Environmental scan and issue awareness: risk management challenges for CCS

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Abstract: Long lists of issues relevant to carbon capture and storage projects have been provided in a number of sources, encompassing the broad categories of technological risks, health and environmental risks and societal risks. From these long lists a selection of ten major issues, broken down into three broad categories, has been made. The selected issues are: 1) government and industry factors (competent regulatory oversight; adequate risk assessment and risk management frameworks; and supportive public policy architecture); 2) environmental risk factors (adequate site-specific characterisations of geological formations for CCS storage sites worldwide; credible monitoring of storage site performance; and the possibility of leaking from storage); 3) socio-economic factors (tolerable economic costs; public perceptions of risks and benefits; information provision, effective communication and stakeholder engagement; and social and public acceptability, including the use of decision support mechanisms). The paper emphasises that what is unique about carbon capture and storage, considered as a major set of risk issues of global proportions, is how proactively these relevant major risks and risk factors have been identified and characterised by major institutional actors, especially industry and governments.

Keywords: issue awareness; environmental scan; risk management; environmental risks; government; industry; socio-economic factors.

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1 Introduction

The theme of issues awareness, carried out through an 'environmental scan' of diverse sources of existing discussion on a program objective – in this case, large-scale capture and storage of carbon – is the first in the series of steps that make up the generic Integrated Risk Management Framework (IRMF), which is applied to the CCS case (Larkin et al., 2019a). This placement is in part driven by the increasing and vital importance of stakeholder engagement in the formal practice of risk management for all developed economies. Both industry and regulators have learned, over a long period of time and with respect to many different risk issues, that they can be blindsided by public concerns about risks not recognised in their formal assessments. Both are well-advised to maintain an ongoing scan of the social environment in order to detect and evaluate those concerns.

The purpose of this article is to give a general introductory survey of the major issues associated with CCS, many of which are explored in greater detail in other articles in this special issue, so that they can be arrayed together and provide an overview of all of the major challenges.

In general this development signals a notable difference between today's practices and those of the past. Starting in the late 1970s, when managing risks was conventionally, for the most part, a behind-the-scenes collaborative exercise between only two parties – namely, governments and industry – pressures for involvement of a wider set of interested parties mounted steadily. The initial responses were, for example, a denial that there was any problem worthy of discussion at all; or charges that various 'outsiders' had a poor grasp of the scientific evidence behind hazard characterisations or exposure pathways; or claims that citizens and environmental groups had no appreciation for risk-benefit trade-offs. [Many examples will be found, from across different types of risks, in the case studies collected in Leiss and Chociolko (1994), Leiss (2001) and Leiss and Powell (2004)].

Underlying all of these responses was the implicit suggestions that public concerns were generally ill-founded and irrelevant to the practice of good risk management. Typically, efforts to understand the perceptions of risk that lay behind public concerns, to explain and defend the integrity of risk assessments and to communicate honestly and transparently with those whose contrary evaluation of acceptable risks reflected different social values, were made – if at all – far too late to head off protracted controversies.

The treatment of carbon capture and storage (CCS), during the first decade in which it has been featured as an important response to GHG emissions and climate change, shows how far we have advanced beyond the limitations of past practices. The 2005 Special Report on Carbon Capture and Storage by the Intergovernmental Panel on Climate Change (IPCC, 2005, 2006) was perhaps the defining moment, one that first prominently called attention to this technology and its global importance in limiting GHG emissions. Very quickly thereafter, major institutions, including national and regional governments, public-interest groups and industry consortia, began issuing regulatory and non-regulatory guidance documents – many of them intended for use by the interested public – on CCS (Larkin et al., 2019b). These included:

1 risk assessment and management operational frameworks

2 practical manuals on stakeholder engagement, risk perceptions and risk communication

3 a plethora of technical studies on all aspects of CCS within the value chain phases of capture, transportation, injection and storage, including the disclosure of the many different and complex types of risks associated with these.

This was accompanied by the explosive growth of published academic literature, in both established journals and in new journals devoted primarily or exclusively to CCS, on these subjects.

2 Risk management of CCS

CCS includes four separate processes and their associated technologies (alternatively, three processes, if injection and storage are treated together):

1 *CO_2 capture*: isolating the carbon dioxide gas that is naturally present in the burning of fossil fuels (coal, oil, natural gas), as well as the gas produced in industrial waste streams, such as at ethylene plants and compressing it into a liquid state.

2 *CO_2 transport*: moving the liquefied CO_2 from its point of origin to a suitable site for long-term storage, either on land or beneath the ocean.

3 *CO_2 injection*: using appropriate injection well technology to move the liquefied CO_2 into the underground location.

4 *CO_2 sequestration*: storing the liquefied CO_2 into a suitable geological medium that is likely to hold it in place, deep underground, for thousands of years.

The risk management of CCS deals with "risks that are unique to carbon capture and storage, i.e., those risks associated with the long-term storage of CO_2 as a reactive, mobile, and buoyant fluid in geologic reservoirs" [CSLF, (2009), cover page]. The first comprehensive and general review of these risks, appearing in the 2005 IPCC Special Report on Carbon Capture and Storage, already assessed the two main categories of associated risks, the local (short-term) and the longer-term ones, as quite low. Of the first, the Special Report said (p.12), "the local health, safety and environment risks of geological storage would be comparable to the risks of current activities such as natural gas storage, enhanced oil recovery (EOR) and deep underground disposal of acid gas." And of the second (p.14): "For well-selected, designed and managed geological storage sites, the vast majority of the CO_2 will gradually be immobilised by various trapping mechanisms and, in that case, could be retained for up to millions of years." [An excellent early overview of the whole set of issues involving CCS, including risks, can be found in Benson (2007, 2008)].

The following comprehensive list is taken from a summary description of the Australian GEODISC projects [CSLF, (2009), pp.35–6], where 'potential risk and uncertainty factors' are listed as follows:

- containment – leakage through permeable zones in seal, faults, wells, seal and at the facility
- regional and local scale over-pressurisation
- capacity – exceeding spill point, over-filling, lack of capacity
- reduced injectivity
- earthquake induced fracturing
- rock fabric failure
- migration direction
- infrastructure failure – well head, pipeline, compressor, platform or decommissioning
- failure and facility environmental damage
- stakeholder and public perception
- inadequate source
- groundwater displacement
- regulatory change and legal claims (licensing, ownership, liability)
- contamination (surface water and groundwater, soils, petroleum resources) and subsurface biological concerns
- injection engineering conditions
- project costs (viability).

Note that this comprehensive list includes a wide variety of factors that influence risks, including health and environment, technology and societal factors. [For another comprehensive list of issues specific to a regulatory context, see CSLF (2012), Appendix, Table 3].

Actual projects undertaking CCS – in particular, those carrying out sequestration only, rather than EOR – are still few and far between around the globe. Thus this effort to document what CCS is intended to do and how the risks associated with it, particularly in the storage phase, can be assessed, managed and controlled within acceptable bounds, amounts to a proactive campaign to engage the public and to provide a credible account of the technology and its risks, well in advance of the possible full deployment of what is forecast to be literally thousands of CCS projects operating around the world.

There are few other examples where this has been done for a significant risk management scenario [nanotechnology and synthetic biology come to mind (European Commission, 2009, 2014b)]. It stands in marked contrast to much earlier experience around the world with major risk management issues, where institutional actors were either blindsided by unanticipated risks – such as the prion diseases in animals – or where protracted struggles had to be waged against entrenched economic interests in order to achieve an appropriate response to serious risks affecting large populations – such as the cases of tobacco use, asbestos and agricultural pesticides. In this longer context, the early attention to major factors in managing CCS risks might – hopefully – stand as an encouragement to do likewise when new risks come to light.

The original expectation that was set for CCS may be phrased as follows: If a sufficient number of large-scale CCS projects are put in place around the world, with new ones coming into play as earlier ones are completed, together they will make a very significant contribution to the meeting of future greenhouse-gas (GHG) reduction targets by many industrialised nations. A few high-profile CCS projects – e.g., Norway's offshore Sleipner and Snøhvit ventures and Weyburn-Midale (EOR) in Saskatchewan – have been storing CO_2 underground for some time now. Within a relatively short period of time, a significant number of new CCS projects – some of them quite large and expensive – have been scoped out, planned, financed and in some cases, are under construction – around the world.

For an overview and analysis of global CCS projects see the Global CCS Institute (GCCSI, 2018) (summary, Appendix, Table 1). As of September 2018, there are 18 projects in operation globally (four with dedicated sequestration), five under construction (one sequestration) and another 15 in early or advanced development planning (seven sequestration) (GCCSI, 2018). There was a 50% increase in the number of projects operational or in development from 2011–2014, a time of growing confidence in the application of CCS technology at large scale (GCCSI, 2014).

3 List of major issues affecting CCS feasibility

One notable issue is excluded from consideration in this list below, namely, technological feasibility. This is because none of the challenges in this dimension, which are thought to lie almost exclusively in the capture dimension, are expected to represent intractable barriers to the successful implementation of CCS. According Young-Lorenz and Lumley (2013, p.5063) (see also IEA, 2013): "Our results indicate that the most critical barriers to widespread commercial adoption of Geosequestration are not technology- or capacity-related, but instead relate to issues of public acceptance and economics." Indeed, Viebahn and Chappin (2018, p.1) analysed the gap between the expected and actual deployment of CCS, particularly for geological sequestration. Their bibliographic assessment of relevant published peer-reviewed papers found that 31% of the articles addressed non-technical issues, including "public perception, policy, and regulation, providing a broader view on CCS implementation on the regional or national level, or using assessment frameworks." Viebahn and Chappin (2018) further suggested that these areas need to be strengthened to meet the challenges in implementation.

The list of ten issues that will be considered here represents a selection from among the range of issues that many important players in the CCS area – governments, large industry and important Environmental Non-Governmental Organizations (ENGOs) – consider to be critical to the future of CCS as a GHG mitigation strategy. Specifically, the ten issues chosen are the ones that are most likely to attract wide public attention and thus are those which are likely to have, in the long run, significant influence on the public acceptance of CCS. All of them are treated at greater length in this special issue (references provided in the present article are illustrative only). The list is as follows, grouped under three headings: government and industry factors; environmental risk factors and socio-economic factors. All of them have been widely recognised by many key institutional actors at a very early stage in long-term planning and deployment of CCS projects, especially the sequestration-only ones (that is, the ones that are specifically designed to be a response to climate-change scenarios).

a Government and industry factors:
   1 competent regulatory oversight
   2 adequate risk assessment and risk management frameworks
   3 supportive public policy frameworks.

b Environmental risk factors:
   4 adequate site-specific characterisations of geological formations for CCS storage sites worldwide
   5 credible monitoring of storage site performance
   6 the possibility of leaking from storage.

c Socio-economic factors:
   7 tolerable economic costs
   8 public perceptions of risks and benefits
   9 information provision, effective communication and stakeholder engagement
   10 social and public acceptability, including decision support mechanisms.

4 Short descriptions of ten key issues

4.1 Government and industry factors

4.1.1 Competent regulatory oversight

CCS projects are necessarily complex multi-phase undertakings, entailing significant high-impact or high-consequence risks (the probabilities of which may of course be assessed as low), thus requiring oversight by competent regulatory authorities in all the many nations and regions where these projects may be rolled out. Many jurisdictions in North America and Europe have been very proactive in this regard, although there is still more to do as experience with demonstration projects for CCS is gained. These matters are discussed by Bankes (2019) and Larkin et al. (2019b).

The issue of long-term liability for stored carbon dioxide is a major topic in the development of government regulatory structures for CCS (for Canada, see Bankes, 2019). In each of the IEA's Legal and Regulatory Reviews (IEA, 2011, 2014, 2016), national progress on long-term liability for stored CO_2 is reported. As explained by IEA (2011, p.9):

> "Long-term liability is generally used to refer to any liabilities arising after the permanent cessation of CO_2 injection and active monitoring of the site."
>
> "Generally, before liability is transferred from the operator, three requirements are imposed: evidence that there is no significant risk of physical leakage or seepage of stored CO_2; a minimum time period having elapsed from cessation of injection; and a financial contribution to long - term stewardship of the site, to minimise the financial exposure of the entity designated to take on long - term liability."
>
> "The contributions to this edition illustrate that, in jurisdictions that provide for transfer of responsibility, operators are generally required to demonstrate before transfer that stored CO_2 is behaving in a predicable manner and does not pose a significant risk to human health or the environment."

In both Europe and North America, most governments are generally agreed that, if the above mentioned conditions are met satisfactorily, liability at a specific storage site will be transferred from industry to government at a specified point in time (e.g., 20 years after cessation of injection). Virtually all jurisdictions are following this approach (Bankes, 2019; Larkin et al., 2019b)

4.1.2 Adequate risk assessment and risk management frameworks

Risk assessment for CCS has a twofold character:

1. generic risks in the capture, transport and injection dimensions, which are similar to well-characterised risks and experience over many decades, in other industrial sectors
2. site-specific risks for the individual geological formations where storage is contemplated.

Detailed assessments for many proposed specific sites will have to be prepared in the coming years, since both formal compliance with environmental assessment laws and regulations, on the one hand and public belief in the essential safety of these operations, on the other, will require stringent risk management practices.

To be sure, a significant level of effort has already been put into the development of frameworks for risk assessment and risk management of CCS, in individual sub-national jurisdictions, at the national level and by organisations representing member states. These frameworks vary considerably in level of detail, but also have many elements in common (Larkin et al., 2019b). An ongoing concern in this area is the variation in key technical terminology and usages around the world (see Korre and Durucan, 2009; NETL, 2011, 2017): This inhibits the development of a common language in the assessment and management of the risks associated with CCS and thus presents potential difficulties in communicating risk to the public.

Another important dimension to this issue is the complexity of the risk assessment for CCS, which is a function of the multi-dimensional aspect of the technology (i.e., the integration of capture, transport, injection and storage). This complexity demands a response in terms of prioritisation of the relative severity of various impact scenarios, especially those which are high-impact, low-probability cases (Larkin et al., 2019c; Sarkarfarshi et al., 2019).

4.1.3 Supportive public policy frameworks

The need for CCS and indeed the entire rationale to justify the costs of this elaborate worldwide undertaking is strictly a function of the need to control or mitigate GHG emissions as a response to global climate change concerns. Climate change policy is necessarily the larger setting in which CCS deployment and the engagement with local stakeholders, must occur. The benefits of CCS in this context, therefore, are one side of the benefit-cost economic analysis of CCS (Heyes and Urban, 2019). Furthermore, since adequate climate change policy must be achieved at a global level, for otherwise it cannot succeed at all, the same is true for CCS. During the period of the Kyoto Accord, individual nations and the international community experienced great difficulty in embracing climate change policy. While still not binding, nationally determined contributions to the firm and aspirational targets of the Paris Agreement may begin to decrease the uncertainties about the justification for full deployment of CCS projects to mitigate GHG emissions in certain sectors.

The potential interaction between CCS and climate-change scepticism is a possible function of the degree of public willingness to pay for the non-trivial costs of CCS, for example, through electricity prices or a carbon tax. This is because of the obvious rationale for CCS, namely, to sequester human-produced carbon underground so as to prevent it from being released to the atmosphere as a greenhouse gas. To the extent to which those costs appear to be onerous, the easiest response of all is to deny that the entire, elaborate and expensive CCS endeavour is needed because adverse effects from climate forcing via GHGs is either ‘unproven’ or a ‘hoax’.

To the extent to which this challenge is taken seriously, it will be necessary for the members of the scientific community who will be communicating about the risks of CCS to also be heavily involved in communication about climate change science overall. Thus responding to this challenge through effective communication on climate change science ought to be an integral part of CCS public engagement from the very beginning. In our view, it would be excessively risky and irresponsible not to do so and avoiding this challenge would jeopardise the very large up-front investments in the initial CCS projects that both governments and industry will be making.

4.2 Environmental risk factors

4.2.1 Adequate site-specific characterisations of geological formations for CCS storage sites worldwide

The sheer scale of the need for credible, detailed, site-specific characterisations of geological formations for two to three thousand projects worldwide is daunting. In the United States alone, under the auspices of the Regional Carbon Sequestration Partnerships program, dozens of potential sites have been undergoing preliminary characterisation and validation for CO_2 storage since 2003 (NETL, 2003). Just the USA and China alone, as the two predominant GHG emitters on the planet and with heavy dependence on generating electricity from coal, will require, perhaps, hundreds of widely-scattered storage sites. The total number of sites required globally will be very large indeed: "To achieve 50% reduction in energy-related CO_2 emissions by 2050 (all approaches and technologies) requires 100 CCS projects by 2020; 3000 projects by 2050" (IEA, 2010; European Commission, 2014a). While the 2020 target will not be achieved, this projection includes continued reliance on coal and oil, which is now being challenged by a 'leave it in the ground' philosophy (McGlade and Ekins, 2015), which if successful would require less storage of carbon.

Thus the generic 'safety case' for permanent CO_2 storage facilities must be built up out of this heterogeneous collection of individual safety assessments around the world. (By way of contrast, most nations will have only a single storage site for high-level nuclear waste). Large-scale failures of containment or other negative outcomes in one country could then have 'ripple effects' in terms of public perception of risk, whether or not actual performance had been achieving its objectives (Price and Oldenburg, 2009; Rodosta et al., 2011).

Some idea of the scale of the effort can be had by considering the steps undertaken by the US Department of Energy to screen four candidate sites, two in Texas and two in Illinois, for the 'FutureGen' project before selecting a preferred site in Illinois [see Leiss (2009) for full discussion and references on the site selection process]. While federal funding was cancelled in 2015, the FutureGen Power Plant was conceived as a nominal 275MW, near-zero-emissions facility producing hydrogen from coal to generate electricity; it was designed to remove 90% of the coal's carbon and 99% of its sulphur (the latter to be processed for sale), capturing approximately 1.1 $MtCO_2$/yr for sequestration. Some idea of the scope of the project analysis undertaken by the US Department of Energy is given by the sheer size of the final published reports – close to three thousand pages. The risk assessment report itself runs to 400 pages and this document provides what is still, to the best of our knowledge, the only published presentation of a comprehensive site-risk assessment methodology for CCS (see also Larkin et al., 2019c, 2019d; Sarkarfarshi et al., 2019).

To begin, the twin charts dealing separately with pre-injection and post-injection scenarios outline the environmental pathways for three broad types of risk: acute and chronic human health risk and ecological risk. The site characterisation summary for the four sites includes approximately thirty different parameters, dealing with the nature of surface ecosystems (aquatic and terrestrial ecology), subsurface features, seismicity and the geological features of the seal and reservoir in the deep underground zone (target area). An overview of the risk assessment approach is provided for both the pre- and post-injection scenarios, which consists of the following steps:

1 specifying health and ecological toxicity criteria for both scenarios

2 failure modes, release scenarios, exposure analysis and consequences analysis for the pre-injection scenario

3 leakage pathways and exposure and consequences analyses for the post-injection scenario. The four post-injection leakage pathways evaluated are: upward leakage through caprock and seals; release through faults; migration into non-target aquifers; and upward migration through wells. The exposure analysis considers both human and ecological receptors. A comprehensive risk summary is summarised in nine tables, broken down (for human health impacts) into adverse effects, irreversible adverse effects and life-threatening adverse effects; predicted probabilities of release for all scenarios, uncertainties and data gaps are specified.

4.2.2 Credible monitoring of storage site performance

The environmental risk assessment for CCS may be considered in light of experience in underground storage of liquids to date and Table 3.1, pages 9–10, in a 2007 report from the US National Petroleum Council (2007) lists some of the associated challenges:

- Although there is 30 years of experience in injecting CO_2 for enhanced oil recovery (EOR), there is little experience with storage in saline formations, which is the favoured destination for permanent storage of CO_2 in non-EOR projects.
- Although there is 15 years' experience with injecting acid gas underground, these are relatively small volumes, whereas CO_2 injections will be massive.
- Although there is long experience (in the USA) with injecting liquefied hazardous waste underground, CO_2 is, unlike these substances, both buoyant and reactive.

There is a good, detailed review of 'technical challenges' in CCP (2009), *A Technical Basis for Carbon Dioxide Storage*. This publication frames the issues in terms of strategies for risk control, in the following four categories (see also Jenkins et al., 2012):

a Selecting a storage site:

> "What criteria matter most and what data is collected to evaluate objectively the suitability of a proposed site?"

b Leakage from storage into aquifers or to the surface:

> "The issues surrounding well integrity cement and well construction techniques for wells exposed to CO_2."

c Monitoring and verification:

> "A good monitoring program will serve to avoid potential problems as opposed to providing indication of problems that have already occurred."

d Operation and eventual closure of the site:

> "Practical regulations can be created that provide realistic assurance that the process will be safe and effective. In addition, the maximum storage potential

> of given systems and what this means for injection rates and pressures is examined."

The most detailed document in this area is the National Energy Technology Laboratory's (2017) Best Practices for Monitoring, verification and accounting of geological storage project. (This general topic is usually referred to as MMV – monitoring, measurement and verification – but in the USA, it is also called MVA – monitoring, verification and accounting.) The NETL (2009, p.ES-1) report notes that the objective of best practices in this domain is to demonstrate

> "...95 percent and 99 percent retention of CO_2 through GS [geological sequestration] by 2008 and 2012, respectively. The 95 percent and 99 percent retention levels are defined by the ability of a GS site to detect leakage of CO_2 at levels of 5 percent and 1 percent of the stored amount of CO_2 into the atmosphere."

The most widely-quoted long-term retention target for underground storage of carbon dioxide is 99% of injected CO_2 remaining underground for 1,000 years (IPCC 2005, 2006). It may be asserted with confidence that the development of robust protocols for credible monitoring and verification and the testing of these protocols in public engagement processes, is absolutely essential for risk acceptability of CCS. Larkin et al. (2019e) further discuss Canadian regulatory practice, regarding CCS including the role of monitoring.

4.2.3 Leaking from storage

The possibility that CO_2 stored underground in a sequestration project may be re-released, due to any type of failure in either the storage process or the geological formation, is one of the most serious issues that could be raised about CCS. The entire rationale for CCS is based on the proposition that the gas, once injected underground, will stay there indefinitely. Were it not to do so, it could represent a significant environmental and health threat, as well as an enormous waste of money. Therefore understanding fully the nature of the response to these events is a worthwhile undertaking. See Sarkarfarshi et al. (2019) for a taxonomy of potential CCS hazards and Larkin et al. (2019d) regarding best expert judgements for leakage scenarios.

To date there have been at least three instances where possibilities of the actual or potential leakages of stored CO_2, from either enhanced-oil recovery (EOR) or sequestration-only projects, have received international attention. (Leiss and Larkin (2019) provide a fuller discussion of these cases with the relevant references). Perhaps the most high-profile of the three concerns Statoil's Sleipner project, which has been injecting CO_2 beneath the seabed in the North Sea since 1996, where questions were raised in late 2013 about the integrity of the Utsira formation where the Sleipner gas is being injected – and, it must be emphasised, there is no evidence to date that any leakages have actually occurred (MIT, 2018). The second concerns the In Salah project in the Algerian desert, begun as an on-shore sequestration project connected to a gas field development in 2004 and eventually operated by three partners, Britain's BP, Norway's Statoil and Algeria's Sonatrach. Injection was suspended in 2011 due to pressure increases (Bui et al., 2018) and has not yet been resumed as a result of concerns over leakage. Again, the questions raised about this project have not yet been resolved.

Third, there is the so-called 'Kerr incident', involving the alleged leaking of CO_2 from the Weyburn-Midale EOR Project in Saskatchewan into surface areas of a neighbouring farm. These allegations were extensively studied in commissioned reports (Leiss and Larkin, 2019).

4.3 Social factors

4.3.1 Tolerable economic costs

The economic costs of CCS are the other side of the benefit-cost analysis of CCS that is analysed by Heyes and Urban (2019). Here we consider just the implications of the fact that to date governments in different countries and regions have provided the bulk of the funding for CCS demonstration projects. For CCS to succeed in the long run and on an ongoing basis, however, the public eventually must be persuaded to pay for it through one mechanism or another, such as directly in the form of a carbon tax, or indirectly by governments setting a price for carbon within a cap-and-trade system, or as a surcharge on electricity prices, or by some other mechanism.

Nevertheless, NETL estimated in 2008 (now NETL, 2013) that the incremental capital cost of carbon capture technology, in comparison with a non-capture power plant, would add anywhere between one-third to 100% of the costs per kW/hour of electricity. In Al-Juaied and Whitmore (2009, p.33, Table 6), there is a comparison of seven studies (dated 2006–2008) on costs of carbon capture in terms of dollars per ton of carbon dioxide avoided [the list of studies includes the widely-available McKinsey & Company (2008); see also David and Herzog (2005)]. The results ranged from a low of $25-45/t to a high of $120-180/t for current costs, but significantly lower at the high end of the stated range by 2030. In general, the current costs for CCS in those studies were thought to be roughly comparable to the costs of choosing other ways of constraining carbon emissions through alternative energy generation technologies (wind or solar). Canada's First Ministers' Specific Mitigation Opportunities Working Group (2016) listed alternative policy tools for wide-ranging economic sectors, including for electricity generation and large industry. Like many other options, CCS-related projects were priced at between $50–$100/t (as were non-emitting renewable energy supply such as wind or solar).

An associated risk communication factor is the perception – among some members of the public, at least – that the money could be better spent on renewable projects. In 2009 the US General Accounting office asked the US Department of Energy for a 'bottomline' estimate of the increase in the price of electricity resulting from CCS, to which the response was: 35 to 77% [GAO, (2008), p.23; this estimate was based on the 2007 version of NETL (2013)]. However, the Australian Government (2013) estimated that the 'levelised cost of electricity' with CCS technologies would decrease from 2025 to 2050.

Among the decisive 'other factors' in the prospects for successful deployment of CCS projects is whether they can be done at a cost that is 'acceptable' to the public, since after the start-up phase (subsidised by grants from governments) these costs will have to be internalised, especially in electricity prices. Every prognosis indicates that the full (unsubsidised) costs – which are largely incurred in the capture phase – will be substantial. Of note, the operators of both the Boundary Dam and Shell Quest projects in Canada (both costing more than $1B (Larkin et al., 2019e) suggest costs should be reduced by 20%–30% in subsequent projects. Thus the challenge here is: will governments, as the expected leaders in the RA/RM decision-making exercises, be candid with the public about the expected costs to consumers of CCS on an ongoing basis? If they are, how will this affect the public acceptability of CCS in the near term? If they fail to do so, will this failure likely affect the longer-term prospects of CCS?

4.3.2 Public perceptions of risks and benefits

Doubts about public acceptance based on perceived risks, as well as low awareness about CCS, have frequently been cited as key barriers to CCS deployment by advocates in industry, government and the ENGO sector (e.g., Shackley et al., 2009; Bäckstrand et al., 2011). Overcoming this challenge is therefore dependent on narrowing the disparity between experts' and laypersons' perceptions of risk. This issue is fully discussed by Leiss and Larkin (2019).

At the earliest stages of this research there was little study on what the dimensions of risk perception might be in the public domain, because most studies and surveys focused on the general acceptability of CCS as a mitigation strategy. Where general risks were identified, Mander et al. (2011) and agencies such as the IEA and GCCSI found the greatest risks to be associated with regulation, governance, finance and generally with the basic CCS concept itself. In those studies where the focus was on the dimensions of perception towards the health and environmental risks emanating from the components of the CCS chain, discussion remained at a high level. However, even this opinion research met with some criticism because the knowledge base of respondents was generally low, thereby leading to responses that are not necessarily based on informed opinion (Wallquist et al., 2012).

Wallquist et al. (2012) examined how public perception affects the political climate for CCS as well as particular concerns at the local level, suggesting a need to break down the CCS chain into its separate capture, transport and storage components when risk perception is being investigated, particularly at the project or community level. Similarly, in Canada, Boyd et al. (2017) assessed support or opposition to CCS and sources of funding using regression models for the relationship to risk perceptions, perspectives on climate change and trust in government. This public opinion survey found overall low support for CCS, but with variations depending on proximity to projects.

Other authors have reported on methodologies to ascertain risk perceptions and how discussions between experts and laypersons can lead to less uncertainty or acceptance of uncertainty (Mander et al., 2011). In this regard, Lachapelle et al. (2014) found that in the policy realm, individuals assign higher levels of credibility to experts when the dominant media frames are consonant; but when expert assessments compete with dominant media frames, the influence of the expert is muted.

4.3.3 Information provision, effective communication and stakeholder engagement

At an early stage of the process, in 2005, the G8 leaders requested that the IEA and the Carbon Sequestration Leadership Forum work to address the barriers to public acceptability of CCS. Since then, there have been many articles published about outcomes of communication methodologies; opinion shaping factors; audiences; media coverage; and public acceptance of new (energy) technologies. For example, L'Orange Seigo et al. (2014) identified thirteen concepts that could be the basis for risk communication. Government and non-government organisations have also published numerous guidebooks on communication and engagement strategies and case studies (Larkin et al., 2019b; Leiss and Larkin, 2019).

There are two scales of activities for the challenge of monitoring risk perceptions and doing credible risk communication activities: At the project level, where the highest risks and uncertainties may exist in the local community where capture, transport or storage exists or is proposed; and at the regional, national or even international level where CCS technology is discussed as a global CO_2 mitigation option.

However, for the study period 2002–2009, Ashworth et al. (2010) reviewed 33 case studies of CCS related communication and research activities and noted that "overall the expenditure in the area of communication and public awareness has been insignificant when compared with the allocated budgets of the CCS technological research and development programs." The majority of surveys were to inform researchers, policy and environmental NGOs, with relatively little communication activity that has targeted the general public. Both Boyd et al. (2017) (for Canada) and Ashworth et al. (2015) (globally) report on findings that overall public awareness of CCS remains low. Kefford et al. (2018) surveyed CCS professionals around the world, finding extremely pessimistic expectations for CCS to meet the Paris agreement target, with the socio-political factor of public awareness perceived as one of the two greatest barriers to deployment across regions.

4.3.4 Social and public acceptability

Ultimately, favourable public opinion in many different countries must be the foundation of the 'social license to operate' for CCS projects. As argued in the article by Leiss and Larkin (2019), acceptability is a function of four prior stages in a chain of social factors:

1. the detailed understanding of public perceptions of the risks and benefits of CCS
2. adequate information provision and rigorous communication of the risks and benefits of CCS with interested parties in a variety of social media
3. effective and unbiased mechanisms for stakeholder engagements, often over long periods of time
4. clear evidence that stakeholder inputs have been taken seriously, during the engagement processes, as shown in the 'reasons for decision' issued by regulatory authorities.

It is the responsibility of project proponents, usually governments and industry, to ensure that all aspects of all stages in this chain are delivered and managed competently, leading to a desired level of public confidence in the ultimate outcomes. Case studies show that failures with respect to even one important aspect along the chain can doom a project (Feenstra et al., 2010). In some instances, involving the kind of complex energy policy issues that are raised by CCS, the use of formal decision support frameworks has been shown to be helpful to citizens (Campbell-Arvai et al., 2019).

5 Conclusions

What is – quite literally – unique about carbon capture and storage as a major set of risk issues of global proportions is how proactively these relevant major risks and risk factors have been identified and characterised by major institutional actors, especially industry and governments, as well as the scholarly research. As of the time of writing, it is still pretty much the case that the objectives and need for CCS are unfamiliar to large swathes of the public in many different regions of the globe, including those where large demonstration projects are already under way. But the institutional actors have not hesitated to forge ahead in developing elaborate, highly-credible risk characterisations for the CCS enterprise. This proactive approach should provide a distinct advantage to CCS project proponents when the full scrutiny of these projects occurs in wider public dialogues.

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Appendix

Overview of CCS Project Database (adapted from GCCSI, 2018)

Table 1 Summary of large scale power plant CCS projects worldwide

Country	*No.*	*Feedstock*	*Capture capacity (Mtpa)*	*CO_2 Fate: EOR Sequestration*	*Status: O = operating ED = early development*
USA	1	Coal	1.4	EOR	1 O
Canada	1	Coal	1.0	EOR	1 O
UK	1	Natural gas	3.0	1 GS offshore	1 E
Other EU and Norway	0				
China	4	Coal	1.0–2.0	1 GS; 3 under evaluation	4 E
Rest of world	2	Coal	1.0	2 GS offshore	2 E
Total	9[1]			2 EOR; 4 GS; 3 evaluation	2 O; 7 E

Note: [1]26 projects in 2014.

Table 2 Summary of non-power plant carbon dioxide capture and storage projects

Country	*No*	*CO_2 source*	*Capture capacity (Mtpa)*	*CO_2 sink: EOR Sequestration*	*Status: O = operating AD = advanced development ED = early development C = construction*
USA	10	Natural gas, Petroleum coke, corn, coal	0.4–8.4	9 EOR; 1 saline	8 O; 2 AD
Canada[1]	4	Natural gas, coal, bitumen	0.3–3.0	3 EOR; 1 saline	2 O; 2 C

Notes: [1]Canada's Fort Nelson CCS project is not listed and efforts to ascertain the status following the sale of the initial proponent, Spectra Energy, to Enbridge were unsuccessful. [2]25 projects in 2014.

Table 2 Summary of non-power plant carbon dioxide capture and storage projects (continued)

Country	*No*	*CO2 source*	*Capture capacity (Mtpa)*	*CO2 sink: EOR Sequestration*	*Status: O = operating AD = advanced development ED = early development C = construction*
Europe	4	Natural gas, other	0.7–1.2	4 saline	2 O; 1 AD; 1 ED
Australia, UAE, Brazil	6	Gas, coal, steel	0.8–5.0	3 EOR; 3 saline	3 O; 1 C;1 ED; 1 AD
China	5	Natural gas, coal	0.4–2.0	4 EOR 1 under evaluation	1 O; 2 C; 2 ED
Total	29[2]			19 EOR; 9 saline; 1 evaluation	16 O; 5 C; 4 AD; 4 ED

Notes: [1]Canada's Fort Nelson CCS project is not listed and efforts to ascertain the status following the sale of the initial proponent, Spectra Energy, to Enbridge were unsuccessful. [2]25 projects in 2014.

Table 3 Summary of commercial EOR projects using anthropogenic carbon dioxide

Country	*No.*	*CO_2 source*	*Capture capacity (Mtpa)*	*CO_2 Sink: EOR Sequestration*	*Status: O = operating P = planning C = construction*
USA	9	Natural gas, Petroleum coke, coal	0.4–8.4	EOR	7 O; 2 AD
Canada	3	Natural gas, coal, bitumen	0.3–3.0	EOR	1 O; 2 C
Saudi Arabia, Brazil, China	7	Natural gas, coal	0.4–1.0	EOR	4 O; 2 C; 1 ED
Total	19				12 O; 4 C; 2 AD; 1 ED

Table 4 Summary of projects cancelled or inactive (as of 2016 most recent figures publicly available)

Canada	4
Alberta	3
Saskatchewan	1
EU	16
Norway	3
USA	15
Rest of World	3
Total	41

Source: MIT (2019)