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Regulatory and social analysis for the legitimation and market formation of carbon dioxide (CO_2) capture and storage technologies

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Abstract: Deployment of carbon dioxide (CO_2) capture and storage (CCS) depends on regulatory and public perception issues as much as on technological developments. This chapter assesses, from an innovation system perspective, the technological, regulatory and social situation for CCS, and clarifies the current plans for regulation in various countries. Besides estimating the impact prospective regulation is likely to have on CCS implementation, this chapter reviews the experience in the social sciences with public perception of CCS. We conclude that legitimation and market formation of CCS, and to a lesser degree (and in some countries) institutions to influence direction of search and entrepreneurial experimentation have to be further developed for CCS implementation. A global demonstration programme as well as guidelines for public engagement and communication would be instrumental in achieving this.

Key words: carbon dioxide capture and storage, CO_2, technological innovation systems, regulation, climate policy, innovation.

3.1 Introduction

As climate change is gaining ground on the political agenda and carbon dioxide (CO_2) capture and storage (CCS) is emerging as an essential element in any climate mitigation portfolio (IPCC, 2007; IEA, 2008a), the question of making mature CCS technology a reality has become urgent. This chapter assesses, from an innovation system perspective, the prospects for CCS technology to mature quickly.

In comparison with other low-carbon energy supply technologies, CCS has a number of distinguishing characteristics relevant to its regulation and implementation. First, CCS is paradoxically both a new and a known technology. It is relatively new because development in a small number of focussed research groups started in the early 1990s, but the technology has only really come on the broader agenda fairly recently, since the publication of the IPCC Special Report on CCS (IPCC, 2005). CCS, however, also starts from a high base. The technology comprises relatively known components:

CO_2 separation from flue gases is routinely done in the fossil fuel industry and refineries; CO_2 transport by pipeline is a mature technology; and injection of CO_2 in geological reservoirs has been done for decades for various purposes, but primarily for enhanced oil recovery (EOR). A full CCS chain can be built from mature components. However, a significant role for CCS is only possible if capture options, in particular, are demonstrated at scale. Hence, CCS is both a mature and a demonstration technology and its journey through the innovation chain does not develop according to the regular sequence of R&D, demonstration, deployment and diffusion.

Second, CCS is not carbon-neutral and does not reduce emissions to near-zero levels, like renewable and nuclear energy do. It can be characterised as providing significant but imperfect mitigation. The energy penalty, remaining and additional upstream emissions of post-combustion capture, for instance, add up to an emission reduction of 70–80 % compared to a conventional coal-fired power plant (Viebahn *et al.*, 2007). This has consequences for the long-term viability of CCS, as low stabilisation levels require emission reductions beyond 80 % below 1990 levels after 2050 (IPCC, 2007), and hence for long-term policies for CCS.

Finally, CCS is an end-of-pipe technology that is more compatible with the current energy system than other low-carbon electricity supply technologies. Rather than replacing coal-fired power production, CCS reduces its climate impacts. This has two important and countervailing consequences. On the one hand, the lack of the co-benefit of a transition to a fully sustainable, non-fossil energy system and the potential risk of CO_2 seepage from reservoirs mobilises some environmental movements against CCS (Greenpeace, 2008), although others take an advocative position on CCS (Stangeland, 2007). On the other, CCS is the only option that provides a future perspective for the fossil fuel industry in a carbon-constrained world, as it allows for the continued use of coal and gas for power production, and it provides opportunities for the oil industry in EOR and as storage reservoir operators.

These principal characteristics of CCS have implications for the way it is perceived and deployed by actors, and for the way it evolves. In order to evaluate the evolution of a technology, the concept of a Technological Innovation System (TIS) will be used in this paper. The TIS approach (Hekkert *et al.*, 2007; Bergek *et al.*, 2008) is grounded in the theory of National Innovation Systems, coined by Lundvall (1992) but goes beyond that by providing policymakers and other stakeholders with means to advance a technology by changing specific aspects of the system. Bergek *et al.* (2008) define a TIS as a 'socio-technical system focused on the development, diffusion and use of a particular technology (in terms of knowledge, product or both).' A TIS can be national or international, and its main elements are structural components and functions. Structural components can comprise actors, networks or institutions, both specific for a technology or with a more generic applicability. As structural components are less flexible, attention is often more focussed on improving functions. The functions used in this paper are introduced briefly in Table 3.1.

Table 3.1 Functions of a technological innovation system according to Bergek *et al.* (2008)

Function	Description
Knowledge development and diffusion	How well the TIS performs with respect to its knowledge base and how knowledge is diffused and combined. Knowledge includes not only scientific and technical knowledge, but also product, market and logistic knowledge.
Resource mobilisation	The extent to which the TIS is able to mobilise competence/human capital through education in specific scientific and technological fields as well as in entrepreneurship, management and finance, financial capital (seed and venture capital, diversifying firms, etc.), and complementary assets such as complementary products, services, network infrastructure, etc.
Market formation	The phase and shape of the market as well as the institutional stimuli for the technology to proceed. Three market formation phases are distinguished: nursing markets, in which a 'learning space' is opened up, in which the TIS can find a place to form; bridging markets, which allow volumes to increase as well as number of actors; and mass markets in terms of volume of the technology roll-out, often several decades after the formation of the initial market.
Influence on the direction of search or guidance	The balance of incentives and pressures for firms and organisations to enter the TIS. Indicators include the belief in growth potential, incentives from price factors, regulatory pressure and visions of leading customers.
Legitimation	Legitimacy is a matter of social acceptance and compliance with relevant institutions. The technology (and its proponents) needs to be considered appropriate and desirable by relevant actors in order for resources to be mobilised, for demand to form and for actors in the new TIS to acquire political strength.
Entrepreneurial experimentation	The number and variety of experiments taking place in the field of the technology, particularly in the later phases of market formation. Indicators include the number of new entrant firms and different types of applications.
Development of positive externalities	The extent to which the technology can create positive effects in other systems. This includes not only positive economic spill-over effects of the technology itself, but also the opportunities it provides to existing firms to enter new markets.

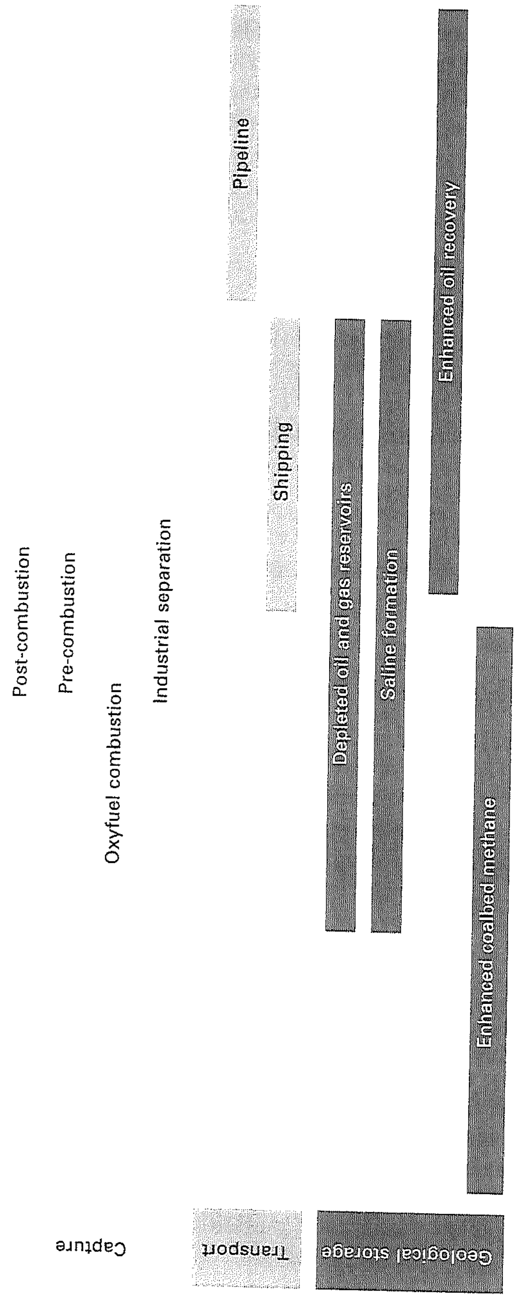
The TIS method has been applied to CCS for the case of Norway earlier (Alphen *et al.*, 2009). Discussing a global TIS for CCS can unravel the structural components and functions, and provide a basis for the choice of international policy intervention. This chapter therefore expands the national TIS analysis to a global level, thereby necessarily losing some of the detail that was present in Alphen *et al.* (2009). In view of the priorities identified above, the overall question to be answered in this chapter is: *How may a global TIS for CCS be enhanced, particularly with regard to market formation and legitimation?*

The chapter starts with an assessment of the current status of CCS technology and the CCS technology innovation system in Section 3.2. As the outcome of this evaluation points specifically at weaknesses in the market formation and public legitimation, Section 3.3 goes into public perceptions of CCS technology and in Section 3.4, current and prospective regulation are discussed, with a view to shedding light on the market formation and influence on direction of search for CCS. Section 3.5 draws policy conclusions and provides an outlook for CCS.

3.2 Technological maturity and the carbon dioxide (CO_2) capture and storage (CCS) innovation system

3.2.1 Technological maturity of CCS

Various components of CO_2 capture, transport and geological storage are in different stages of technological maturity (see Fig. 3.1). Some capture technologies, particularly in industrial sectors such as gas processing and ammonia, are commercial, but in the power sector, where the largest potential for CCS deployment resides, full-scale demonstrations remain to be built. The main barrier to full-scale demonstrations of CO_2 capture in the power sector are the high upfront capital costs of an additional 500–1200 US$/kW (IEA, 2008b), or an additional US$ 250–600 million for a 500 MW power plant. CO_2 transport does not pose technological challenges, although only a few CO_2 ships currently exist. Current pipelines are mostly in sparsely populated areas, but regulation and risks in urban environments seem manageable (EC, 2008; IEA, 2008b). In the field of geological storage, storage in depleted oil and gas fields and saline formations has been implemented on a few occasions but is not completely understood in all types of reservoirs. EOR using CO_2 is a commercial technology for oil recovery, but for permanent CO_2 storage has only been demonstrated in one large-scale project; the Weyburn project in Canada. Enhanced CoalBed Methane recovery has not yet seen a demonstration at full scale.



3.1 Stages of maturity of CCS capture, transport and storage components (Coninck *et al.*, 2009).

3.2.2 Economic incentives for CCS

Since Fig. 3.1 was first drawn in 2005, and despite the extensive talk on CCS after the IPCC Special Report on CCS was published, the maturity of CCS components has changed little and progress on CCS demonstration has been limited. Although a few new CCS projects at scale have been started in the gas processing sector, lack of incentives, rising commodity prices and the investment risk associated with first-of-a-kind installations have been shown to be important barriers to implementation of power-sector CCS. CCS seems prone to run into the 'valley of death' (Murphy and Edwards, 2003) associated with technological demonstration, representing the phase between full public funding when a technology is in the R&D phase, and primarily private financing when a technology is more mature and responds to market signals.

The valley of death looms specifically with CCS in the power sector, as the capital costs of that option are highest, and the technical complexity of demonstrating the capture process at full scale is large. There is an ongoing debate on how to finance CCS demonstrations in this sector (ZEP, 2007). Given that full-scale projects should function normally in the power market and should be operated by a power company that can benefit from the learning in the first CCS plant, it can be expected that the private sector should cover most of the investment. However, as CCS demonstrations are not viable because of high costs, low and volatile CO_2 prices and technological risks, a funding role for the public sector is also required. A public–private partnership, for instance through a combination of a carbon market price with capital subsidies, or a guaranteed carbon price that would be sufficient to cover the carbon abatement cost of CCS would therefore be most obvious to fund full-scale demonstration of CCS in the power sector (Gibbins and Chalmers, 2008; Groenenberg and Coninck, 2008).

For sectors where CO_2 capture technology is mature, such as for high-concentration or gas processing CO_2 sources, the situation is quite different. As the technological risks are limited, a market signal should suffice for deployment. However, these market signals are often not in place, or other barriers prevent further roll-out of CCS (IEA, 2008b). Norway provides a stable and significant market signal for its offshore industry through a CO_2 tax, which has delivered the Sleipner and Snøhvit projects. The European Union provides a market-based incentive for CCS in several sectors via its EU Emissions Trading Scheme (ETS), but prices are currently low and volatile. The United States, Canada and Australia do not currently have structural incentives for CCS. As long as CCS is not allowed in the Clean Development Mechanism, it is unlikely that the developing-country potential for low-cost mitigation in the gas processing, refinery and ammonia sectors will be realised (Zakkour *et al.*, 2008; Bakker *et al.*, 2009).

3.2.3 The CCS 'technological innovation system'

This section uses the TIS methodology to characterise the general situation around CCS, the main differences between countries and where international cooperation is most pronounced. Table 3.2 provides a discussion of the TIS structural elements for CCS with examples from various countries and internationally.

Table 3.2 Structural elements of the CCS TIS

Structural elements	Description for CCS (examples of elements)
Actors	Private sector: • Oil and gas industry (Shell, Saudi Aramco) • Coal industry (AngloCoal, Rio Tinto) • Power companies (RWE, Duke Energy) • Technology manufacturers (GE, Bosch, ALSTOM, Mitsubishi Heavy Industries) • Engineering companies (Schlumberger) • (Re)insurance companies (SwissRe, AIG) • CCS industry associations (CCSA) Government: • Energy departments • Environment departments • Regulators and mining authorities • International organisations (IEA and its implementing agreements, UNFCCC, IPCC, Global CCS Institute) Civil society • National or international environmental NGOs (Greenpeace, EDF) • Local organisations/organisers of local resistance (Environmental Justice; local political parties) Non-governmental, independent: • Academia: research institutes and universities (engineering and social science)
Networks	National research programmes (US Regional Sequestration Partnerships, Netherlands CATO) EU research programmes (CO_2-Geonet, GeoCapacity, CO_2REMOVE and many others) International conferences (GHGT-conferences, Green Power conferences) Carbon Sequestration Leadership Forum IEA GHG R&D Programme networks and meetings (summer schools) UNFCCC Conferences of Parties and other meetings
Institutions	Legal: existing and emerging legislation Policy: EU Emissions Trading Scheme, Norwegian offshore carbon tax Culture/routine: some countries have strong links between the private sector, government and academia (Japan, Australia, The Netherlands)

Almost all industrialised countries have an interested government and an active civil society. In the private sector, there is more variation between countries. Factors include whether the country has strong manufacturing industry, has fossil fuel resources, a power sector based on fossil fuels, or an insurance industry. Networks are both national and international. The CCS networks show strong links between academia and industry in most countries as well as internationally. Institutions differ more between countries. Both policy and legislation are in various stages of development, as the urgency of climate change and hence the need for CCS are not similarly acknowledged. There is little exchange between governments on legislative issues. In some countries, there is a strong innovation system: industry, research and government cooperate in a relatively harmonised way and there is much mutual trust and cooperation. In other countries, this institution is less strongly developed, but this is compensated by stronger entrepreneurial experimentation in the private and finance sectors.

Table 3.3 describes how the functions of the CCS TIS can currently be characterised. The function *knowledge development and diffusion* related to CCS receives attention from industrial, scientific and public funding parties, as indicated for instance by the increase in R&D budgets, although diffusion of knowledge is in its infancy. The European Commission had good reasons to make any funding to CCS demonstrations from its Economic Recovery Plan (Council of the EU, 2009) contingent on knowledge sharing by the beneficiary. The need for information sharing is also one of the objectives of the Global CCS Institute (GCCSI, 2009), recently founded to advance CCS globally.

Resource mobilisation is crucial for advancing any technology, both in earlier phases of development as well as when the technology is diffused widely. For research, the EU and more recently the USA make available financial resources to a selection of CCS demonstrations, but financial institutions are only moderately interested in CCS. The human capacity of CCS is increasing rapidly but most likely insufficient to enable full roll-out.

Market formation in the bridging market that CCS currently is could be further improved. The institutional embedding of CCS is most progressed in the EU; in most other developed countries, legal systems are still under development, whereas in developing countries work has been very limited in this area. *Guidance on the direction of search* for further CCS development so far is limited to the targeted number of CCS demonstrations that would need to be realised. Although there is a great belief in the potential of the technology, and the G8 supported the ambition to have 20 large-scale demonstrations by 2010, with the intention to have broad deployment by 2020 (G8, 2008), structural incentives are still largely absent or insufficient. Although CCS has been included in emissions trading schemes in the EU

Table 3.3 Functions in the CCS TIS

Function	Description
Knowledge development and diffusion	• In most industrialised countries, R&D capacity is relatively good and growing rapidly. • Publications on CCS are plentiful and growing. • For existing and new technologies, patents are being filed, but there is no assessment of how many.
Resource mobilisation	• The human capacity on CCS is rising, both in quality and in quantity. Existing training for geologists or engineers are applicable to CCS. Additional specific training is provided on some occasions. • Mobilising of financial resources from the financial sector has been modest, although governments (EU, Australia, Canada, USA) have raised significant amounts in their economic stimulus packages and through other means. Also equity has been invested into CCS.
Market formation	• The market stage for CCS can be characterised as a 'bridging market' – it is beyond the 'nursing market' stage, the number of players growing rapidly but it is too soon to speak of a 'mass market'. • Institutional stimuli are being put into place in the EU and other countries considering strong climate policy while planning new coal-fired power plants or maintaining CO_2-intensive industries. • Potential market size in the longer term (IEA, 2008a) is significant.
Influence on the direction of search or guidance	• CCS is clearly still awaiting regulatory pressure. In the EU and Norway this is probably strongest with the EU ETS and the offshore carbon tax. • There appears to be a strong belief in growth of the technology, but no clear direction of search in the different capture options. • Companies are interested in CCS and are investing in research.
Legitimation	There is a clear split between actors in legitimation of CCS. CCS is considered appropriate and desirable by most private sector actors, academia and by developed country governments, but much less so by civil society and many developing country governments (Hansson and Bryngelsson, 2009; Shackley *et al.*, 2009).
Entrepreneurial experimentation	• Most entrepreneurial experimentation takes place within existing oil/gas and power companies. Some new companies have entered the market, but they face the incumbents which are often more resourceful and have easier access to e.g. underground storage reservoirs. • Between capture technologies, there are investors

Table 3.3 Continued

Function	Description
	in post-combustion as well as pre-combustion and oxyfuel combustion. • There is no company (except for the gas industry) that controls the whole CCS chain, so for CCS in the power sector, power companies need to collaborate with companies active in the underground. The institutions for that are still largely absent.
Development of positive externalities	With a few exceptions of enhanced hydrocarbon recovery and conditional security of energy supply benefits, development of positive externalities for CCS is limited.

and the emerging system in the USA, the CO_2 market prices are as yet too low to stimulate widespread diffusion of the technology.

Legitimation is crucial, referring to acceptance of a technology by both policy makers and society at large. While understanding of the need for CCS technology among policymakers is on the rise, the larger public appears reluctant to accept the technology, and strategies for effectively involving the public in decision-making on CCS remain to be applied. Finally, *entrepreneurial experimentation* has increased steeply since CCS became an option, judged by the number of proposals for CCS pilots and demonstrations (CSLF, 2009). This points at a strong will from industrial parties to pioneer in this field, as well as a willingness to take (limited) risks, although lack of financial support, public support and even technical information have led to the cancellation of a number of planned CCS demonstrations (Hansson and Bryngelsson, 2009).

The preliminary and rough analysis of the CCS Technological Innovation System does not reach the depth that country TIS studies, such as Alphen *et al.* (2009), have. However, it does confirm Hansson and Bryngelsson's (2009) findings that there is an apparent discrepancy between the optimism of many CCS actors and the performance of the Innovation System functions. In the field of human capacity and belief in growth of the technology, CCS seems well developed. Possible problems arise with legitimation, direction of search and market formation, and to a lesser degree (and in some countries) entrepreneurial experimentation and resource mobilisation. We identify two areas where the TIS of CCS requires most work: legitimation with respect to public perception and participation, the topic of the next section, and in market incentives for CCS, the topic of Section 3.4.

3.3 Legitimation: results and gaps in social scientific research regarding public perception and participation

Bergek *et al.* (2008) define legitimation as 'a matter of social acceptance and compliance with relevant institutions'. There is no need to look far for examples of how lack of legitimation can lead to technology failure, on both a local and a more global scale. An early experiment with ocean storage was cancelled in Hawaii after a number of local organisations formed a coalition and resisted the location of a small CO_2 injection facility in the ocean (De Figueiredo, 2003). In Barendrecht, a town near Rotterdam in the Netherlands, local resistance to CO_2 storage in two gas fields grew over the course of 2009. Although the national government has decided in favour of the project, local resistance is likely to at least delay the project substantially. On a global scale, broad resistance to nuclear energy has resulted in far less implementation of the technology than was initially projected. CCS, as a large-scale technology with local risks, which is associated with 'dirty coal' and which does not have clearly discernible co-benefits, risks lack of public legitimation.

This section is limited to public opinion and will not discuss legitimation from a policymaker or industry viewpoint. As suggested in previous sections, policymakers, albeit slowly in some cases, are beginning to understand the relevance of CCS technology for the global climate. Aspects related to market formation are discussed in the next section. Industry is becoming increasingly appreciative as the viable business case that CCS may at some point offer. Although agenda-setting by industry and policy is certainly important, this section will provide a detailed discussion focusing on the more contentious issue of perception and involvement by the public at large.

What is the current status of public opinion and of public involvement? Would the public agree that the choice of CCS for CO_2 emissions is a legitimate one? Several issues arise when trying to answer these questions, and more than one of these issues is associated with the status of the scientific research on these topics.

Another issue is how to define the status of public opinion. From the perspective of development of the CCS innovation system, public opinion could be defined as 'good' when the public is generally positive about CCS. However, from a societal perspective, one could argue that public opinion should be of high quality, being stable, well-informed and considered. This is related to the different possible goals of public participation, one of which can be democratic–idealistic, aiming at giving people the opportunity to develop well-informed opinions on which they can base their decisions. Another goal is purely instrumental, as a way to either gain complete agreement about the

need for CCS or at least to avoid possible protest against implementation of CCS technology, specifically around demonstration sites.

With these perspectives in mind, we will discuss the issue of the current status of research on public opinion regarding CCS. This includes how knowledge on public opinion is generated and how it should be interpreted. Based on this, we will discuss which questions remain. We will then go into the effects of these gaps in current knowledge about public opinion and public involvement for the estimation of current legitimisation of CCS technology in the context of the TIS.

3.3.1 Current status of research on public opinion: issues encountered

In recent years, empirical research regarding public attitudes towards CCS has been developed in several countries. Except for an early study in the Netherlands in 1998 that incorporated the possibility of CCS technology among other options for energy, the earliest studies focusing on public awareness or opinion of CCS technology emerged around 2004. Faced with the question of how the public might react to CCS technology, these studies tried to investigate if the main goal of CCS, CO_2 emission reduction, was in fact an issue for the public, if the public was aware of the possibility of CCS, and how this possibility would be evaluated in light of further information.

Awareness of CCS technology

There have been two studies which tried to place CCS in a broader context by investigating if the public considers CO_2 emissions as a problem to be solved. Giving people several societal issues to rank, Curry *et al.* (2007) reported that protecting the environment was the eleventh highest ranked priority for Americans, while Palmgren *et al.* (2004) found that respondents ranked 'reducing climate change' as the lowest social priority of the 15 choices offered to them.

Moreover, most of the studies done so far have encountered a profound lack of awareness. For instance, Reiner *et al.* (2007) compared awareness of CCS in large adult samples in the USA, the UK, Sweden and Japan. They found low awareness in all four countries, ranging from 22 % of respondents confirming they had heard or read about CCS in Japan, to as little as 4 % of respondents confirming this in the USA. A more recent study in Japan (Itaoka *et al.*, 2009) showed similar results, with 7–18 % of respondents stating that they knew of CCS to some extent. In a survey of 900 respondents in Australia, 29.9 % of respondents were able to give meaningful answers when asked what they understood about CCS (Ashworth *et al.*, 2006). A less representative but more recent Australian study confirmed those average

Recent Dutch studies also show a significant influence of perceived benefits of CCS (Best-Waldhober *et al.*, 2008; 2009). These studies both combine a large sample with elaborate information from experts on aspects and consequences of CCS options. Although part of the sample of the second study became on average more positive after information, further analyses show that there is little to no relation between respondents' opinion before information and after information. This means that a large portion of the respondents changed their opinion, becoming either more negative or more positive. Another factor influencing opinions of CCS that became apparent from this study was that, in the opinion of the respondents, CCS compares slightly unfavourably with other climate mitigation options such as efficiency, wind energy, nuclear energy or energy from biomass.

3.3.3 Knowledge gaps regarding public opinion and involvement

The size of the CCS knowledge gap with the general public can be seen as an indicator for the current state of the innovation system function of public legitimation. Due to the recent start of research on this topic, the limited financial resources available and the politically sensitive nature of the topic, several gaps remain in the knowledge about public opinion and involvement in CCS technology. Gaps that we will discuss here are the development of public awareness and opinion over time, the lack of knowledge about lay arguments and concepts, the lack of knowledge of public information needs, effects of both location and local context, need for effective strategies for public involvement/participation, and lessons from case studies of (planned) demonstration projects for CCS technology.

First, as Malone *et al.* (2009) point out, 'surveys and polls measure public opinion at one point in time. Opinions are dynamic'. It would be informative to know how public awareness and public opinion evolve over time and which factors, such as media coverage, influence this process. Several studies acknowledge this, and in some countries measurements of awareness have been repeated more than once. Given that the first studies started only a few years ago, longitudinal studies are still at an early stage.

Second, as argued before in this section, there is still much to learn about the arguments that the public deems important for making decisions about CCS technology, and the possible misconceptions people might have. Several studies, including some mentioned above, have investigated possible considerations of lay people regarding CCS technology, but the results are somewhat mixed and many questions remain. Are considerations from the general public the same as those from people living close to a possible storage site? Are these considerations influenced by culture, by context, by demographics? Is public understanding and acknowledgement of anthropogenic global warming a driver or a prerequisite for a positive perception of CCS technology?

Being able to answer these questions could provide insight into the information needs of the public. How to inform the public is more than a scientific question though. As stated earlier, the issue of informing the public can be viewed from an instrumental point of view or from an ethical point of view. We would propose that people should have the right and opportunity to participate in the debate and the decision-making about energy technology, specifically if local activities are an option. Knowing what kind of information is needed by the public for this is crucial, as is securing understandable, balanced and accurate information from multiple sources. However, even if one's view is instrumental, the literature shows that what can be seen as the most ethical road can also be the most effective. Research by Mors (2009) and Terwel (2009) shows that effective communication about CCS relies on trust. People put more trust in environmental NGOs than in the industrial organisations involved or the government. Communication strategies by these stakeholders can be counterproductive because, if the source of the information is not trusted, the information is rejected, which may result in negative public attitudes towards CCS. Of course, information that is perfectly understood and trusted by the public does not guarantee a positive opinion of CCS technology. Balanced information will include both advantages and disadvantages of CCS technology, and the evaluation of these characteristics and consequences will differ between individuals.

The investigation of effective public participation strategies and lessons from case studies are often linked together. This can be risky if the same organisation that is responsible for the design and/or implementation of the participation efforts is also the one evaluating the process and its effectiveness. A bigger issue for defining the status of legitimation regarding public involvement, however, is the early stage of the development of the technology and, consequently, the few demonstration projects currently planned. Although some studies have investigated participation strategies for CCS technology, these studies concerned very early stages of possibly planned demonstration projects (e.g., Raven *et al.*, 2009). However, most of this kind of research is ongoing.[1] Analyses that have been done are either not yet published or concern the early stages of demonstration projects. At the same time, attention devoted to CCS technology in the popular media seems to be on the rise, specifically articles about public protest against CO_2 storage in several locations around the world[1]. Because these protests as well as the media attention are very recent, no scientific analyses have yet been published, making it hard to evaluate the current status of legitimation

[1]Based on personal communication within project meetings and the CCS social scientists network.

regarding public participation and opinion. Media attention might just reflect the first reactions of a small percentage of people involved.

Despite the inauguration of several studies, public legitimation, as a function in the CCS TIS, is still a great unknown. However, early studies as well as observations suggest that in specific project situations and depending on the socio-economic and environmental circumstances, public legitimation may be a cause of concern. Although it is clear that this issue should be more adequately addressed, the instrumental method of 'convincing the public of CCS's merits' is unlikely to work. Rather, resources for real public engagement and, if appropriate, compensation may need to be mobilised.

3.4 Market formation and direction of search: an enabling regulatory framework for carbon dioxide (CO_2) capture and storage (CCS) in the EU

Market formation and direction of search have various aspects. First, they comprise the institutions that ensure that the technology can be implemented safely. Second, the bridging market that CCS currently is should be nurtured towards becoming a mass market through incentive mechanisms. In the case of CCS, this means a successfully implemented demonstration phase, rapid roll-out and structural incentives for diffusion in the longer term.

Following these threads, this section will subsequently review the enabling legal framework for CCS safety in the EU and internationally, CCS demonstrations, and regulations that are relevant for CCS market formation. As the countries of the EU are furthest ahead both on providing incentives and on the legal system of CCS, this section will focus on the EU, with extra attention devoted to Norway. In some places, developments in Australia and the USA will also be discussed.

3.4.1 Regulation of safety of CCS

In recent years, significant progress has been made in regulating CCS. A number of international treaties have been amended to enable CCS, and frameworks for regulating the safety of CO_2 capture and storage have been developed in various regions, including Australia and the USA, and adopted in the EU. The key objective of any of these regional frameworks is to guarantee safe storage of CO_2, with a view to enabling the introduction of the technology. Consequently, the various regulatory frameworks resemble each other on essential aspects such as site selection and monitoring. All focus on the procedures that operators and competent authorities must follow to ensure operational safety, in line with recommendations and expertise obtained in

operations to date (see e.g. Groenenberg *et al.*, 2008). Australia has in place a set of guidelines for monitoring CCS operations, which should support the regions in developing their own regulatory frameworks. In the USA, a draft proposal was tabled by the EPA. In the remainder of this section, we will focus on developments in international and EU regulations, including Norway, as those countries are furthest ahead in CCS market formation and direction of search, and thus provide the most insightful results.

International frameworks

The EU and Norway are signatories to three international treaties relevant to CCS: the London Protocol, the OSPAR Convention and the Espoo Convention. To some degree, therefore, one can speak of an international market formation effort. The London Protocol (LP) is part of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, also referred to as the London Convention. It was amended in 2006 to allow for the sub-seabed storage of CO_2 as of 10 February 2007.

The amendments are relevant for offshore applications of CCS. They regulate the storage of CO_2 streams from CO_2 capture processes in sub-seabed geological formations, for permanent isolation, thereby creating a basis in international environmental law to regulate this practice and forming the institutions needed for CCS market formation. Storage is only allowed, however, if associated substances from the source material and from capture/storage processes are incidental. The amendment of the LP triggered similar work on the OSPAR Convention, which is the North East Atlantic equivalent of the LP. The impacts of large-scale CO_2 geological storage in sites that are either cross-boundary, or close to national boundaries, should be the subject of discussion among concerned Parties of the Espoo Convention of 1991. Transboundary CO_2 transport by pipeline would obviously need to be subject to discussion among the national authorities involved as well.

The EU Directive for the Geological Storage of CO_2

In its Energy and Climate Package, agreed in December 2008, the EU tried to make a strong move towards providing institutional embedding for CCS. The safety of CO_2 capture and storage was regulated in the Directive for the Geological Storage of CO_2. This Storage Directive covers injection and storage of CO_2 in geological formations for large operations. R&D pilots smaller than 100 kt CO_2 per year are excluded, as are ocean storage and enhanced hydrocarbon recovery operations. The Directive focuses primarily on the safety of injection and storage for human health and the local environment. Risks for the global climate are covered by the EU ETS and applicable monitoring and reporting guidelines. The requirements in the Directive regarding safety of injection and storage operations reveal the level of detail that is needed for the legal arrangements of onshore CO_2 storage, and that remain to be overcome in other jurisdictions:

- *Site selection and permit application.* The Storage Directive assumes that the objective of geological storage is permanent containment of CO_2. A good site selection is crucial, and a site may be selected only if there is no significant risk of leakage and if no significant environmental or health impacts are expected to occur. Site selection should comprise data collection, the construction of a static model representing the geological framework and dynamic flow modelling of the CO_2 in the reservoir to support a risk assessment of leakage. This includes a description of the hazards, a quantification of the impacts of leakage for man and environment and an assessment of the risks.
- *CO_2 stream composition.* Following the OSPAR CO_2 Guidelines, the Storage Directive acknowledges that other substances may be present in the CO_2 stream from the CCS processes, but it should consist overwhelmingly of CO_2 and levels of the other substances should not affect the storage or transport integrity. No wastes may be added for disposal.
- *Monitoring and inspection.* Monitoring is essential to assess whether the injected CO_2 behaves as expected and to detect any leakage that might occur. The results of monitoring are to be compared with projections from the dynamic flow modelling to assess whether site performance is satisfactory. A monitoring plan has to be submitted together with the permit application. Should any leakage occur, corrective measures must be taken. During injection of the CO_2, reporting and inspections must take place at least once a year.
- *Post-closure.* After closure, the site remains the responsibility of the operator until legal obligations are transferred to the Member State's competent authority. This may be done only when all available evidence indicates that the CO_2 will be completely contained for the indefinite future. In addition, a minimum period of 20 years applies in principle. After the transfer of responsibility, monitoring may be reduced to a level which still allows for identification of leakages or significant irregularities, but should be intensified if leakages or significant irregularities are identified. Financial provisions are to be made by the operator prior to injection to ensure that all closure and post-closure obligations under the Storage Directive and the ETS directive can be met. The provision should at least be able to cover the costs of monitoring for a period of 30 years.

EU Member States have two years to implement the Storage Directive in their national legislation. Whilst much of it may be mere transposition of

stipulations in the Directive, there are still a number of issues that each of the Member States may resolve differently. Issues include, for instance, the exact allowable composition of CO_2 streams, or the scope of 'legal obligations' that will be transferred after site closure. As to the latter, some may understand this as a transfer of management and monitoring only, while others may see it as including a transfer of liability. This may have consequences for long-term liability and may be affecting the market formation in individual EU Member States. Furthermore, more guidance is needed for competent authorities to be sure that a site can be considered safe, that site performance is satisfactory and that legal obligations can be transferred, once a site has been closed. Although more research, demonstration and experience are necessary to find the answers to these questions, the adopted Storage Directive has enhanced confidence in the safety of CCS operations and allowed for progress on market formation.

3.4.2 CCS in a bridging market: financing demonstrations

The central vehicle for CO_2 emission reductions in the EU is the EU Emissions Trading Scheme (EU ETS), which is discussed in the next section. The EU ETS provides structural incentives for CO_2 emission reductions and enables participants in the scheme to exploit available abatement options at the lowest cost. It does not, however, provide an incentive for investing in more costly and less mature reduction technologies, such as CCS (Groenenberg and Coninck, 2008). Although the ETS directive has been amended recently and has a time horizon up to and beyond 2020 now, emissions prices are still too low to sufficiently stimulate the option. CO_2 forward prices for 2012 and beyond are on the order of 15–40 €/tCO_2. Such prices are insufficient for inducing structural deployment of CCS given the technological uncertainties of components of CCS that are still in the demonstration phase.

Therefore, funds were made available in the new entrants reserve of the EU ETS to provide an extra stimulus for companies to demonstrate CCS. 300 Mt worth of emission allowances will be allocated to demonstrations of CCS and innovative renewable energy demonstrations. Criteria for the allocation of the new entrants reserve funds remain to be drafted; the exact funding depends on the carbon price, and the share of renewable energy estimates for CCS demonstration funding from the new entrants reserve vary from €3 billion to €9 billion. In addition, additional funds for CCS as part of an EU economic stimulus package were agreed in April 2009 (Council of the EU, 2009), comprising another €1.05 billion allocated to 12 projects in the EU.

3.4.3 Towards mass markets: regulation for incentivising CCS

The EU emissions trading scheme

The EU considers the EU Emissions Trading Scheme (2003/87/EC) a crucial and cost-effective instrument for meeting its climate objective of reducing greenhouse gas emissions by at least 20 % in 2020 compared to 1990. It will be important also for the market formation of CCS, after most technological barriers have been addressed in a demonstration phase.

The EU Energy and Climate Package, passed in December 2008, included provisions on ETS inclusion of CCS until 2013, the beginning of the third phase of the ETS. Before that, in the second phase of the EU ETS (2008–2012), CO_2 capture, transport and storage operations will be included, but not as separate ETS installations in their own right. Instead, CCS chains are included in the EU ETS in their entirety, requiring considerable coordination between CO_2 sources, such as power companies, operators of pipelines and storage operators. Installations that operate a full CCS chain would not need to hand in allowances for the CO_2 that is stored.

From 2013 onwards, installations capturing, transporting or storing CO_2 should be covered by the trading scheme 'in a harmonized manner', in order to encourage and provide incentives for full-scale deployment of the option. After 2013, there will be no free allocation of emission allowances for installations in the power sector. Instead, allowances will be auctioned in this sector, and CO_2 captured and transmitted for storage will not count as emitted under the EU ETS. This provides greater regulatory certainty and could enhance capture and storage of CO_2 from power installations. Greenhouse gas allowances under the EU ETS require a monitoring scheme to be in place that is tailored to the various GHG emission sources in an ETS installation, and any emissions to the atmosphere would need to be offset under the EU ETS by returning a respective amount of emission certificates to the national competent authority.

The EU ETS monitoring and reporting guidelines

The inclusion of CCS in the EU Emissions Trading Scheme has created a need for monitoring and reporting guidelines for CCS operations under the scheme. The IPCC already gave an outline for accounting procedures for CCS in its 2006 Guidelines, which provide binding guidance for accounting in the national inventories, such as those to meet the obligations of countries under the Kyoto Protocol. These cover site characterisation, monitoring and the use of history matching to assess site performance.

The Storage Directive does not address uncertainties in the monitoring program or detection limits and, as yet, it is uncertain to what extent the CCS

Annex to the 2007 Monitoring and Reporting Guidelines will contain more prescriptive wording (Wartmann *et al.*, 2009). However, it will be difficult to report emissions from CCS operations at accuracy levels mentioned. The precision of *in-situ* methods, such as seismic methods, pressure measurements, electromagnetic monitoring and gravimetric techniques, is limited. Accuracies for these methods have not been systematically assessed, but it has been estimated that the precision will not likely exceed ±20 % (Benson, 2006). Flux measurements in most cases will be more exact. However, emissions need to be detected and located before monitoring equipment can be installed at the right locations, baseline emissions arising from e.g. the decomposition of soil organic matter would need to be measured too, and all in all substantial efforts may be needed to quantify a relatively small seepage.

Norway

In Norway, the introduction of a carbon tax in the early 1990s proved very effective in cutting back on carbon emissions and directly triggered the storage of CO_2 under the North Sea, notably in the Sleipner operation. It indirectly also led to planned capture operations for gas-based power generation capacity. Still, the carbon tax, even at 40€/tCO_2, is too low to incentivise commercial CCS projects. Similarly, a domestic emissions trading scheme that could be linked to the EU ETS might not be strong enough to trigger more CCS projects. Norway currently uses 100 % hydropower for its electricity production. Although government support is being debated and although the intention is not to allow any emission from gas-based power plants, as yet in Norway no market has formed for CCS (Alphen *et al.*, 2009).

3.4.4 Other incentives: capture readiness and emission performance standards

Other options for CCS incentives were discussed as the Directive for Geological Storage of CO_2 was developed and debated in the EU institutions. Apart from regulating safety and incentives for CCS, it includes a requirement on the capture-readiness of new plants. Member States will need to ensure that operators of all new combustion plants with a rated electrical output of 300 MW or more have assessed a number of conditions, namely the availability of a suitable storage site, and the technical and economic feasibility of both transport facilities and retrofit for CO_2 capture. If these conditions are met, the Directive prescribes that suitable space on the installation site be set aside for the equipment necessary to capture and compress CO_2.

One of issues during discussions with regard to the Storage Directive was the inclusion of an emission performance standard for fossil fuel-based power generation. It was considered unacceptable, notably by Member States with relatively high emissions and limited options to store CO_2, such as in Central Europe. It shows that legitimation for CCS is not general among all countries. Another objection voiced was lack of arguments for duplication of policies: if an emissions trading scheme makes it possible to reach a low level of emissions at minimum cost, then any additional policy or regulation can only increase the cost for reaching that same emission level. Still, a mandatory requirement for emission performance standards for new electricity-generating large combustion plants may be considered again in 2015, during the evaluation of the Storage Directive.

3.4.5 The EU and CCS market formation: a mixed story

In summary, the EU by its attempt to tackle both legislating and incentivising CCS in one Directive showed comprehension of the market formation function in the CCS technological innovation system. It seems to succeed in creating a legal safety regime for CCS, and other countries are currently considering adopting relevant parts of the EU regulation. On the incentives side, modelling studies show that the EU ETS is insufficient to provide incentives for CCS and that the demonstration funds committed might also not suffice. Although the EU takes market formation seriously, it has not succeeded fully in addressing this function.

3.5 Implementation outlook for carbon dioxide (CO_2) capture and storage (CCS) technologies

Discussions of the outlook for CCS technology regularly stop at economic and technological arguments. For instance, it is often heard that CCS could grow to a major, ten to hundred billion dollar global market (IEA, 2008a) – a vision that positively affects the direction of search. Although the technological, geological and economic limits of the technology are also emphasised, those problems are presented as surmountable, resulting in a great deal of technological optimism around CCS. Rather than taking a technocratic view on the condition of CCS, this chapter used a socio-technical method, technological innovation systems, to provide an outlook for CCS technology and arrives at slightly different conclusions.

This chapter argued, based on a global TIS analysis, that in the field of legitimation, market formation and, in some countries, also direction of search and entrepreneurial experimentation, the innovation system is currently insufficient to enable rollout and even demonstration of CCS. The TIS method points at a wide range of issues that all need to be addressed if CCS is to be advanced beyond the 'bridge market' stage. Of the conclusions, those around market formation are probably least contested. It is already widely recognised that CCS needs to be demonstrated at scale in order to address

market formation, direction of search and resource mobilisation issues (ZEP, 2007; G8, 2008; IEA, 2008b). Some government and industry actors are indeed pursuing demonstrations, and governments are making available funds and are formulating flanking policies. The EU is well underway with a legal framework and incentives for CCS, but these are broadly considered insufficient to demonstrate CCS in the short term, and diffuse it in the long term. Other countries largely lack structural incentives for CCS altogether.

The conclusions around legitimation are less broadly acknowledged. Policymakers, albeit slowly in some cases, increasingly understand the relevance of CCS technology for addressing climate change. Industrial parties are becoming more and more appreciative of the viable business case that CCS may offer at some point. However, public perception and involvement is still a contentious issue. Although many experts refer to public acceptance as one of the major challenges for CCS technology (Shackley *et al.*, 2009), research and studies into public perception have been limited. As a result, several questions remain regarding the current status of public perception, opinion and involvement. And even firm conclusions from social scientists – such as that early public engagement should be a standard practice in CCS project planning – are often not broadly acknowledged by project developers, let alone implemented.

Although market formation and legitimation stand out, other functions in the TIS on which CCS performs relatively well, such as private sector legitimation and knowledge development, knowledge diffusion, resource mobilisation and further guidance will also require constant and increasing attention from all actors involved in the system. Responsible actors for these functions are limited to a small number of directly involved industrial or governmental actors. It should also be noted that demonstration of CCS at scale is essential for all functions in the CCS TIS.

CCS is often characterised as an industrialised-country mitigation option. Indeed, the lion's share of current knowledge development is taking place in developed countries; particularly the EU, the USA and Australia (Tjernshaugen, 2008). Future models, however, project that the long-term demand for CCS is greater in developing countries than in industrialised countries (IEA, 2008a) and that deployment in emerging economies should start in the period 2020–2030. In those countries, the functions of the CCS TIS are less developed and CCS is likely to require more time to mature. In most developed countries, during the past couple of years significant development of human capacity, regulatory frameworks and political awareness has taken place. This points at a current need to identify structural components and develop functions for CCS in developing countries. As demonstration of CCS has collective action characteristics, it has been argued that a publicly funded, internationally coordinated demonstration programme would be able to make this happen (Coninck *et al.*, 2009).

A last point might suggest an omission in the TIS methodology. As the TIS methodology concerns the advancing of a technology, it is not a methodology for evaluating whether a technology can be phased out again. CCS is a technology where an exit strategy may be as important as an entry strategy. Not only is the underground storage potential limited, CCS to some actors is only acceptable as a temporary solution to climate change on the road to a fully renewable-based energy system (Stangeland, 2007; Greenpeace, 2008). CCS has been called a 'bridging technology' by many players. This means that a strategy to rid the energy system of CCS after it has contributed to bridging the time required to transition to a renewable energy system is important. Research on methods to achieve this has been largely absent.

3.6 Sources of further information and advice

- IEA (2009) *Technology Roadmap Carbon Capture and Storage*. Paris, France, IEA.
- CATO: Netherlands research programme on CCS, including CCS innovation systems (www.co2-cato.nl).
- Global CCS Institute: www.globalccsinstitute.com.

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4

Energy supply planning for the introduction of carbon dioxide (CO_2) capture technologies

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Abstract: Planning for the future energy supply mix is a very challenging undertaking which requires consideration of various drivers and decision criteria. This chapter will address the multi-period energy planning problem with carbon dioxide (CO_2) emission constraints and the option of CO_2 capture and storage (CCS). The objective of the current chapter is to present a novel multi-period mixed-integer non-linear programming (MINLP) model that is able to realize the optimal mix of energy supply sources which will meet current and future electricity demand and CO_2 emission targets, and lower the overall cost of electricity. The modeling framework discussed is based on an objective function that minimizes the net present value of the cost of electricity (COE) over a given time horizon. The formulation incorporates several time-dependent parameters such as forecasted energy demand, fuel price variability, construction lead time, conservation initiatives, and increase in fixed operational and maintenance costs over time. The model is applied to a case study in order to examine the economic, structural, and environmental effects that would result if an electricity sector was required to reduce its CO_2 emissions to a specific limit. The case study examines a scenario in which the electricity sector must comply with CO_2 emission limits similar to a Kyoto target. The presented model offers many potential benefits to the energy sector. In addition to providing an optimal solution for meeting future electricity demand, it can help meet emissions targets while minimizing the overall cost of electricity. Furthermore, although the case study was aimed at Ontario's future energy supply mix, it could also be readily applied to other regions or even countries as a whole.

Key words: energy supply, emissions targets, multi-period mixed-integer non-linear programming, carbon dioxide capture and storage, cost of electricity.

4.1 The emerging energy challenge and a case from Ontario, Canada

The ratification of the international Kyoto protocol, as extensively discussed in other chapters throughout this book, imposes additional pressure for many governments to reduce CO_2 emissions. For example, under the Kyoto protocol, which was signed by the Canadian government in 1998 and ratified in 2002, Canada agreed to reduce greenhouse gas (GHG) emissions by 6% below 1990 levels by 2008–2010.