8.2.2. Research question 2

How can the development and deployment of CCS technologies be accelerated based on these insights into the historical dynamics and current performance of CCS Technical Innovation Systems in industrialized countries?

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 or explore more low-cost CCS opportunities. 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 guidance - in terms of clear legislative and regulatory frameworks and the creation of legitimacy by the public - may also be improved. Based on the main drivers and barriers encountered for further growth of the CCS Innovation Systems, presented in the previous section, a general technology management strategy has been developed that would help alleviate the current barriers to the technology's future deployment in industrialized countries.

This policy strategy, aimed at stimulating the further build-up of CCS Innovation Systems, consists of three interrelated elements targeting the fulfilment of different sets of system functions simultaneously, namely: 1) stimulate technological learning; 2) create financial and market incentives; and 3) improve regulation and legitimization for CCS.

Stimulate learning by doing

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. It is necessary that various promising technologies, and in particular CO_2 capture technologies integrated in power facilities, should be demonstrated at commercial scale to advance technological learning and bring down its costs.

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, international CCS network organizations and domestic CCS consortia could play an important role. The latter group could also focus its effort to reduce the current “first mover disadvantage” for early CCS project developers and induce more entrepreneurial activities through the development of “a common user” CO_2 transportation and storage infrastructure needs to be facilitated. With respect to the latter it is recognized that more pre-competitive storage site characterization work is needed. This could substantially lower the project lead times, upfront costs and thereby the financial risks for new entrepreneurs that wish to enter the CCS market.

Create financial and market incentives

The implementation of sound climate policies 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 Trading Schemes in all countries under study – possibly with bonus allowances for CCS projects– in combination with Emission Performance Standards for power plants could be a strong policy mechanism to create a market for CCS on the mid- and longer term. Furthermore, the possibility to include Enhanced Oil Recovery operations in combination with storage in the European ETS should be further explored, as the additional revenues from oil production could make CCS commercially viable on the short term (as is the case in CCS projects in North America).

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. It’s 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, 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.

Improve regulation and legitimization for CCS

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, cross boarder transport of CO_2 needs to be permitted under international treaties (especially in Europe).

Third, timeframes and responsibility for the different liability types (operational, local, and climate) need to be articulated and assigned. Fourth, 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 could therefore provide approvals on a one-time basis to allow the first projects to move ahead; then they could use the subsequent learning to develop legislation and guidelines for broader application of future CCS projects.

Finally, 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 of stakeholders and the general public, 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. The support of the latter group could be achieved by giving these local communities the opportunity to voice their concerns at an early stage and by emphasizing or providing benefits related to the project. 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.

8.2.3. Research question 3

How can the assessment of dynamics and performance of Technical Innovation Systems be improved based on methods from other fields of innovation research?

One of the objectives of this study is to methodologically strengthen the Innovation System Functions approach by introducing quantitative methods that stem from other fields of innovation research. In the case studies presented in this thesis, several methods have been used to gain insight in the fulfillment of different system functions; social network analysis has been applied to detect network formation, and gain more insight in the function of “knowledge diffusion”. Bibliometric- and project analyses was used to assess the fulfillment of the functions “knowledge development” and “entrepreneurial activities”. Furthermore, media analysis was done to provide additional insights in the function: “Creation of Legitimacy”. Below the strengths and weaknesses of these methods in terms of its applicability for TIS analysis will be discussed first. Then, the more “traditional methods” used in Innovation System Functions literature applied in this thesis will be reviewed.

Project analysis

In order to assess the variety and advancement in the CCS knowledge base (Function 2) and the level of Entrepreneurial Activities (Function 1), two comprehensive project databases have been constructed for the cases of Canada and the United States. The databases contain around 150 CCS projects each that have been carried out in North America between 2000-

2009, involving more than 400 actors in total. The following data has been recorded for each project in the database:

1. The name and organizational background (e.g. oil and gas industry, universities) of the actors involved in a project.
2. The technological focus of the project, distinguishing between three categories: CO_2 capture, CO_2 storage, and other CCS areas, including CO_2 transportation, public acceptance and policy analysis. The capture projects have then been subdivided into post-, pre-, and oxyfuel combustion; and in storage there have been three main types of geological reservoirs distinguished, i.e. saline aquifers, oil & gas fields (depleted and producing) and coal seams.
3. Each project has been classified in terms of 'distance to market'. A project is considered: a) basic and applied R&D; b) demonstration (early prototypes up to full-scale working devices) and c) pre-commercial (commercial scale- and integrated demonstration projects).
4. Finally, the start and end date, as well as the budget and funding available for the project have been recorded in order to gain insight in distribution of costs among the CCS component technologies over time.

With respect to the completeness of the database it is important to note that data on projects that have already finished are more difficult to acquire compared to projects that are still ongoing. A small part of the increasing amount of funding for CCS RD&D could thus be explained by the more difficult collection of data for earlier years, but is not significant enough to rebut the observation that the number, budgets and variety of CCS projects has increased significantly over the past decade. A second issue concerning data availability relates to private investments in CCS research, as CCS R&D projects do also take place in behind 'closed doors' in various industrial labs. Although this could explain part of the difference between the relatively low investments in R&D of CO_2 capture technologies (which are IP sensitive), compared to CO_2 storage projects, it is unlikely that the possible lack of private industry data is the sole reason for this multimillion-dollar difference. It's argued that CO_2 storage facilities have been demonstrated more often in large-scale capital-intensive projects, and that CO_2 capture technologies are still in the R&D phase, which requires fewer resources. Furthermore, it should be noted that the majority of CCS RD&D is co-funded with public money, which requires publication of project data.

Despite the possible incompleteness of the project databases for reasons listed above, the analysis of CCS projects is considered very helpful in the quantitative assessment of an emerging TIS, as it provides important insights in the fulfillment of the function "Entrepreneurial Activity" and "Knowledge Development"; not only in terms of the (increasing) amount of projects or investments made into R&D and commercial scale demonstration of the technology, but also in terms of the variety that has been created in the CCS knowledge base (based on allocations of RD&D budgets across CCS technologies). Furthermore, the project database also provided insight in the number of new entrants and diversifying firms entering the system, another indicator for measuring the level of entrepreneurial activity in an emerging TIS.

Moreover, the results retrieved from the project analysis have provided a first indication to the overall system performance indicator, namely technology diffusion or technology deployment. The growing presence of entrepreneurs in the system and the increasing amount of large-scale integrated CCS projects that are under development indicate that companies are better able to turn the potential of new knowledge, available funding resources and emerging markets into concrete action (i.e. the development of CCS projects) to generate and take advantage of business opportunities. In this respect the project analysis may also be used to measure progress against the recommendation made by the G8 Leaders at the 2008 Hokkaido Toyako Summit that 20 large-scale CCS demonstration projects should be launched by 2010 and to achieve broad deployment of CCS by 2020.

Social Network Analysis

Social network analysis has been applied to identify the actor networks involved in the American and Canadian CCS Innovation Systems between 2000 and 2009. The social network approach assumes that the linkages among actors can favour or impede the development of innovations in the system. The analysis identifies size and connectivity of the network structure as a major factor to help the system evolve. The size of the network is characterized by three measures: number of actors, the size of the largest component –i.e. connected parts of the network- and average distance between actors in the network. The connectivity of the network is determined based on the average number of linkages per actor (mean degree) and the clustering coefficient, a measure to determine the existence of relative dense clusters in the network. Social network analysis can also be performed on actor level. The number of linkages of an actor (node degree) and its betweenness are centrality measures indicating the position of an actor in the network. The betweenness of an actor is determined by the number of times that it is positioned on the shortest path between other actors.

In this study, two actors have been considered to be related when they are involved in the same CCS project. Involvement could take the form of a cooperative R&D effort, a policy network, but also a commercial joint venture. In order to specify the relations between actors in the Innovation System, the CCS project database as described above has been used. It was assumed that organizations that are involved in the same CCS project have the possibility to exchange knowledge among each other.

It was also assumed that the links among actors are equally strong and bilateral. Thereby this study overlooks the large number of informal links and the variety of interconnected individuals active within such a network. Furthermore no attention was paid to quality of a link; e.g. in terms of research outcomes, or the number of times representatives from the partnering organizations do actually meet. Additional surveys seem an obvious choice for gathering such complementary data and may provide interesting directions for future research. However, such analyses were considered beyond the scope of this research, as the main interest lies in the possibility of actors to exchange knowledge with other actors in the system in order to gain more insight in the function ‘Knowledge Diffusion’.

For that purpose the applied method proved to be very useful. It was found that the number of organization involved in CCS projects in North America, as well as the number of linkages per actor increased significantly over the past decade. Moreover the increasing clustering coefficient - a measure to determine the existence of relative dense clusters in the network- in combination with a relatively short path length between actors indicates that the network suffices the criteria of a ‘small world network’. As simulations have shown, a small world network is the most efficient structure to achieve knowledge diffusion.[2]

Next to gaining insight into the size and connectivity of the actor networks involved CCS, several important shifts in the composition of the network were retrieved as well. First of all, a growing share of private industries at the expense of research institutions and universities was observed. The increasing number of new specialized firms entering the system as well as the more central position of private enterprises –mainly oil and gas companies- in the North American CCS networks point to a change from an R&D based system towards an innovation system that is conducive to the (commercial) deployment of CCS technologies.

One important observation made from the results of the Social Network Analysis of CCS actor networks in North America was that these networks have grown really fast over the past decade, while technology diffusion was still absent. An interesting area for further research would be to investigate if Social Network Analysis could be used to develop more objective measures to investigate the overall TIS performance (in contrast to the performance of one specific function) that allows for comparison on a system level, as it is not dependent on diffusion rates, or market shares of the technology in focus. Avenues for further research will be further discussed in Section 8.3.

Bibliometric analysis

In order to gain further insight in the CCS knowledge base (Function 2) for the case of Canada, the scientific output of research institutes has been systematically analyzed between 2000 and 2008 using the scientific publications documented in the Scopus abstract and indexing database. The bibliometric analysis not only points to a shift in focus of scientific publications that describe CO_2 storage research towards publications of CO_2 capture research, but also provides evidence for an increasing amount of studies into non-technical aspects CCS; e.g. public acceptance and regulatory issues. This can be explained by the increasing importance of the social, economic and political aspects of a novel technology when it reaches the implementation phase. In reality the amount of non-technical studies might be even higher, as the used Scopus database has a bias towards natural sciences. Other studies have found that bibliometric analyses that make use of Google Scholar are more beneficial for the fields of business, finance, economics and social sciences in general.

[2] To analyze the relationship between network structure and knowledge diffusion, the knowledge base and knowledge variation within regular, random, and small-world networks have been measured. In the result, it was confirmed that the small-world network was the most efficient and equitable structure to achieve knowledge diffusion and make a return for all the actors. In contrast, in a network where knowledge is converged on only a few actors, thus not giving considerable merit to the majority for collaboration or network activity, the neglected majority will hesitate to participate in the innovation system. This could finally result in failure of the system.

The search strategy focused mainly on using keywords. The importance of the CCS research field was investigated by determining the relative growth of publications. The first strategy to construct a database of publications was to use the term ‘CCS’ literally as search words. The advantage was that the included data had a high probability of really belonging to that field. The second strategy was to use a group of keywords that together described or ‘constructed’ the CCS research field, i.e. a combination of “Carbon/CO2, Capture/Separation, and Storage/Sequestration. These keywords were collected by scanning relevant literature.

When choosing for publication searches two main methodological questions arise: what is the quality of the data? And what is the search demarcation? To answer the first question, the data used came from high quality and widely used databases. Only for the most recent years problems might arise due to the update frequency of the publication database and the latency time between the execution of the research and publication. The search demarcation is rather more difficult. The best way to test this is to take a sample from the resultant search and study its contents for relevance. This was done for the publication searches and it showed some problems using keywords that define the field.

Despite the possible time delay between obtaining the actual research findings and scientific publication, as well as the methodological difficulties with the search demarcation, the bibliometric method has been proven useful in terms of specifying the type and variety of scientific knowledge that is being produced. It also gives an indication if the research community is aligned with industry when the technical topics of the papers are compared with type of CCS projects that are developed in the real world.

However, the additional value provided by the bibliometric analysis, as applied in this thesis, compared to the results generated from the projects databases and social network analysis is considered marginal. A bibliometric may therefore be more applicable for the analysis of Technological Innovation Systems that are in an earlier phase of the build-up process when large R&D consortia are not present yet. Another option would be to focus on a different bibiliometric method, namely citation analysis. Data from citation indexes and co-authored articles can be analyzed to determine the popularity and impact of specific articles, authors, and publications, but it can also be used to identify interrelationships between authors from different organisations and schools of thought. The latter can be used to identify trends in the development research networks and the potential for knowledge exchange (function 3).

Media analysis

In order to gain more insight in the fulfilment of Function 7: “Creation of Legitimacy”, the role of the print media in framing CCS technology in their communication to the public has been further investigated in the analysis of the Dutch CCS Innovation System. Therefore all documents related to CCS in the main Dutch daily newspapers were retrieved from the LexisNexis® Academic database (LexisNexis 2010), first for the period 1991-June 2006 and later on also for the period till April 2009, resulting in a set of 887 news articles.

In the content analysis of the Dutch news articles on CCS, first of all, the events that triggered the publication of these articles have been recorded in the database; e.g. such as policy announcements, or the release of scientific reports. The extent to which external events stimulate media coverage has been explored, as well as the influence of these events on the way the press perceives and portrays CCS. An increase in ‘trigger events’ can change the way the media interpret and, subsequently, presents CCS to the public.

The legitimacy for CCS can be depicted by the distribution of positive, negative, and neutral articles over time. Articles have been classified ‘positive’ if the majority of statements used in the article were in favour of CCS, ‘neutral’ if the number of negative and positive statements was balanced, and ‘negative’ if the majority of statements and the overall impression of the article were negative towards CCS. A fourth category has been introduced, indicating whether CCS is mentioned in an article but not discussed as such. Finally, the main arguments in favour or against CCS have been distilled from each article, as well as the type of actors linked to these arguments if they have been cited in the article.

A second researcher checked this classification, after which differences were discussed to harmonize the classification procedure. In cases of doubt, more attention was paid to the title and the first few lines of the article. Despite these measures to improve objectivity in the analysis of the way CCS is portrayed in the Dutch print media, it might be possible that another researcher obtains (slightly) different results due to the value judgment that has to be made when classifying the news articles. Also the large amount of news articles to be analysed as part of the media analysis posed challenges for the researcher. However, it is not expected that the major outcomes of the media analysis presented in this thesis would change when the analysis was replicated by different researchers.

Based on the recorded information it was possible to portray a picture of the public CCS debate over time. The results of the media analysis on the portrayal of CCS in the Dutch media show that, up till 2008, the information on CCS is neither dramatized, nor hyped by the media. Even though various actor groups such as the general public, government, environmental lobby groups and industry position themselves differently towards CCS, the technology was presented in a balanced to positive way, with great emphasis on the benefits of allowing continued fossil fuel use, while addressing climate change concerns. Despite the fact that the concerns about CCS have not overshadowed the main promise that CCS is part of the solution to climate change, in the first trimester of 2009 the media did pay more attention to the possible weaknesses of this technology, than on its advantages. This was mainly caused by the negative portrayal of the Barendrecht project in the most recent period of the analysis. Since the period of analysis stops at April 2009, if this negative portrayal of CCS in the media continues if a decision on the execution of the Barendrecht CO_2 storage is made or if this trend will be broken once the news value of this project diminishes.

Even though it can be argued that the national debate on CCS is captured by the news papers is partial and unbalanced (partly because of the judgement made by the journalist on the news value of a CCS related event), the messages given by the media regarding CCS have an impact on the legitimacy of CCS across the society at large.[3] In that respect, the media

[3] The level of impact of the writing press on the reader of the news articles may be subject of further investigation.

analysis proved to be useful to answer the two main indicative question for this fulfilment of this function, i.e. how is the technology depicted in the media? And what are the main arguments of actors pro or against the deployment the technology? Furthermore, the media analysis can be done in conjunction with an Event History Analysis; a method that it has been used in this thesis to analyse TIS dynamics.

Event History Analysis

Event History Analysis has been proven to be a useful way to systematically analyze complex longitudinal data. This process approach conceptualizes development and change processes as sequences of events. By gathering data that indicates how the process unfolds over time, a timeline and narrative of events can be constructed that provides significant insights into the development and change processes. In this thesis History Event Analysis has been applied in the analysis of the Dutch CCS Innovation System.

The data collection contains the events that are reported at system level relevant to the development of CCS. The sources of data for the event analysis comprehend the Lexis Nexis TM academic news archive (LexisNexis 2010), specialized journals, and scientific literature. Then each event related to the development and deployment of CCS technologies has been listed chronologically in a database, for example workshops on the technology, and the start-up of R&D projects. The database has then been structured according to year of the event, reference articles, event description, and system function. The event database was then used to construct a narrative that describes the appearance and evolution of the TIS.

The problem encountered in collecting the data is that the availability and the quality of event data varied over time (like for the project database). For the more recent periods it was easier to collect data from archives, especially those containing digitalized media. A solution to this problem was to complement the primary dataset of events with historical accounts from secondary literature. Also, additional information from interviews was used. Despite the above, it not a trivial task to construct a function interaction pattern based on the identification of event sequences. After all, events do not all follow up on each other in neat sequences. The narratives constructed as part of the case study should therefore be considered as stylized simplifications of reality (wherein a lot of noise data has to be filtered out) and not be interpreted as literal accounts of what has happened.

When being critical, one could argue that with thorough literature research and a comprehensive series of interviews with experts, you could reach the same outcome; i.e. a narrative gives you stylized version of the main events (and the relationships between them) in the recent history of a technology development process. However, when following a process approach the validity of the narrative is much better grounded. The latter is important for theory development around the build-up processes of (sustainable) Technological Innovation Systems.

Literature review and interviews

In order to map out the historical dynamics of the Innovation Systems in terms of (interactions between) functions and ascertaining to what extent the Innovation System Functions have been fulfilled, semi-structured interviews have been conducted with the main actors involved in the development and deployment of CCS in all the five case study countries presented in this thesis. In order to improve the comparability and reliability of the case studies, a set of indicative questions that provide insight in the fulfilment of the functions have been applied. The results of the interviews have then been verified and complemented by additional literature review of scientific as well as 'grey literature' (e.g. professional journals, financial yearbooks, roadmaps and policy papers). The extensive literature survey was particularly useful to gain insight in the fulfillment of the 'soft' functions, like Guidance and Market Creation, which could not easily be measured with quantitative measures, like social network Analysis and biblometrics.

In total, about a hundred interviews have been conducted with senior representatives from industry, research, government and environmental groups across the five the different countries under study. 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). When choosing for interview based research the main methodological question that arises is: is the sample of interviewees large- and robust enough to validate the results? A first answer to this question would be that the sample size of a hundred interviewees (around 20 per country) is rather large when compared to other interview-based research. It's also argued in Chapter 6 of this thesis that the sample size of a hundred interviewees covers 7.5-10% of the core international CCS community based on the number of delegates in major (inter)national CCS conferences and symposia. Furthermore, the used sample size that is common in opinion poll research or large internet based Delphi studies. Moreover, with cross-referencing as well as external justification, the validity of the group of interviewees was guaranteed for all case studies.

The expert judgment based performance assessments were mostly in agreement with the results of the historical analysis (that made use of all the methods described above). For example, the results show a sharp increase in CCS RD&D activities, as well as high potential for knowledge diffusion in the fast growing actor networks. These functions received the highest expert rating. In similar fashion the slow development of market incentives for the CCS and the lack of regulatory guidance resulted in relatively low scores on these functions. The main discrepancy related to the function 'mobilization of resources'. Even though the results show a substantial increase in CCS investments, the majority of experts argue that current budgets are not sufficient to realize large-scale CCS deployment on the short term.

To minimize the personal bias of the researcher and to further assess the systems' performance, the interviewees also reflected 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 also have given their view on what should be done to improve the fulfilment of system functions that are impeding a higher performance of the system. The correlations found between the scores given for each of the Innovation System Functions within and across countries were remarkable.

The results presented in Chapter 6 of this thesis show that the CCS experts participating in this research are relatively satisfied with the extensive knowledge base and CCS knowledge networks accumulated over the past years (functions 1 & 2). And that in order to advance the overall performance of the Innovation Systems it is considered necessary to direct policy initiatives at the identified weak system functions, i.e. entrepreneurial activity, market formation and resources mobilization. The evaluation of the CCS Innovation Systems based on expert judgments and questionnaires also proved to be useful in terms of its ability to pinpoint the key drivers and barriers for further Innovation System growth. Again the similarities found across countries were remarkable in this respect; thereby confirming the suitability of the used sample size and the validity of the proposed technology management strategy as outlined in Section 8.2.2.

A major downside of the literature review and interview based research is the huge investment in terms of research resources: the archival work, conducting interviews and maintaining a database with interview transcripts and literature. Especially considering the rapidly changing dynamics of the CCS Innovation Systems staying up to date with the latest developments has proven challenging. A system function that is considered weak at one point in time might perform strongly one year later. In particular, with regard to the time dependency of the interview data (when used for strategy development) it is important to verify and update the results with the interviewees on an ongoing basis. The later proved to be difficult, given that the research presented in this thesis describes the dynamics and performance of CCS Innovation Systems in Europe, North America and Australia. This might have implicated the comparability of the cases presented in this thesis.[4] Future research could be directed at setting up a quick scan of TIS dynamics that maintains scientific rigor but at the same time requires fewer resources. Avenues for further research will be further discussed in Section 8.3.

Group Decision Support Systems

Based on the current performance of the system, in relation to what is reasonable to expect taking the historical development of the TIS into account and according to the judgment of key actors in the system, it is possible to specify strategic actions in terms of what should be done to improve the fulfilment of those system functions that were seen as obstructing positive system dynamics and thereby impeding a higher performance of the entire CCS Innovation System.

[4] With regard to case-study comparability, it should be noted that despite the fact that the interviews for the various case-studies were conducted in different time periods, the scores given with regard to the performance of the seven Innovation System Functions by CCS experts across the countries under study were in agreement.

In the analysis for the Netherlands, the strategy development process has been facilitated by an additional workshop with CCS experts, that were brought together in an Electronic Board Room (hardware) with a Group Decision Support System (software). This interactive, computer-based system facilitates participants to communicate simultaneously and anonymously on unstructured and semi-structured problems by brainstorming, giving comments, and voting on statements. In the Dutch case study the characteristics of a Group Decision Support System have been used to encourage open discussions between the stakeholders on the strengths and weaknesses of the Dutch CCS Innovation System and to construct strategies that would accelerate the build-up of CCS Innovation System in the Netherlands.

Despite the often cited flaws of using a GDSS relating to an increased possibility of 'free riding', creating an information overload and obtaining relatively slow feedback compared to more traditional ways of group interaction techniques, the use of the system proved to be very useful for the purposes of this study from a couple of perspectives. First of all it is efficient as you have the ability capture information from a group of people at the same time. Second, it allows you to use "the bigger brain", as the involvement of different stakeholders can lead to a clustering of information and insights that, together, have a surplus value. And, third, the involvement of a variety of interests may broaden the insight into the needs and points of view of different participants, which may contribute to the acceptance of solutions. This provides a more solid basis for advice on strategies to accelerate the development of deployment of CCS.

Comparative research

Each case study will yield insights that hold for a particular TIS. It is argued that a comparative analysis between different TISs across nations is a powerful way of improving the understanding of decision makers, as it provides an opportunity to learn from a broad range experiences regarding the development of CCS technologies in other countries. Most importantly, the question of how these systems are performing could be answered on the basis of comparison, as a comparative analysis also allows for a cross-national comparison on a function level; e.g. differences in focus of R&D programs, level of entrepreneurial activity, and variation in regulatory frameworks. Therefore a comparative approach towards performance assessment is considered useful. Especially in combination with the performance evaluation based on expert judgements, taking into account the methodological drawbacks involved when making use of interview based data as outlined above.

In this thesis the performance of CCS Innovation Systems in the US, Canada, the Netherlands, Norway and Australia has been evaluated and compared. However, some of the results might be too context specific and therefore not be a useful basis of comparison. What might be considered as a problem in the US (e.g. government interference in the market) can be perceived as solution in another country, like the Netherlands. Furthermore, one should also 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. Finally, the comparative analysis focused 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. However, one could also argue that these in depth studies could help to fill in the general deployment strategy outlined in this study. And if this in-depth knowledge is not available yet, the outcomes of the performance assessment could actually guide areas for further research.

8.3. Recommendations for further research

Based on the answers to research questions discussed above a number of recommendations for further research can be suggested.

Case replication

Recently, the Innovation System Functions approach has been adopted by an increasing number of scholars. Nevertheless, the number of empirical studies conducted is still low. The methods for performance assessment presented in this thesis provide a powerful basis for conducting case studies in such a way that they can be compared. The following research avenues are of particular interest:

- The TIS approach might also be applied on a project level. For example it would be interesting to do a TIS analysis for the Rotterdam CCS Network project. This project has the same goal as a TIS, i.e. the development and deployment of new technology, involves a large number of actors and is being influenced by large variety of institutional factors. Such an analysis would allow for another level of detail (e.g. minutes of meetings and interviews with all stakeholders involved). This could create more insight into the "micro dynamics and performance" of a Project based TIS.
- CCS is often portrayed as competitor to renewable energy technologies. It might be interesting to explore the concept of "competing Technological Innovation Systems"; whereby the research focus would be on the crossover events between to Technological Innovation Systems (e.g. biomass gasification and CCS). Such analysis may point out these 'competing systems' can benefit from each other's growth.
- More case studies could be conducted on existing fossil fuel based energy technologies that are comparable in terms of complexity and size to CCS, for example offshore oil drilling, or LNG transportation. This could generate more insights in the market expansion stage of mature TISs. It can be expected that the dynamics will be very different in this stage and that the set of system functions may have to be adjusted to conceptualise them accurately.
- The Innovation System Functions approach may also be applied to other technological fields outside the domain of sustainable development. The outcomes of these studies would make it possible to explore to what extent the Innovation System Functions approach is applicable to other technological domains (e.g. information technology).

Improvements to method

For all the research avenues suggested above, the performance evaluation based on expert judgments in combination extensive literature review or with event history analysis provides a fruitful basis for the systematic analysis of a TIS. However, it is worthwhile to further explore the use of quantitative methods presented in this thesis in the analysis of emerging Technological Innovation Systems. The following research avenues are of particular interest:

- Social Network Analysis could be used to develop more objective measures to investigate the overall TIS performance (in contrast to the performance of one specific function) that allows for comparison on a system level, as it is not dependent on diffusion rates, or market shares of the technology in focus. Such an analysis could focus on the characteristics of the operating part of the TIS, namely the actors and their networks. An interesting starting point here would be the article of Alkemade and Hekkert (2008)[5], which poses several hypothesis changes in actor-networks that would describe the build-up process of a Technological Innovation System. Social Network Analysis may provide statistical measures to test these hypothesis.
- Another option would be to expand the bibiliometric methods, and include citation and patent analyses. Data from patent and citation indexes can be analyzed to determine the development of the CCS knowledge field and to identify interrelationships between scientists and inventors from different organisations. The latter can be used to identify trends in R&D and the potential for knowledge exchange (functions 2 & 3).
- Finally quantitative economic and financial models could be applied to ascertain further insights in the fulfillment of the functions market creation and mobilization of resources.

Refinement of system functions

There are numerous refinements that can be made to the Innovation System Functions approach. The studies presented in this thesis were specifically aimed to provide a better understanding of the performance of CCS TISs. This required the analytical scope to be broad. A downside is that the details of various activities and structures underlying these interactions were somewhat lost. By focusing more on the development of specific activities or structures, it will be possible to contribute to a richer insight into the nature of particular system functions. The following research avenues are particularly relevant:

- The ‘Guidance function’ as defined in this thesis covers a broad variety of activities, including expectations, promises, legislation, targets and policy directives. It would be useful to conduct additional theoretical and empirical analysis on this particular function and explore whether it is worthwhile to split up this category; e.g. between promises/expectations/targets and policies/directives.
- Another system function that should be subjected to a more refined analysis is the Creation of Legitimacy function. It was shown that political activities have played a crucial role in the expansion of a TIS but the actual organisations that performed the

[5] Alkemade, F. and M. Hekkert (2008). Development paths for emerging innovation systems: implications for environmental innovations. Working paper series. Utrecht, Innovation studies group (ISU), Utrecht University.

lobby have not been studied in detail. It would be useful to conduct additional theoretical and empirical analysis on this particular function; also to explore if it is worthwhile to split up this category between lobby by advocacy coalitions and public support/acceptance.

Creating broader and better acceptance of CCS

Based on the results presented in this thesis it may be worth to investigate whether alternative technologies and approaches to be applied in CCS could lead to a broader or better acceptance of CCS across various stakeholder groups and the public at large. Hereby one could think of the following research avenues:

- Reservoir engineering studies to increase the (intrinsic) safety of CO_2 storage.
- The development of common (international) methods for CO_2 storage site selection, monitoring and verification, and risk assessment.
- Next generation CO_2 capture technologies that would substantially lower the energy penalty (and costs) involved with CO_2 capture.
- The potential and benefits of combining biomass based power production with CCS, as well as the application of CCS in other emissions-intensive industrial sectors like cement, iron and steel, chemicals, and pulp and paper.
- Outstanding legal and regulatory issues with regard to the implementation of CCS projects; e.g. timeframes and responsibilities for different liability types.

Samenvatting, conclusies en aanbevelingen

In dit hoofdstuk zullen eerst de achtergrond, doelen en reikwijdte van deze thesis worden samengevat. Daarna zullen de voornaamste conclusies van de analyses uit voorgaande hoofdstukken worden gepresenteerd. Ten slotte worden aanbevelingen voor verder onderzoek uiteengezet.

Achtergrond

De toenemende antropogene emissie van broeikasgassen in de atmosfeer zal naar verwachting resulteren in mondiale klimaatsverandering met ernstige potentiële consequenties voor ecosystemen en de mensheid. De meest dominante bron van broeikasgassen die bijdraagt aan de toename van atmosferische concentraties sinds de industriële revolutie is de verbranding van fossiele brandstoffen, zoals kolen, olie en aardgas. Op dit moment is afvangst en opslag van koolstofdioxide (CO_2) de enige oplossing die de technologische potentie heeft om CO_2-emissies van kolencentrales en andere industriële processen substantieel te verlagen. Deze technologie wordt afgekort met CCS (Carbon dioxide Capture and Storage). Het uiteindelijke doel van CCS is om CO_2 op te slaan in de diepe ondergrond voor geologische tijdschalen (vele duizenden jaren). Op deze manier kan CCS de CO_2-emissies veroorzaakt door verbranding van koolstofhoudende brandstoffen, die waarschijnlijk de primaire energie voorziening zullen domineren tot op zijn minst de eerst helft van de 21ste eeuw, aanzienlijk reduceren.

Ondanks de erkende noodzaak om CCS technologie snel te demonstreren, is er op dit moment nog steeds geen volledig met CCS geïntegreerde elektriciteitscentrale op commerciële schaal gebouwd. Innovatiewetenschappers hebben betoogd dat het technologisch ontwikkelingstraject tussen Research and Development (R&D) en commercialisering zeer complex is en wordt gekenmerkt door hoge technologische onzekerheid, hoge investeringen en een wisselwerking tussen vele maatschappelijke en politieke krachten die de uiteindelijke uitkomst van deze demonstratie fase beïnvloeden. Als dit deel van het innovatieproces niet goed wordt gemanaged, hetzij door beleidsmakers of door industriële partijen, kan dit leiden tot de ontwikkeling van technologieën die niet overeenkomen met de marktvraag of de afwezigheid van succesvolle technologische innovatie in het geheel.

Dit proefschrift is gericht op de vraag hoe de ontwikkeling en het grootschalig inzetten van CCS-technologieën versneld kan worden. De sociaaleconomische omgeving waarin een technologie wordt ontwikkeld - genaamd het ‘Technologisch Innovatie Systeem (TIS)’- is hierbij van groot belang. Technologieën worden ontwikkeld binnen de context van een systeem van actoren, netwerken en instituties (denk aan regelgeving). Een goed presterend Innovatiesysteem versnelt technologische ontwikkeling, terwijl een slecht functionerend Innovatiesysteem technologische innovatie belemmert.

Een TIS-benadering focust op de processen die bepalend zijn voor de vorming van het systeem. Dit wordt gedaan door een verzameling van zeven sleutelprocessen in kaart te brengen, ook wel systeemfuncties genoemd. Systeemfuncties zijn belangrijke processen die nodig zijn voor een Innovatiesysteem om te ontwikkelen en te groeien, en daarmee de commerciële kansen van de nieuwe technologie te verhogen. Elk van de zeven systeemfuncties omvat een essentieel aspect van technologie ontwikkeling, namelijk experimenteren door entrepreneurs, kennisontwikkeling, kennisdiffusie in netwerken, richting geven aan het innovatieproces, creëren van markten, mobiliseren van middelen en creëren van legitimiteit voor de technologie in kwestie.

Gezien de prominente rol die CCS nu inneemt in de wereldwijde pogingen om klimaatmitigatie doelen te bereiken en gegeven het bestaande gebrek aan kennis met betrekking tot het CCS-innovatieproces, is de eerste doelstelling van dit proefschrift om inzicht te verschaffen in de opbouw van Technologische Innovatiesystemen rondom CCS in een aantal vooraanstaande landen met betrekking tot de ontwikkeling van CCS, namelijk de Verenigde Staten, Canada, Australië, Noorwegen en Nederland. De tweede doelstelling is hieraan gerelateerd, namelijk om aan te tonen hoe de verkregen inzichten in de dynamiek en prestaties van de CCS Innovatiesystemen in geïndustrialiseerde landen nuttig kunnen zijn voor technologiemanagers die de toekomstige (commerciële) toepassing van CCS willen versnellen. Het derde en laatste doel van dit proefschrift heeft betrekking op de bijdrage aan de bestaande literatuur ten aanzien van systeemfuncties door het toepassen van verschillende kwantitatieve methoden ter beoordeling van de prestaties van het TIS.

Samenvatting van de belangrijkste resultaten en conclusies

In het onderstaande worden de antwoorden op de onderzoeksvragen van dit proefschrift samengevat en de belangrijkste lessen geleerd uit de case studies benadrukt.

Onderzoeksvraag 1

Welke inzichten geven de systeemfuncties in de opbouw en prestaties van Innovatiesystemen rondom CCS in de Verenigde Staten, Canada, Noorwegen, Nederland en Australië en wat zijn de belangrijkste factoren die van invloed zijn op de verdere groei van deze systemen?

In dit proefschrift is de opbouw van nationale CCS-Innovatiesystemen beschreven voor Noorwegen, Nederland, de Verenigde Staten, Canada en Australië. De resultaten tonen aan dat convergerende perspectieven van onderzoekers, (industriële) ondernemers en overheden over het belang van CCS in de vermindering van de uitstoot van kooldioxide, hebben geresulteerd in een snelle groei van CCS-Innovatiesystemen in de geanalyseerde landen. Dit is bijvoorbeeld zichtbaar door de toetreding van actoren in het systeem, de uitbreiding van de hoeveelheid beschikbare kennis; toenemende connectiviteit in CCS-kennisnetwerken; succesvolle demonstratie projecten van CCS; toenemende beschikbaarheid van publieke en private financiering voor CCS, veranderingen in de wetgeving ter bevordering van de technologie, de oprichting van belangengroepen voor CCS; en een sturende overheid die de ontwikkeling van CCS bevordert.

Ondanks de toenemende complexiteit als gevolg van een verhoogde activiteit met betrekking tot alle systeemfuncties, laat de evolutie van de CCS-Innovatiesystemen in alle landen eenzelfde positief interactiepatroon tussen de systeemfuncties zien. Als gevolg van heldere emissie reductiedoelstellingen *(Functie 4: richting geven aan het innovatieproces)* en een toenemende legitimiteit voor politici en belangengroepen om CCS-technologieën te steunen *(Functie 7: creëren van legitimiteit)*, vergrootte de overheid enerzijds de beschikbaarheid van financiële middelen *(Functie 6: mobiliseren van middelen)* en zorgde zij anderzijds voor de nodige marktstimuli *(Functie 5: creëren van markten)*. Dit resulteerde in een stijging van het aantal R&D programma's ten aanzien van CCS *(Functie 2: kennis ontwikkeling)* en ontketende vervolgens ondernemersactiviteiten gerelateerd aan de demonstratie van de technologie *(Functie 1: experimenteren door ondernemers)*. Deze experimenten met de technologie werden vaak uitgevoerd in brede samenwerkingsverbanden om kennis te delen en vaardigheden aan te vullen *(Functie 3: kennisdiffusie in netwerken)*. De onderzoekers en bedrijven die betrokken waren bij deze experimentele projecten genereerden hoge verwachtingen ten aanzien van het potentieel van CCS *(functie 4: richting geven aan het innovatieproces)* en lobbyden vervolgens voor meer financiële middelen en nieuwe regelgeving *(Functie 7: creëren van legitimiteit)*. Door deze positieve terugkoppeling tussen systeemfuncties werd de opbouw van het systeem versterkt en daarmee de kansen voor een snelle diffusie van CCS-technologie verhoogd.

Zoals weergegeven in Hoofdstuk 2 van dit proefschrift, werd één van de vroegste positieve interacties tussen systeemfuncties waargenomen in de opbouw van een CCS-Innovatiesysteem in Noorwegen. De invoering van een CO_2-belasting voor offshore olie en gas activiteiten begin jaren negentig *(Functie 5: creëren van markten)* was de aanleiding voor de Noorse oliemaatschappij Statoil, om opties te onderzoeken voor een kosteneffectieve CO_2-afhandeling voor hun gaswinning activiteiten bij offshore Sleipner West gasveld (*Functies 2: kennisontwikkeling)*. Vervolgens, investeerde Statoil € 94 miljoen in een CO_2 scheidingsinstallatie (*Functie 6: Mobiliseren van middelen*) en begon in 1996 met het injecteren van 1 miljoen ton CO_2 in de Utsira formatie, een groot aquifer ten zuidwesten van Noorwegen *(F1: experimenteren door ondernemers)*. De succesvolle uitvoering van dit project en de betrokkenheid van vele nationale en internationale onderzoeksgroepen in de ontwikkeling hiervan (*Functies 3: kennisdiffusie)* heeft geleid tot vele andere CCS activiteiten in Noorwegen, waardoor de verdere groei van het systeem werd versterkt.

De CCS-Innovatiesystemen in andere begonnen pas echt op te komen na het jaar 2000, toen CCS onderdeel werd van nationaal klimaatbeleid en financiering beschikbaar werd gesteld voor R&D. Ondanks de relatief late start vergeleken met Noorwegen, toonden de CCS-Innovatiesystemen in Nederland, Australië en Noord-Amerika een snelle opbouw. Een van de functiepatronen die heeft geleid tot deze "inhaalslag" is een terugkerende lobby door bedrijven. Hierdoor werd een basis gecreëerd voor positieve verwachtingen die resulteerde in intensievere lobby's voor meer middelen om projecten op te starten. Deze positieve functiedynamiek op basis van lobbyen, de mobilisering van middelen en projectontwikkeling, in combinatie met de overkoepelende noodzaak om de uitstoot van broeikasgassen te verminderen bij het gebruik van fossiele brandstoffen, hebben er onder andere voor gezorgd dat de afgelopen tien jaar het bedrag beschikbaar voor de ontwikkeling van CCS is verhoogd van enkele miljoenen tot miljarden euro's.

Echter, waargenomen positieve functie interactiepatronen en de verhoging van de vervulling van individuele systeem functies zijn geen garantie voor een voorspoedige ontwikkeling van CCS in de toekomst. Bijvoorbeeld in Nederland kan het ontbreken van maatschappelijk draagvlak voor een project *(Functie 7: het creëren legitimiteit)* waarbij CO_2 in een uitgeproduceerd gasveld zou worden opgeslagen onder een woonwijk in Barendrecht, resulteren in een negatieve spiraal van processen. Door een gebrek aan publiek draagvlak willen bedrijven misschien niet meer investeren in soortgelijke CCS projecten door de kans op reputatie schade. Evenzo, politici (als vertegenwoordigers van de bevolking) zouden mogelijk de publieke financiering van demonstratieprojecten van CCS kunnen stopzetten, waardoor de opbouw van het TIS als geheel kan stagneren.

Dit voorbeeld laat zien dat technologische innovatie een complexe uitkomst is van een veelvoud aan beslissingen en processen die wordt bepaald door de zwakste schakel (of systeemfunctie) in het proces. Inzicht in de relatieve sterktes en zwaktes van Technologische Innovatiesystemen in termen van functies is daarom cruciaal voor het ontwikkelen van strategie voor technologiemanagers die de toekomstige (commerciële) toepassing van CCS willen versnellen en vormt de basis voor beantwoording van de tweede onderzoeksvraag.

Onderzoeksvraag 2

Hoe kan de ontwikkeling en het grootschalig inzetten van CCS-technologieën worden versneld op basis van de verkregen inzichten in de historische dynamiek en de huidige prestaties van CCS-Innovatiesystemen in de geïndustrialiseerde landen?

Dit proefschrift toont aan dat de uitgebreide kennisbasis en CCS kennisnetwerken, opgebouwd in de afgelopen jaren, nog niet ten volle zijn benut door ondernemers om de markt te verkennen voor CO_2-afvangst concepten die verbonden zijn elektriciteitsopwekking. Het is daarom noodzakelijk om beleidsmaatregelen te richten op de geïdentificeerde zwakke systeem functies, dat wil zeggen ondernemerschap, markt creatie en het mobiliseren van middelen. Bovendien kan de functie ‘richting geven aan het innovatieproces’ in de meeste landen ook worden verbeterd, met name in termen van duidelijke wet- en regelgeving en het creëren van legitimiteit onder het publiek.

Op basis van meer dan honderd interviews met experts die betrokken zijn (geweest) bij de ontwikkeling van CCS in Nederland, Noorwegen, Australia, Canada en de Verenigde Staten, is een strategie ontwikkeld die kan worden gebruikt om de verdere opbouw van CCS-Innovatiesystemen in geïndustrialiseerde landen te versnellen. Deze strategie bestaat uit drie onderling samenhangende elementen gericht op de simultane vervulling van verschillende systeemfuncties, te weten: 1) het stimuleren van technologisch leren; 2) het afstemmen van financiële en markt stimuli en 3) de verbetering van de regelgeving en legitimatie ten aanzien van CCS.

Stimuleer technologisch leren door te doen

Naast de voortzetting van fundamenteel onderzoek, is er grote behoefte aan meer grootschalige CCS projecten die elektriciteitsproductie integreren met CCS. De verschillende componenten van CCS (afvangst, transport, en opslag) worden onafhankelijk van elkaar toegepast op industriële schaal, maar volledige integratie en toepassing van deze componenten in grootschalige projecten ontbreekt nog grotendeels. Demonstratieprojecten die de gehele CCS-keten omvatten zijn nodig om praktische ervaring op te doen met de technologie en zowel de technische als de financiële risico's van dergelijke projecten te verminderen.

Om de invoering van een complementaire set aan grootschalige CCS-projecten om mondiale schaal te faciliteren, zijn veranderingen in (inter)nationale samenwerkingsverbanden noodzakelijk. Met het oog op het oplossen van problemen rondom intellectueel eigendom, het integreren van de CCS keten, en het optimaal profiteren van het beschikbare leerpotentieel, is er gecoördineerde internationale actie nodig. Nationale CCS consortia daarentegen, zouden zich meer kunnen inspannen om het huidige "first mover disadvantage" voor vroege CCS projectontwikkelaars te verminderen door het ontwikkelen van regionale infrastructuur voor CO_2-transport en -opslag. Een onderdeel hiervan is precompetitieve karakterisering van geschikte CO_2-opslaglocaties. Dit zou project doorlooptijden, aanloopkosten en daarmee de financiële risico's voor nieuwe ondernemers die de CCS markt willen betreden aanzienlijk kunnen verlagen.

Het afstemmen van financiële en marktstimuli

De uitvoering van een betrouwbaar klimaatbeleid is van vitaal belang voor de ontwikkeling van commerciële CCS-projecten, aangezien sterke economische drijfveren voor CCS op dit moment grotendeels ontbreken. De industriële sectoren waarin CCS kan worden toegepast moeten kunnen rekenen op een langdurige verandering in de institutionele infrastructuur van het Innovatiesysteem die een duidelijke markt voor CCS creëert. De tijdelijke subsidies en belastingvoordelen die tot nu toe worden gegeven, zijn een noodzakelijke eerste stap, maar lijken niet sterk genoeg om de relatief hoge kosten van elektriciteitsproductie met CCS op de lange termijn te compenseren.

De invoering van een emissiehandelssysteem, in combinatie met emissienormen voor elektriciteitscentrales, vormen de basis voor een krachtig pakket aan maatregelen die een markt voor CCS kunnen creëren op de midden- en lange termijn. De mogelijkheid om olieproductie middels de injectie en opslag van CO_2 op the nemen in het Europese emissiehandelssysteem moet worden onderzocht, aangezien de inkomsten uit additionele olie productie, CCS winstgevend kunnen maken op de korte termijn (zoals het geval is bij het merendeel van de CCS projecten in Noord-Amerika).

Echter, rekening houdend met de mogelijkheid dat de CO_2-prijs in de eerste jaren wellicht niet hoog of stabiel genoeg is om voldoende investeringen in CCS te generen, zullen er extra financiële prikkels nodig zijn om de business case voor CCS sluitend te krijgen. Publiekprivate partnerschappen zijn daarom noodzakelijk bij de implementatie van de eerste CCS demonstratieprojecten op commerciële schaal. De miljarden dollars die beschikbaar zijn gesteld door de regeringen van Australië, Canada en de VS, alsmede de miljarden euro's die beschikbaar zijn voor CCS demonstratie in de EU (inclusief Noorwegen en Nederland) na de veiling van 300 miljoen emissierechten, zouden een belangrijke stimulans kunnen bieden voor de eerste projecten die nog niet hebben geprofiteerd van schaalvoordelen, technologische verbeteringen en leereffecten.

Letwel, dergelijke investeringen zijn van essentieel belang zijn, maar deze zullen zinloos blijken bij het ontbreken van een overkoepelend klimaatbeleid dat zich richt op de lange termijn. Een juiste afstemming van korte termijn financiële stimuli die de demonstratie van CCS-technologieën bevorderen en beleidsmaatregelen die op de lange termijn een duidelijke markt voor CCS creëren is daarom van primair belang voor het versnellen van de grootschalige inzet van CCS.

Verbetering van de regelgeving en legitimatie voor CCS

Naast het invoeren van een sterk klimaatbeleid, is het oplossen van de bestaande kwesties met betrekking tot de regulering van CCS één van de belangrijkste acties die moet worden genomen om grootschalige CCS projecten van de grond te krijgen. In de eerste plaats behoeven juridische kwesties rond de eigendomsrechten van de ondergrond verdere aandacht (met name in Noord-Amerika); bijvoorbeeld de interactie van vergunningen voor CO_2-opslag met bestaande rechten omtrent de winning van grondstoffen. Ten tweede moet grensoverschrijdend transport van CO_2 toegestaan worden op grond van internationale verdragen (met name in Europa). Ten derde, zullen de termijnen en verantwoordelijkheden voor de verschillende soorten aansprakelijkheid rondom CO_2 opslag (operationeel, lokaal, en klimaat) beter moeten worden gearticuleerd en toegewezen. Ten vierde, dienen eisen betreffende de operatie van CO_2-opslagprojecten verder gespecificeerd te worden, vooral ten aanzien van de selectie van CO_2-opslaglocaties en verplichtingen rondom het monitoren van CO_2 in de ondergrond. De ervaring die is opgedaan uit de eerste proefprojecten kan worden gebruikt bij de ontwikkeling van deze nieuwe richtlijnen en verordeningen.

Ten slotte kan een sterk reguleringskader de publieke bezorgdheid dat CCS een risicovolle technologie is minimaliseren en daarmee het vertrouwen in CCS verhogen. Het is duidelijk dat zonder voldoende steun van de bevolking, de ontwikkeling van CCS zal stagneren. Daarom moet het vergunningstelsel mechanismen bevatten om CCS projecten te ondersteunen die een brede waaier van stakeholders consulteren en het publiek informeren en betrekken tijdens de ontwikkeling van het project. Open communicatie in een vroeg stadium met belanghebbenden, moet een structureel onderdeel zijn van CCS projecten. Daarnaast moet de technologie gecommuniceerd worden als onderdeel van een breder portfolio aan klimaatverbetering opties.

Onderzoeksvraag 3

Hoe kan de beoordeling van de dynamiek en de prestaties van de Technologische Innovatiesystemen verbeterd worden met behulp van kwantitatieve onderzoeksmethoden?

In dit proefschrift zijn verschillende methoden gebruikt om inzicht te verschaffen in de vervulling van de systeemfuncties; sociale netwerkanalyse is toegepast om netwerkvorming te detecteren, en om meer inzicht te krijgen in de functie van "kennisdiffusie in netwerken".

Bibliometrische- en projectanalyses zijn gebruikt om de vervulling van de functies "kennis ontwikkeling" en "experimenteren door ondernemers" te beoordelen. Bovendien is er een media-analyse gedaan om aanvullende inzichten in de functie "creëren van legitimiteit" te genereren. Hieronder worden de sterke en zwakke punten van deze methoden in termen van hun toepasbaarheid voor TIS analyse besproken. Daarna zullen de meer kwalitatieve "traditionele methoden" kort worden bediscussieerd.

Project analyse

Om de verscheidenheid en vooruitgang in de CCS kennisbasis *(Functie 2)* en het niveau van ondernemersactiviteiten *(Functie 1)* te beoordelen, zijn er twee omvangrijke project databases geconstrueerd voor de cases van Canada en de Verenigde Staten. De databases bevatten elk ongeveer 150 CCS projecten, die zijn uitgevoerd in Noord-Amerika tussen 2000-2009.

Ondanks de eventuele onvolledigheid van de projectdata is de analyse van de CCS projecten als zeer nuttig ervaren in de kwantitatieve beoordeling van een opkomende TIS, aangezien het belangrijke inzichten biedt in de vervulling van de functies ‘experimenten door ondernemers’ en ‘kennis ontwikkeling’, niet alleen in termen van het (toenemend) aantal projecten of investeringen in R&D en de commerciële schaal demonstratie van de technologie, maar ook in termen van variëteit die is gecreëerd in de kennisbasis van CCS (gebaseerd op de toewijzing van R&D budgetten voor CCS).

Bovendien geven de groeiende aanwezigheid van ondernemers in het systeem en de toenemende hoeveelheid van grootschalige geïntegreerde CCS projecten die in ontwikkeling zijn, aan dat bedrijven beter in staat zijn om het potentieel van nieuwe kennis, beschikbare financiële middelen en de opkomende markten om te zetten in concrete actie (namelijk de ontwikkeling van CCS projecten) om daarmee nieuwe ondernemingskansen te genereren.

Sociale Netwerkanalyse

Sociale netwerkanalyse is toegepast om de netwerken van actoren die betrokken zijn bij de opbouw van CCS-Innovatiesystemen in de Verenigde Staten en Canada tussen 2000 en 2009 vast te stellen. Sociale netwerkanalyse gaat er vanuit dat de relaties tussen actoren de ontwikkeling van innovaties kunnen bevorderen of belemmeren. De analyse identificeert de grootte en de connectiviteit van de netwerk structuur als belangrijke factoren in de opbouw van het systeem en creëert bovendien meer inzicht in the functie “kennis diffusie".

Uit de analyses die gepresenteerd zijn in hoofdstukken 4 en 5 bleek dat het aantal organisaties betrokken bij CCS projecten in Noord-Amerika, evenals het aantal verbindingen per actor, sterk zijn toegenomen in het afgelopen decennium. Bovendien laat de toenemende clustering coëfficiënt, een indicator om de aanwezigheid van clusters met een relatief hoge dichtheid in het netwerk te bepalen, in combinatie met een relatief korte afstand tussen actoren zien dat het netwerk voldoet aan het criterium van het “klein netwerkfenomeen” (“small world network”). Zoals simulaties hebben aangetoond, is een “small world” netwerk de meest efficiënte structuur om de verspreiding van kennis te bevorderen.

Naast het verkrijgen van inzicht in de omvang en de connectiviteit van de actor netwerken die betrokken zijn bij CCS, is de netwerkanalyse ook zeer nuttig gebleken om belangrijke verschuivingen in de samenstelling van het netwerk te identificeren. Allereerst, werd een groeiend aandeel van bedrijven gesignaleerd ten koste van onderzoeksinstellingen en universiteiten. Het toenemend aantal nieuwe gespecialiseerde bedrijven in het systeem alsook de meer centrale positie van de olie- en gas industrie in de Noord Amerikaanse CCS-netwerken wijzen op een verandering van een op R&D gebaseerd systeem naar een Innovatiesysteem, dat bevorderlijk is voor de (commerciële) toepassing van CCS technologieën.

Bibliometrische analyse

Om meer inzicht te krijgen in de ontwikkeling van de kennisbasis van CCS *(Functie 2)* voor het geval van Canada, is de wetenschappelijke output van Canadese onderzoeksinstituten tussen 2000 en 2008 systematisch geanalyseerd met behulp van wetenschappelijke publicaties gedocumenteerd en geïndexeerd in een database. De bibliometrische analyse wijst niet alleen op de verschuiving van de focus van de wetenschappelijke publicaties gericht op CO_2 opslag naar publicaties over CO_2-afvang, maar biedt ook bewijs voor een toenemend aantal studies naar niet-technologische aspecten van CCS, bijvoorbeeld over publieke acceptatie en regulering. Dit kan gedeeltelijk worden verklaard door het toenemend belang van de sociale, economische en politieke aspecten van een nieuwe technologie bij het bereiken van de implementatiefase.

Ondanks de mogelijke vertraging tussen het verkrijgen van de feitelijke onderzoeksresultaten en de wetenschappelijke publicaties, evenals de methodologische problemen met de afbakening van de zoektermen, is de bibliometrische methode nuttig gebleken in termen van het specificeren van het type en de variëteit van de wetenschappelijke kennis die wordt geproduceerd. Echter, de toegevoegde waarde van de bibliometrische analyse, zoals toegepast in dit proefschrift, wordt beschouwd als minimaal in vergelijking met de resultaten van de uitgevoerde project analyse en sociale netwerkanalyse.

Media-analyse

De rol van de gedrukte media in de beeldvorming rondom CCS technologie is verder onderzocht in de analyse van het Nederlandse CCS-Innovatiesysteem om meer inzicht te krijgen in de vervulling van Functie 7: “creëren van legitimiteit”. Hierbij zijn alle documenten met betrekking tot CCS in de belangrijkste Nederlandse dagbladen geselecteerd uit de database LexisNexis ® Academic, resulterend in een set van 887 nieuwsartikelen.

Op basis van de geregistreerde gegevens was het mogelijk om een beeld te schetsen van het publieke debat met betrekking tot CCS over grofweg de laatste 20 jaar. De resultaten van de media-analyse laten zien dat, tot 2008, de informatie over CCS noch gedramatiseerd, noch gepopulariseerd werd door de media. Hoewel verschillende actor-groepen, zoals de overheid, milieubewegingen en de industrie zich anders tegenover CCS positioneerden, werd de technologie gepresenteerd op een evenwichtige tot positieve manier. In het eerste trimester van 2009, begon de media echter meer aandacht te besteden aan de mogelijke zwakke punten van de technologie. Dit werd voornamelijk veroorzaakt door de negatieve beeldvorming rondom het Barendrecht CO_2 opslag project in de meest recente periode van de analyse.

In dat opzicht is de media-analyse nuttig gebleken om de twee belangrijkste indicatieve vragen voor de invulling van deze functie te beantwoorden, namelijk: hoe is de technologie afgeschilderd in de media? En wat zijn de belangrijkste argumenten van de actoren voor -of tegen de inzetbaarheid van de technologie? Bovendien kan de media-analyse worden gedaan in combinatie met een ‘event history analysis’, een methode die is gebruikt in dit proefschrift om TIS dynamiek te analyseren.

‘Event history analysis’ en literatuurstudie

Event history analysis is een methode die de mogelijkheid biedt om systeemfuncties te operationaliseren en te meten in termen van gebeurtenissen die zich in de tijd voordoen. Voorbeelden van gebeurtenissen zijn studies, conferenties, fabrieken die gebouwd worden, beleidsmaatregelen die geïntroduceerd worden, etc. Deze procesbenadering zet de ontwikkeling en veranderingsprocessen neer als opeenvolgingen van gebeurtenissen. Door gegevens te verzamelen die aangeven hoe het proces zich ontvouwt in de tijd, kunnen een tijdlijn en een omschrijving van gebeurtenissen worden geconstrueerd die belangrijke inzichten leveren in de dynamiek en de evolutie van het TIS.

Door het volgen van een procesmatige aanpak is de validiteit van de resultaten veel beter gefundeerd. Daarnaast was de uitgebreide literatuurstudie bijzonder nuttig om inzicht te krijgen in de vervulling van de 'zachte' functies, zoals “richting geven aan het innovatieproces”, die niet gemakkelijk kunnen worden gemeten met kwantitatieve methoden, zoals sociale netwerkanalyse en biblometrische analyses.

Interviews

Om de mate van vervulling van Innovatiesysteem functies te beoordelen, zijn er meer dan 100 semigestructureerde interviews uitgevoerd met experts die betrokken zijn geweest bij de ontwikkeling van CCS in de vijf casestudy landen gepresenteerd in dit proefschrift. Om de vergelijkbaarheid en betrouwbaarheid van de case studies te verbeteren, is een set van indicatieve vragen toegepast die inzicht geven in de vervulling van de functies.

Het deskundig oordeel was meestal in overeenstemming met de resultaten van de historische analyse (waarbij gebruik gemaakt was van alle hierboven beschreven methoden). De resultaten laten bijvoorbeeld een sterke stijging zien in CCS R&D, alsmede een hoog potentieel voor de verspreiding van kennis in de snel groeiende actor netwerken. Deze functies ontvingen ook de hoogste waardering van deskundigen. Op soortgelijke wijze resulteerden de trage ontwikkeling van marktstimuli voor CCS en het ontbreken van een leidraad voor regelgeving in relatief lage scores op deze functies.

De evaluatie van de CCS-Innovatiesystemen op basis van interviews met een groot aantal experts bleek zeer nuttig te zijn in termen van haar vermogen om de belangrijkste factoren te identificeren die van belang zijn voor verdere Innovatiesysteem groei. De overeenkomsten die zijn gevonden in de beoordeling van het functioneren van het TIS tussen en binnen de landen waren opmerkelijk en bevestigen de geschiktheid van de gebruikte steekproefomvang en de geldigheid van de voorgestelde technologiemanagement strategie die uiteengezet is in de beantwoording van onderzoeksvraag 2.

Aanbevelingen voor verder onderzoek

In diverse hoofdstukken van dit proefschrift staan aanbevelingen voor verder onderzoek. De belangrijkste aanbevelingen worden hieronder kort herhaald.

Case studie replicatie

Over de laatste jaren is de Innovatiesysteem benadering en het gebruik van systeemfuncties opgepakt door een toenemend aantal wetenschappers. Desalniettemin, is het aantal uitgevoerde empirische studies nog steeds relatief laag. De methoden voor beoordeling van de prestaties van emergente Technologische Innovatiesystemen beschreven in dit proefschrift bieden een sterke basis voor het uitvoeren van case-studies op een dusdanige wijze dat zij kunnen worden vergeleken met ander empirisch onderzoek. De volgende onderzoekslijnen zijn daarbij van bijzonder belang:

- De TIS benadering zou ook kunnen worden toegepast op project niveau, zoals het Rotterdamse CCS Netwerk project. Een dergelijk onderzoek zou een ander detail niveau in de analyse toestaan (bv. op basis van notulen en interviews met alle betrokkenen). Dit kan leiden tot meer inzicht in de "micro-dynamiek" en prestaties van het project op basis van het begrippenkader dat is ontwikkeld voor de analyse van een TIS.
- CCS wordt soms afgeschilderd als “concurrent” van andere duurzame energietechnologieën, zoals biomassa en wind. Het zou daarom interessant kunnen zijn om het concept van "concurrerende Technologische Innovatiesystemen" te verkennen. Dergelijk onderzoek zou zich kunnen richten op de cross-over gebeurtenissen tussen twee Technologische Innovatiesystemen (bijvoorbeeld biomassa vergassing en CCS). Een dergelijke analyse kan laten zien dat deze 'concurrerende systemen' ook kunnen profiteren van elkaars groei.
- Meer TIS analyses zouden kunnen worden toegepast op bestaande (op fossiele brandstoffen gebaseerde) energietechnologieën die vergelijkbaar zijn in termen van complexiteit en grootte met CCS, bijvoorbeeld offshore oliewinning, of LNG transport. Dit kan meer inzicht genereren in de markt uitbreidingsfase van een volgroeid Technologisch Innovatiesysteem. Verwacht wordt dat de dynamiek heel anders zal zijn in deze fase van het TIS en dat de set van systeem functies misschien aangepast zal moeten worden om de dynamiek en prestaties te conceptualiseren.

Verbeteringen van de methode

Voor de hierboven gesuggereerde onderzoekslijnen, voorziet de evaluatie van prestaties op basis van expert beoordeling in combinatie met uitgebreide literatuurstudie, een vruchtbare basis voor de systematische analyse van het TIS. Toekomstig onderzoek zou het gebruik van de kwantitatieve methoden, gepresenteerd in dit proefschrift, in de analyse van emergente

Technologische Innovatiesystemen verder kunnen verkennen. De volgende onderzoekslijnen zijn daarbij van bijzonder belang:

- Sociale netwerkanalyse kan worden gebruikt om meer objectieve indicatoren te ontwikkelen om de algehele prestaties van een TIS te onderzoeken (in tegenstelling tot de prestaties van een specifieke functie) en die een vergelijking op systeemniveau mogelijk maakt. Aangezien sociale netwerkanalyse niet afhankelijk is van diffusie snelheden, of marktaandelen van de technologie in focus leent deze analyse zich uitstekend voor emergente systemen. Een interessant uitgangspunt zou hier het artikel van Alkemade en Hekkert kunnen zijn[6], waarin verschillende hypothesen zijn opgesteld ten aanzien van veranderingen in actor netwerken die indicatief zijn voor het opbouw proces van een Technologisch Innovatiesysteem. Sociale netwerkanalyse biedt statistische methoden om deze hypothesen te testen.
- Een andere optie is om de bibiliometrische analyse verder uit te breiden, en citatie- en octrooianalyses op te nemen in de analyse van het TIS. Gegevens van octrooi- en citatie indexen kunnen worden geanalyseerd om de ontwikkeling van het CCS kennis gebied te bepalen en om onderlinge relaties tussen wetenschappers van verschillende organisaties te onderscheiden. Dit laatste kan worden gebruikt om trends in R&D en de mogelijkheden voor het uitwisselen van kennis te identificeren *(Functies 2 & 3).*
- Kwantitatieve economische en financiële modellen zouden kunnen worden toegepast om verdere inzichten te verschaffen in de vervulling van Functie 5 “het creëren van markten” en Functie 6 “mobilisatie van middelen”.

Verfijning van de systeemfuncties

Er zijn tal van verfijningen die kunnen worden aangebracht in de Innovatiesysteem benadering. De studies beschreven in dit proefschrift zijn specifiek gericht op het verkrijgen van een beter begrip van de prestaties van CCS-Innovatiesystemen. Dit vereiste een brede analytische scope. Door zich meer te richten op de ontwikkeling van specifieke activiteiten of functies, zal het mogelijk zijn om bij te dragen aan een dieper inzicht in de aard van bepaalde systeemfuncties. De volgende onderzoekslijnen zijn daarbij bijzonder relevant:

- De functie 'richting geven aan het innovatieproces', zoals gedefinieerd in dit proefschrift, omvat een breed scala aan activiteiten, met inbegrip van de verwachtingen, beloften, wetgeving, doelstellingen en de beleidsrichtlijnen. Het zou nuttig zijn om extra theoretische en empirische analyses uit te voeren op deze specifieke functie en te onderzoeken of het de moeite waard is om deze categorie op te splitsen, in bijvoorbeeld beloften / verwachtingen en beleid / richtlijnen.
- Een andere systeemfunctie die zou kunnen worden onderworpen aan een meer verfijnde analyse is de functie “creëren van legitimiteit”. Dit proefschrift heeft aangetoond dat de politieke activiteiten een cruciale rol hebben in de opbouw van een TIS, maar dat de werkelijke organisaties die de lobby voeren niet in detail bestudeerd zijn. Het zou nuttig

[6] Alkemade, F. and M. Hekkert (2008). Development paths for emerging innovation systems: implications for environmental innovations. Working paper series. Utrecht, Innovation studies group (ISU), Utrecht University.ns.

zijn om extra theoretische en empirische analyses uit te voeren op deze specifieke functie, mede om te verkennen of het de moeite waard om de lobby activiteiten te scheiden van het creëren van draagvlak voor de technologie in de maatschappij.

Het creëren van een bredere en betere acceptatie van CCS

Gebaseerd op de resultaten gepresenteerd in dit proefschrift is het de moeite waard om te onderzoeken of alternatieve technologieën en benaderingen die kunnen worden toegepast in CCS zouden kunnen leiden tot een bredere of betere acceptatie van CCS bij verschillende belanghebbenden en bij het grote publiek. Hierbij kan men denken aan de volgende onderzoekslijnen:

- Reservoir engineering studies om de (intrinsieke) veiligheid van CO_2-opslag te verhogen.
- De ontwikkeling van gemeenschappelijke (internationale) methoden voor de selectie van CO_2-opslag sites, monitoring en verificatie technieken, en risicobeoordeling.
- Innovatieve CO_2-afvangst technieken die de energievraag van CO_2-afvangst en de daaraan gerelateerde kosten aanzienlijk zouden kunnen verlagen.
- De mogelijkheden en voordelen van het combineren van op biomassa gebaseerde elektriciteitsproductie met CCS, evenals de toepassing van CCS in andere energie intensieve sectoren, zoals cement, staal, chemicaliën, en papier.
- Uitstaande kwesties met betrekking tot wet- en regelgeving ter ondersteuning van CCS, bijvoorbeeld termijnen en verantwoordelijkheden voor de verschillende soorten aansprakelijkheid rondom CO_2-opslag.

Dankwoord / Acknowledgements

Ik dank Marko Hekkert voor zijn vertrouwen en motiverende begeleiding in de totstandkoming van dit proefschrift. Daarnaast dank ik Wim Turkenburg en Ruud Smits voor hun kritische blik op mijn promotieonderzoek en de scherpe vragen die mij telkens weer op juiste spoor zette. Het was mij een groot genoegen dat ik met zulke ervaren wetenschappers heb mogen samenwerken.

Het voert te ver om hier alle mensen te bedanken die een (in)directe bijdrage hebben geleverd aan dit proefschrift; er zijn simpelweg te veel colloquia, workshops en conferenties geweest waar ik goede contacten aan heb overgehouden. Desalniettemin wil ik een aantal mensen noemen die naast mijn promotoren belangrijk zijn geweest voor mijn academische vorming, namelijk: Wilfried van Sark, Erik Lysen, Jan Faber, Andrea Ramirez, Peta Ashworth. Ook gaat mijn dank uit naar de studenten die ik heb mogen begeleiden tijdens hun afstuderen en van wie ikzelf ook het een ander heb opgestoken. Chris Eveleens, Paul Noothout, Alco Kieft en Jochem van Ruijven; jullie allen bedankt voor de fijne samenwerking.

Verder ben ik dankbaar voor alles en iedereen die mijn leven kleur hebben gegeven;

Mijn collega's in Utrecht – altijd weer een plezier om naar mijn werk te gaan

Nachtenlang praten en lachen met mijn beste vrienden

Viswedstrijden met de familie Bol

Zelfgemaakte kroketten van Opa van Alphen

Toevallige passanten die een gewone dag onverwachts leuk maken

's Ochtends naar school fietsen over de Boterdijk

Papa en mama – oftewel vrijheid en liefde

Het vliegtuig dat mij al naar alle uithoeken van de wereld heeft gebracht

Het Ideale Energiegewicht – duurzaamheid en innovatie in een notendop

Annemarie; altijd mijn lieve zusje

Kudelstaart, Pech-de-Lartel, Nimbin, en Eys – alles heeft zo zijn eigen schoonheid

Rembo & Rembo en Roald Dahl – een geweldige kindertijd

Het eindeloze Australië en de Texelse duinen

Het Global CCS Institute – de wereld lijkt groot, maar is oh zo klein

Het Alkwin Kollege te Uithoorn – de mooiste vriendschappen zijn er begonnen

De Bloemenveiling in Aalsmeer waar ik veel vroege uurtjes heb doorgebracht

Mijn sterrenkijker en duikbril die mij elke keer een andere wereld laten zien

Eva; mijn belangrijkste bron van energie die ik zo duurzaam mogelijk zal blijven aanwenden

Klaas van Alphen, Maart 2010

Curriculum Vitae

Klaas van Alphen was born on the 16th of October 1980 in Amstelveen, the Netherlands. He completed his secondary education at the Alkwin Kollege (Gymnasium) in Uithoorn, the Netherlands in 1999. After a year of travelling around the world he started his studies of Natural Sciences and Innovation Management at the Utrecht University. His specialization in the field of Energy & Materials included a semester of Energy Physics at the University of the Western Cape, South Africa and an Internship at the United Nations Development Program (UNDP), Republic of the Maldives. During his employment in the Maldives, his tasks differed from the quantification and evaluation of available solar and wind resources for electricity applications, to the evaluation of policy instruments in terms of their suitability to develop a domestic market for renewable energy technologies. This work resulted in several publications.

In 2005, Klaas started his PhD research into the development and deployment trajectories for carbon capture and storage technologies. This research was conducted at the Department of Innovation and Environmental Sciences (Copernicus Institute for Sustainable Development and Innovation, Faculty of Geosciences, Utrecht University). Aside from conducting this research, Klaas assisted in teaching MSc courses on Theory of Innovation and Organization and; Analysis of Energy System Dynamics. He also supervised MSc students with their final thesis and participated in contract research for the Ministry of Economic Affairs and SenterNovem. Furthermore, during his PhD research , he completed the Dutch graduate school of Science, Technology and Modern Culture (WTMC) and participated in several research networks, like the Dutch Knowledge network on Carbon Capture and Storage (CATO); the Technology, Management and Policy Graduate Consortium (TMP); and the Knowledge network on System Innovations and Transitions (KSI).

Besides Klaas' interest in more innovative and sustainable ways of producing energy, he is since 2008 also involved in a project that addresses the demand side of the energy system. Klaas was the co-founder and chair of 'Stichting 2050', a Dutch foundation which stimulates a more efficient use of energy resources by providing objective information on climate- and energy related issues to a broader public. In this role he co-authored a book and newspaper series called "The ideal energy weight". This book was advertised by National Geographic as "The Energy Diet aims to help you take a step-by-step approach toward a lifestyle that is healthier for the planet, and may end up saving you money."

In October 2009, Klaas emigrated to Australia, where he now works for the Global CCS Institute. In his role as Senior Advisor, he has been responsible for the assessment of applications for financial support of commercial scale CCS projects and management of key global industry/commercial relationships with CCS project developers. Klaas also represents the Global CCS Institute in the Technical Working Group of the Carbon Sequestration Leadership Forum and recently joint the Executive Committee of the International Energy Agency's Greenhouse Gas R&D Programme.

List of publications (Peer reviewed articles)

- Klaas van Alphen, Marko P. Hekkert, Wim C. Turkenburg (2010). Accelerating the deployment of carbon capture and storage technologies by strengthening the innovation system. International Journal of Greenhouse Gas Control, Volume 4(2), p396-409.
- Klaas van Alphen, Paul M. Noothout, Marko P. Hekkert, Wim C. Turkenburg (2010), Evaluating the development of carbon capture and storage technologies in the United States. Review Article. Renewable and Sustainable Energy Reviews, Volume 14 (3), p971-986.
- Klaas van Alphen, Jochem van Ruijven, Sjur Kasa, Marko Hekkert, Wim Turkenburg (2009). The Performance of the Norwegian Carbon dioxide, Capture and Storage Innovation System. Energy Policy, Volume 37(1). p43-55.
- Klaas van Alphen, Huden S. Kunz, Marko P. Hekkert (2008). Policy measures to promote the widespread utilization of renewable energy technologies for electricity generation in the Maldives. Renewable and Sustainable Energy Reviews, Volume 12(7), p1959-1973.
- Klaas van Alphen, Marko P. Hekkert, Wilfried G.J.H.M. van Sark (2008). Renewable energy technologies in the Maldives—Realizing the potential. Renewable and Sustainable Energy Reviews, Volume 12(1), p162-180.
- Klaas van Alphen, Quirine van Voorst tot Voorst, Marko P. Hekkert, Ruud E.H.M. Smits (2007). Societal acceptance of carbon capture and storage technologies. Energy Policy, Volume 35(8), p4368-4380.
- Klaas van Alphen, Wilfried G.J.H.M. van Sark, Marko P. Hekkert (2007) Renewable energy technologies in the Maldives—Determining the potential. Renewable and Sustainable Energy Reviews, Volume 11(8), p1650-1674.
- Klaas van Alphen, Christian Eveleens, Marko P. Hekkert, Wim C. Turkenburg (Forthcoming). Evaluating the Canadian carbon capture and storage innovation system: relating innovation system structure and functioning. Submitted to Energy Policy, under review.

Other Publications

- Klaas van Alphen and Herman van der Meyden (2008). "The ideal energy weight – find the right green balance" Kosmos Publishers, Utrecht/Antwerp. ISBN: 9789021541259.
- Klaas van Alphen and Herman van der Meyden "How to reach the ideal energy weight" - newspaper series consisting of 12 articles in the national newspaper Nrc-next. The article series touched upon various issues around energy savings and was published every Thursday from the 11th of September until the 18th of November 2008.