COMMUNICATING LEAKAGE RISK IN THE HYDROGEN ECONOMY: LESSONS ALREADY LEARNED FROM GEOENERGY INDUSTRIES

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ABSTRACT

Hydrogen may play a crucial part in delivering a net zero emissions future. Currently, hydrogen production, storage, transport and utilisation are being explored to scope opportunities and to reduce barriers to market activation. One such barrier could be negative public response to hydrogen technologies. Previous research around socio-technical risks finds that public acceptance issues are particularly challenging for emerging, remote, technical, sensitive, uncertain or unfamiliar technologies - such as hydrogen. Thus, while the hydrogen value chain could offer a range of potential environmental, economic and social benefits, each will have perceived risks that could challenge the introduction and subsequent roll-out of hydrogen. These potential issues must be identified and managed so that the hydrogen sector can develop, adapt or respond appropriately.

The geological storage of hydrogen could present challenges in terms of the perceived safety of the approach. Valuable lessons can be learned from international research and practice of CO_2 and natural gas storage in geological formations (for carbon capture and storage, CCS, and for power, respectively). Here, we explore these learnings. We consider the similarities and differences between these technologies, and how these may affect perceived risks. We also reflect on lessons for effective communication and community engagement. We draw on this to present potential risks to the perceived safety of - and public acceptability of – the geological storage of hydrogen. One of the key lessons learned from CCS and natural gas storage is that progress is most effective when risk communication and public acceptability is considered from the early stages of technology development.

1.0 INTRODUCTION

The usage of hydrogen as a fuel substitute for energy, heating and transport has received growing attention, as a key contributor to a low-emissions future for many countries. "The primary consideration in delivering hydrogen is attention to safety and community awareness" (Commonwealth of Australia, 2018). Safety and community awareness/acceptance of new technologies is challenging; however, it is possible to draw strong parallels from other relevant emerging technologies and developments such as the implementation of carbon capture and storage (CCS) and underground gas storage (UGS). CCS and UGS industries provide examples of demonstrated successes and failures that can provide lessons learned for future proponents of a hydrogen economy.

The Hydrogen Economy was first coined in the late 1960s/early 1970s [1]. As hydrogen is rarely present as a free gas in "reservoirs" like natural gas [2], other methods were developed to isolate or generate hydrogen. Hydrogen generation is now being upscaled and the use of renewable energy has been introduced to reduce the carbon intensity of hydrogen fuel. Economics have tended to be a major barrier to uptake of hydrogen, as a number of factors, such as enabling fuel-to-market were previously overlooked, e.g. storage and transport/pipeline costs [1]. There is a renewed effort at developing a hydrogen economy in Australia and other parts of the world to service demand for low-emission fuels, and hydrogen is regarded as a clean alternative. A number of recent studies (e.g. [3]) have noted the

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role hydrogen will play in decarbonizing not only the energy sector, but decarbonizing the industry and transportation sectors.

A range of countries are considering becoming hydrogen exporters, such as Australia, Norway, Brunei and Saudi Arabia [4]. Japan and South Korea have developed formal, government led strategies for transition to hydrogen imports (from LNG and other fuels). Japan currently imports fossil fuels for 94% of its energy imports, with South Korea importing 81% of its energy [4]. Europe, notably Germany, France and the UK, have defined investments in a range of activities to accelerate deployment of hydrogen energy, while there are a few initiatives in China and the USA. The articulation of the Japanese strategy demonstrates large-scale enduring commitment to the uptake of hydrogen in country, so addressing all aspects of safety for the full value chain is becoming increasingly urgent. Therefore identifying, understanding and communicating the risks (perceived or otherwise) of hydrogen utilization becomes a critical factor in the adoption of (or pushback against) the emergence of the use of this fuel.

Here we look to technology analogues to better understand the potential public attitudes around the development and adoption of hydrogen technologies. In particular, we draw on experience of public attitudes towards the safety of UGS and the geological disposal of CO_2. The aim of this work is to highlight potential sensitivities for the hydrogen sector to consider going forward.

1.1 The hydrogen technology and value chain

There are a range of hydrogen technologies, including forms of hydrogen production, storage, transport and use, as shown in Fig. 1, each of which will have different associated safety risks. The production of hydrogen for feedstock is a long-established technology, the novelty of hydrogen for energy is its widespread application for emissions reduction.

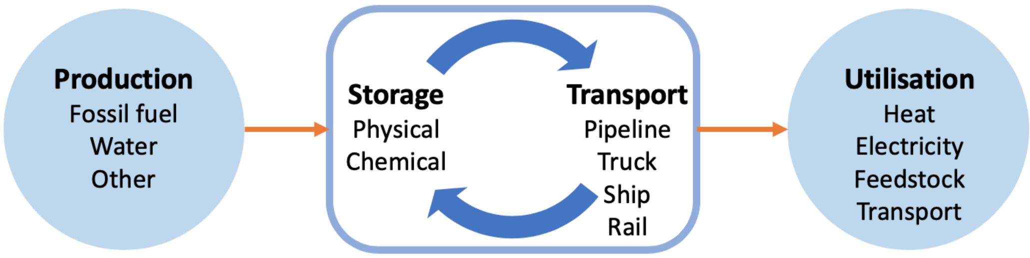

Figure 1: Schematic of the hydrogen value chain, adapted from Bruce et al. [5]. Each step has associated technical, social, economic and environmental risks.

There are different hydrogen feedstocks and processes for the production of hydrogen. The most common production technology is the steam reforming of natural gas, though hydrogen is also generated from coal gasification. Carbon dioxide (CO_2) is a significant by-product of fossil fuel derived hydrogen, but could be mitigated via CCS to maintain low carbon footprints [6]. The main alternative feedstock is water, whereby water molecules are split into oxygen and hydrogen by electrolysis, which could be powered by solar or wind energy to produce ‘renewable’ or ‘green’ hydrogen. There are other possible feedstock options in addition to these, for example, biomass can be used to produce ‘biohydrogen’, and offers negative emissions hydrogen [7, 8], and there are plans in the UK to generate hydrogen from waste plastic [9].

The transport and storage of hydrogen is a key aspect of the value and technology chain (Fig. 1). Storage and transport may be in the form of pure hydrogen, or via chemical conversion into more energy-dense or more stable materials such as ammonia or methylcyclohexane – i.e. fuel cells [10]. The most appropriate transport medium will depend on the material being handled (i.e. hydrogen or conversion material), and the country/regional context. For example, small-scale road-based transport of liquefied hydrogen, as well as general storage is likely to be less efficient in Australian climates than in more temperate regions, since the gap between the cryogenic hydrogen temperature (-253°C) and ambient conditions causes heat ingress into cargo and storage areas [11]. Hydrogen has high potential value to re-purpose gas grids, through gas mixing, however the infrastructure would need to be upgraded to be able to transport high concentrations of hydrogen.

The storage of hydrogen is likely to become a limiting factor for large scale hydrogen projects, particularly if large volumes of hydrogen are being produced by electrolysis using excess renewable electricity during periods of low demand. Small volumes of hydrogen can be stored in surface tanks; their size is limited due to cost and safety. Small volumes could also be stored in the domestic distribution pipeline networks [12]. Underground geological formations, in contrast, can offer capacity to hold significant volumes of hydrogen [13]. There is a nascent underground hydrogen storage industry, with pilot/demonstration activities and several in commercial operation. Two primary types of geological hydrogen stores are anticipated: salt caverns (whereby gas is injected into natural or engineered cavities in thick salt formations), and reservoir-caprock systems (whereby the hydrogen is injected into a porous and permeable reservoir formation, such as a saline aquifer or a depleted hydrocarbon field, which is capped by an impermeable seal, both of which are used for CCS). Although salt cavern storage is limited by small capacity and high costs, three such projects are operational; two in the US and one plant in the UK. Hydrogen storage in reservoir-caprock systems is more attractive owing to the larger size and scale of the potential store [13], but there are currently no commercial projects injecting hydrogen into porous media [14].

Useful parallels can be drawn between the conceptualization and delivery of hydrogen as a novel energy approach, and more established technologies such as the transport and storage of natural gas (well established), or of CO_2 for CCS (emerging). For example, hydrogen storage may occur in caverns in salt (like some natural gas stores) or in geological formations with a reservoir-caprock systems, such as natural gas storage and CO_2 storage. Further, natural gas, CO_2 and hydrogen may be transported by pipelines; or via road, rail or ship. The choice of technologies affects not only potential technical risks, but also the societal challenges hydrogen may face. This includes issues of risk perceptions and risk acceptability around the development of new technologies, and, for example, around managing large volumes of (unfamiliar) gas. Understanding these different risks can advise the development of the hydrogen economy.

To this end, we consider the similarities and differences between hydrogen storage and other geoenergy technologies such as CO_2 storage and natural gas storage to clarify where the similarities and differences between these technologies may lie (Section 2). We then review key findings and advances in leakage risk perception, and also communication and risk management of these technologies (Section 3), and then consider what these could mean for public acceptance of hydrogen technology and make recommendations for hydrogen development going forward (Section 4). However first we outline why perceived safety is such an important issue to consider at this early stage of technology development (Section 1.2) and what we know about public perceptions of hydrogen already (Section 1.3).

1.2 Why is the perceived safety of hydrogen so important?

The transition towards a zero-carbon future requires widespread systems change at a range of scales - from how we use energy in our homes, to international energy infrastructure. The extent and scale of change requires rapid and widespread technology innovation, scale-up and roll-out. This presents a range of technical challenges, including challenges around safety, efficiency and others. Further, it presents societal challenges; the nature of and rate of technology transition depends on widespread uptake of change. That is, it depends on public acceptance of and engagement with the changes that are being implemented, which must be designed to be in line with what the publics will tolerate, accept, or support. Community resistance to planning decisions has delayed or terminated a range of different energy developments and has long been recognized as a delay to deploying energy infrastructure which may form part of the low-carbon energy transition [15, 16].

The perceived safety of the technology chain is known to be a strong component shaping public attitudes. Public acceptance of new technologies interweaves issues of technical complexity, procedural, participative and distributive justice, risk perception and governance of developments [17], and depends on a number of factors, including perceived risk and benefits, and trust in risk management [18]. How technologies are perceived by communities depends on multiple factors, but essentially comes down to the balance of perceived benefits and the risks. Different groups can perceive the same risks differently [19]. When risks are perceived to be high, the associated benefits are perceived to be low, and vice versa [20]. Thus, identifying areas of disconnect between the risks perceived by lay publics and technical risks as perceived by experts can help to guide communications and messaging of a technology or development, by identifying elements where lay publics' understandings of risks may be inaccurate or lacking. However, perceived risk is not necessarily reduced in the face of 'evidence', for a range of reasons, including perceptions of controllability (risks that are perceived to be uncontrollable are much less tolerable) and also trust in the evidence-provider or other actors [21].

Public acceptance is particularly relevant to technologies that need public funding to support pre-commercial development [22]. In such cases, the views of the publics can influence the political will (in terms of the level of support for the technology). This is in addition to decision-making at the project-level, where good understanding of public attitudes can guide more effective decision making about technology development, siting, and monitoring, and can shape community engagement processes to be fair and effective and increase the likelihood of getting buy-in from the people in the immediate vicinity of the project.

Therefore, with anticipated hydrogen markets globally, there is a growing need to map and understand public attitudes towards hydrogen technologies at this nascent stage of technology development. However, studying public perception can be particularly challenging for emerging, remote, technical, sensitive, uncertain or unfamiliar technologies [23]. Further, exploring lay perceptions of geological hydrogen storage could be additionally confounded by the unfamiliarity of the subsurface, yet, to date, few studies have explored public attitudes to geological storage of hydrogen [22].

1.3 What do we know about public perception of hydrogen safety?

People consider safety and cost to be among the most important factors in determining preferred choices of energy options. The safer and cheaper the option is perceived to be, the more acceptable it is [21]. In their review of 6 studies of public perception of hydrogen, Ricci et al [24] found that people reported low levels of concern about hydrogen safety, even though many had expressed concerns about safety in qualitative discussions. Participants also held largely positive beliefs about and attitudes towards hydrogen technology, but this positive viewpoint might be skewed by the large proportion of respondents that were undecided on this matter, and the generally very low knowledge of hydrogen as a fuel. Sherry-Brennan et al [25] investigated public attitudes to a hydrogen-wind project on Unst (Shetland), and found hydrogen energy was generally positively evaluated despite participants being aware of and acknowledging the potential risks posed by the properties of hydrogen such as its explosiveness and flammability. In a much more recent study in Australia, Lambert & Ashworth [22] finds that the public attitudes towards hydrogen are generally neutral. As has been shown for other technologies, the level of perceived or actual knowledge positively correlates with participants' overall attitude to hydrogen technology [22].

The main benefits that the Australian public associate with the use of hydrogen technologies relate to the environment, and include reduced greenhouse gas emissions and other pollutant emissions [22]. Linked to this, most people prefer hydrogen production from renewable sources [22], and there is some concern around using coal (a fossil fuel) or water (a scarce resource in Australia) as the fuel with which to generate hydrogen [22].

Messaging is known to be important in shaping public attitudes to emerging technologies, and the generally positive attitude towards hydrogen in Ricci et al. [24] is thought to be due to largely positive framing of the technology, or, conversely, an absence of negative framing. Providing negative information about the safety of hydrogen was found to significantly reduce acceptance, whereas the effect of positive information was marginal (see ref in [24]). Trust – or more correctly, distrust – was identified to be a key factor that shaped public beliefs, attitudes and expectations [24]. In Australia, where public attitudes are largely positive, the majority (77%) of Australian publics trusted that adequate safety precautions would keep any risks under control.

Currently, few studies have explored public attitudes to hydrogen storage. Lambert & Ashworth [22] report that in focus group discussions some participants expressed concerns about the use of carbon capture and storage as part of the hydrogen chain, largely owing to the perceived environmental risks posed by geological CO_2 storage. The study does not report whether these participants expressed similar concern for hydrogen geological storage, but there are some concerns with hydrogen being stored underground, with only 42% supporting this approach [22].

In sum, while work to date suggests that publics may have a neutral or even positive attitude towards hydrogen, given the limited empirical literature on public views on hydrogen storage, we turn to analogous technologies.

2. ANALOGUES FOR THE GEOLOGICAL STORAGE OF HYDROGEN

The geological storage of CO_2 and natural gas (UGS) provide analogues from which to learn from to understand the perceived risks of the geological storage of hydrogen and other aspects of the emerging hydrogen economy. Compressed air energy storage (CAES) is another emerging geoenergy technology [26]. However we do not consider CAES in this work because the technology is in its infancy, more-so than hydrogen storage. It is important to recognise that political and societal challenges have played an important role on how UGS and also CO_2 storage has developed, and we draw on examples in the following section. But first, we compare the technologies themselves.

2.1 CCS and natural gas storage analogues

Globally, there are currently 18 active commercial scale CCS projects. In this sense, CCS is an emerging technology. However, all the components of the CCS technology chain have been technically feasible for decades, and there is a reasonably lengthy history of activity. The first CO_2 injection project, Sleipner, located in the Norwegian North Sea, started injecting CO_2 for storage in 1996. However, it was 18 more years until the first fully integrated CCS project (i.e. the full CCS chain), Boundary Dam in Canada, commenced CO_2 injection. So, why has development and uptake been so slow, particularly given that the geological storage of CO_2 is considered to be fundamental to the delivery of a net zero emissions by 2050 [27]. There have been many challenges that have hindered CCS development. These have tended to be economic and financial rather than technical or procedural, and relate to a lack of economic drive [27].

UGS is a well-established technology that has been used as an economical method for managing gas delivery for over 90 years with a reported, with a reported 630 facilities in operation in 2009 [28]. Underground storage presently occurs in salt or rock caverns, depleted hydrocarbon reservoirs or abandoned mines, and saline aquifers. Based on industry performance, UGS is deemed to have excellent health, safety and environmental record [28]. However there have been some incidences of gas leakage in recent years in the US which have caught global media attention, including the blowout at Aliso Canyon in Los Angeles in 2015 [29].

Table 1 compares some of the key properties and behaviours of each of these gas storage types to illustrate how comparable these industries are. Table 2 compares the chemical and safety properties of the gases, such as toxicity and flammability.

Table 1: A comparison of the CO_2, hydrogen and natural gas storage process and the current and projected development of these technologies.

			Hydrogen storage	UGS	CCS
Summary	**Production**		Generated from hydrogen-rich feedstocks (i.e. water, fossil fuels).	Extracted from geological resources (i.e. natural gas), or generated from organic materials e.g. biogas	Generated from natural gas production, fossil fuel combustion for energy or other by-product of industrial processes (point emission sources). Captured from air (Direct Air Capture)
	Transport		Pipeline, ship, or trucks		
	Storage	*Phase*	Dense phase hydrogen	Dense or gas phase natural gas.	Dense phase CO_2.
		Geological parameters	Reservoir-caprock systems, or salt caverns	Reservoir-caprock systems, or salt caverns	Reservoir-caprock systems; large saline aquifers.
		Injection cycle	Repeated injection/production on demand i.e. filling a ship, seasonal variation etc.	Cyclical injection storage for seasonal variation	Disposal of CO_2 intended never to come to surface.
		History	First proposed in 1970s [30]	Since 1915 [28]	CO_2 has been injected at Sleipner since 1996, but the first full chain CCS plant opened in 2014.
Global status of gas storage		**Current**	Ten sites worldwide, 6 salt caverns, 3 aquifers, one depleted natural gas field [12]	Common globally, either in salt caverns or saline formations/depleted gas fields. Tends to be shallow geological depth. UK stores 3-4%, Germany 19%, France 24% and USA 18% of annual consumption [31]	At the start of 2018, there were 18 commercial CCS CO_2 injection projects, a further 5 in construction, and a series of smaller projects worldwide [32]. 40 Mt annual capture in 2017 [31]
		Forecast by (2050)	Global demand for hydrogen anticipated to be 530 million tonnes [4]	Likely increase, in the medium term. Could be overtaken by hydrogen by 2050.	Abatement options evolving from storage to include utilisation, direct air capture.

2.2 Comparing analogues

Reservoirs for hydrogen and UGS will tend to be shallower than CO_2 disposal, where storage depths are usually selected to provide conditions where injected CO_2 will remain in supercritical (dense) phase i.e. depths of greater than ~800 m [33]. For hydrogen this depth is much shallower (~200 m below surface at typical geothermal gradient [13]). For all gas storage technologies, the surface footprint of the geological store is small, and most visual impacts, if any, would be related to monitoring of the store.

Long transport distances between source and store are not favorable for CCS, due to the effect on transport cost and risk, but it is generally more likely to be accepted if the storage site is located in areas where there are fewer affected communities and the geological resource is large. However for repeat use storage sites such as hydrogen stores and UGS, the distance between source and store also affects the resource response time. These applications need much smaller storage capacities than for CO_2 storage, and so there should be more plentiful geological resources, some of which may be located close to resource demand.

The primary concern for all forms of geological storage is leakage. While the most likely potential leakage pathways of CO_2, natural gas and hydrogen may be similar (poorly sealed wells, un-imaged faults etc, c.f. [34]), the impacts of leakage will be different owing to the properties of the three gases. Light gases like hydrogen readily disperse, whereas CO_2 ponds in depressions due to its greater density. Understanding the fate of hydrogen that might leak to surface especially given its large range for its flammable limits introduce different risks to that of CO_2 (Table 2).

Table 2: Summary of the different properties of H_2, CH_4 and CO_2. Natural gas is normally a blend of light hydrocarbons (LHCs) but is predominantly CH_4.

Stored medium		**H_2**	**CH_4 (+ LHCs)**	**CO_2**
Atmospheric concentration (ppm, %)		0.5*	1.798**	405.70** (0.41%)
GWP* **		N/A	36	1
Toxic		No	No	Yes
Odour		No	No (odorised by mercaptans).	No
Visible		No	No	No
Auto-ignition temperature °C		570	595	N/A
Explosive or flammable limit (%)	Lower (LEL/LFL)	4	4.4	N/A
	Upper (UEL/UFL) %	75	16.4	N/A

*[35]
**Cape Grim measurement from February 2019 [36] (https://www.csiro.au/en/Research/OandA/Areas/Assessing-our-climate/Latest-greenhouse-gas-data).
***[37]

3. THE PERCEIVED RISKS OF UNDERGROUND GAS STORAGE

First of all, there are very few modern studies regarding perceived risks of UGS. This is likely because it reflects that natural gas is a widespread and accepted energy technology, and therefore there may be little need research around public perceptions, even following a series of widespread events in the US. As such, much of this section concerns public perception of leakage from CO_2 stores.

3.1 Perceived risk of gas leakage

L′Orange Seigo et al. [38] report that the most commonly held concern about CCS is that the injected CO_2 might leak from the storage site back into the atmosphere, and concerns about how this leakage might occur, and resultant environmental impact. This fear is exacerbated by the fact that, because CO_2 is regarded as a pollutant, it has associations with toxicity.

Publics may envisage leakage to be quite dramatic. Publics often express fear of over pressurization, and L′Orange Seigo et al. [38] report that people often believe there might be sudden blowouts or explosions at the surface or deep underground, or that CO_2 injection might cause earthquakes, and that these earthquakes might compromise the storage integrity. Shackley and Gough [39] found that leakage in the style of the well-known Lake Nyos disaster from 1986 was commonly articulated, or raised as a potential impact of CO_2 leakage.

The studies find that, in line with previous work in the field of risk of such leakage on ecosystems is also raised as a concern. Further to perception and technology acceptance, the perceived risk of CCS is negatively related to the trust in stakeholders [40] and in acceptance of the technology [41]. Public perception of risk is reduced if monitoring approaches are trusted [40], and detailed monitoring is deemed to be beneficial in terms of public acceptability of the technology and trust in the regulation [43, 44].

Public support for CCS is dependent upon the acknowledgement that climate change is real, and must be mitigated [45]. However, publics may also view CCS as unsustainable. CO_2 stores are finite, and the technology is often associated with coal or gas power stations. Moreover, publics and stakeholders with more egalitarian leanings may also argue that CCS perpetuates a fossil fuel economy and by extension reliance on the negatively-perceived fossil fuel industries [45]. Such views may be exacerbated by concerns around CO_2 leakage, since this would undermine the purpose of CCS, as well as concerns that investment in CCS would detract from funding for renewable or more sustainable technologies. Nonetheless, it is not necessarily the case that there is a direct link between proximity to storage sites and perceived risks. If storage sites are located close to current or recent subsurface activity and/or onshore energy infrastructure, then communities may be more familiar with subsurface processes. It may even be the case that social licences to operate which developers have gained from previous operations in the area can be ‘transferred’ to CCS practices [42, 46].

3.2 Conceptualising leakage

For many, geoenergy technologies such as CCS can appear largely “imaginary” [47]. This may be because the scale is difficult to envisage, the projects are far from centres of population, the surface footprint of storage activities is comparatively small or the technology is still at the conceptual stage. Similarly, concerns regarding leakage are likely exacerbated by misconceptions around the nature of the subsurface, which laypeople find difficult to conceptualise [48]. These concerns are wrapped up in misconceptions around the natural geostatic pressure in a CO_2 storage site, and the belief that because CO_2 is a gas it must inevitably rise to and leak out at the surface. Indeed, there is much room for misconceptions around leakage, and leak impact, particularly where there are misinterpretations of the technicalities of the process. For example, if it is perceived that CO_2 is stored in the form of “a large bubble” of gas in the rocks, it could be understood that the bubble could burst at any time, and so the perceived risk is deemed to be high [49].

Not only is the subsurface challenging to conceptualise, so is the storage timeframe. To those not familiar with geoscience or, say, astronomy, are unfamiliar with geological timeframes on the order of many thousands to many millions of years. The timeframes of any potential CO_2 leak is likely to be very long, as shown by the study of natural analogues. For example, Lu et al [50] found that CO_2 took ~80 million years to diffuse 12 meters into a caprock, and CO_2 leakage to surface along faults can occur for hundreds of thousands of years [51, 52]. These timeframes are beyond the everyday thinking, and are even difficult for geologists to conceptualise [53]. Such abstract geoscience concepts present further challenges for public engagement on CCS.

3.3 Communicating leakage

The need for effective engagement and communication around CCS and its role in risk perception and management is well recognised and has been a subject of research and engagement [e.g. 54, 55]. This is particularly necessary given the low levels of public knowledge about CCS [56], and perhaps more significantly, given the unfamiliarity of the underground geological realm. Widespread lay misconceptions of the physical conditions and processes encountered at depth often means that awareness-raising campaigns have met with mixed success. Several studies, including Upham and

Roberts [57] have found that as public participants gained more information about CCS, group discussions became increasingly confused, and their opinions negatively affected. However, more recent work from Dowd et al. [58] suggests that such problems could arise because of flaws in the assumed public knowledge of CO_2. They found that providing information on the scientific characteristics of CO_2 reduces the potential for misunderstanding of CCS, and prevents the degree of negative opinion change.

Significant efforts have been undertaken to develop materials that have helped to inform a range of stakeholders about CCS concepts [23], and there are examples of excellent community engagement ranging from research projects such as QICS [59] to large CCS proposals like those in Tomakomi [46] which showcase the value of early and prolonged engagement. That said, there are mixed results in the literature regarding the effect that information has and the communication tools that may be used by these communication programmes have on risk perceptions [38]. The effect is generally small, and different kinds of information have different effects (i.e. increase or decrease the perceived risk). This perceived risk could be complicated by imagery. It is a well-known proverb that "a picture speaks a thousand words", howeverproblems of scale, conventional visualisations of the CCS process generally present overly simplified and schematic depictions of the geological subsurface [60]. As expressed by Stewart and Lewis [61] *'…CCS communications should focus on information and images that quickly help non-experts improve their understanding and avoid information and images that might only increase risk perception without resulting in a better understanding of CCS.'* Some of these will include imagery and communication materials from pilot and commercial scale CCS projects, and also from research, which may be employed to illustrate impact and risk (or lack thereof). Indeed, natural analogues for CO_2 leakage are globally widespread, and have been studied around the globe to understand the surface expression of leakage, and there is a case for making these images and data more widely available to enhance communication of leaked risk [62].

In addition to natural analogues, pilot scale or demonstration projects can also provide a window into storage risks. Indeed the conduct of surface release or shallow release projects aim to deliberately emit gases of known quantities, and the impact for a given leakage rate can be quantified. Knowing exactly the volumes being emitted enables both calibration and demonstration of impact of the leak and can provide an opportunity to work with stakeholders, including regulators, to better plan for both guidance and risks for larger scale projects [63].

4. TRANSLATING THESE LEARNINGS TO HYDROGEN STORAGE

We have presented learnings about the perceived risks around gas leakage from CO_2 storage (a technology which faces challenges regarding risk perception and communication) and from UGS (a widely accepted technology) so as to advise on the potential societal concerns towards hydrogen storage – and specifically regarding leakage from hydrogen stores. First, we consider the differences between CO_2, natural gas, and hydrogen storage which could limit how translatable or applicable these learnings are, before we suggest key messages for the hydrogen sector, as a first step towards managing the social acceptability of hydrogen.

4.1 How similar might the perceived risks be?

While CO_2, natural gas and hydrogen storage follows the same principles - the storage of gas in geological formations – there are differences in rationale that may affect public perception of risks and the acceptability of the technology. Hydrogen and natural gas are a valuable commodity. CO_2 is a pollutant, a waste product and a cost. If hydrogen is used for domestic power, the publics will be familiar with the gas and its use. The fact that underground hydrogen storage offers temporary storage of a useful resource, and not a form of waste disposal (i.e. intended to remain in the subsurface for geological timescales) may make hydrogen storage more acceptable to publics than CCS. It seems likely that renewable hydrogen will be more favourable than hydrogen derived from fossil fuels, given that work from CCS shows that publics are more accepting of long-term sustainable goals. Indeed, learning from CCS [64], it may be the case that if hydrogen is largely generated from fossil fuel, or hydrogen activities are operated by the same developers and operators connected to fossil fuels, there is risk that the technology will be unacceptable. This could be especially so if early hydrogen projects are supported by public funding, since it could be perceived that the private sector is somehow profiteering from the public purse in the low-carbon transition [65].

All three gases (CO_2, H_2, and CH_4) are odourless and not visible, and so are difficult to detect with the human senses, but only CO_2 classifies as toxic (Table 2). Humans tend to be more fearful of unseen or undetectable compounds such as gases. That said, public awareness of the properties of these gases (i.e. whether or not you can smell or see them) can itself be quite low [65]. This low level of knowledge in itself means that it is difficult to postulate about how the style and impacts of a hydrogen leak from a geological store might be perceived in comparison to a CO_2 or natural gas leak, since the lay public are likely not to know, for example, that hydrogen disperses more readily than CO_2.

As for leakage from the geological formation, hydrogen is a smaller and lighter molecule than natural gas and CO_2, and being nimbler it could therefore could leak more readily [13]. By contrast, the small size of hydrogen molecules could lead to more tortuous pathways through the subsurface. The potential leakage pathways will be very similar for CH_4, CO_2, and hydrogen. However, unlike CO_2 injected for disposal, hydrogen will have a comparatively brief time in the subsurface formation in which to leak from if being used up after temporary storage [13]. That said, from a technical perspective, UGS and hydrogen storage could be considered to be more complex than CO_2 storage since the repeated injection and production cycles associated with these technologies and the resulting variable subsurface pressure (i.e. dynamic geomechanical impacts) pose enhanced uncertainty regarding the rock behaviour, and therefore the sealing capability of the different rock formations to prevent leakage over time. However, this is unlikely to be a major influence on public perspectives of leak risk. Rather, the same issues around how publics conceptualise the subsurface i.e. one of the present challenges for CCS, will likely be the same set of challenges for hydrogen and many other georesources.

It is interesting to consider whether, for the different gases, the perceived leak pathways or the potential perceived impacts of leakage would be similar or different. Both natural gas and hydrogen are flammable, unlike CO_2, and research suggests that hydrogen's explosive properties are quite well known amongst the publics [25]. In the case of leakage of hydrogen, the main concern could therefore be around the risks of explosion or fire. Here, local context could play a role in the perceived risk; in some seasons, fires are a major risk in Australia and in the USA. In this case, the perceived risk and therefore acceptability is likely to depend also on the proximity to the storage formation.

Another learning to consider concerns monitoring and measurement. Since both methane and hydrogen are present at much lower conditions in our atmosphere, they may be easier to detect above background, which has implications for ease of detection and monitoring. These two gases might therefore be easier to monitor for and measure than CO_2, for which variations in background concentration due to natural processes can be problematic [67]. The ease of monitorability may enhance risk perception.

Natural analogues for CO_2 stores and leaks have proven valuable in understanding the impacts of leakage, developing monitoring tools, informing storage site selection, and providing communication resources around CO_2 leakage and impacts. Such analogues do not exist for hydrogen, and so hydrogen release field experiments or pilot injection projects may be necessary.

There are other learnings to be translated between the technologies, not just about risk of leakage. For example there may be parallels that could be drawn with regards to the political narrative or messaging regarding CO_2 storage and hydrogen. In the UK, a recent report by Turner et al [68] indicates that the political narrative of presenting CCS as part of a climate mitigation strategy (i.e. reducing CO_2 emissions), rather than as part of an industrial or business strategy (i.e. creating jobs, stimulating the economy), has affected how CCS has been received by policy makers, businesses and publics. Further, it is very likely that

Generally the best predictor of acceptance of CCS is the perceived benefit, rather than the perceived risks [38]. This links into the findings that it is the perceived benefit which is the strongest factor affecting public acceptability [38]. If the only perceived benefits are long term and not tangible (mitigating climate change), but the perceived risks are short term and tangible (expensive, leakage, harm) then societal uptake is likely to be low.

4.2 Messages for the hydrogen storage sector

A nebula of issues surrounds public acceptance of new technologies, including challenges around trust, efficacy, fairness, perceived risk, and so on. Understanding these issues, and what the hydrogen industry can do to allay, adapt, or address concerns, will be fundamental to the roll out of any hydrogen economy. This is true also for hydrogen storage. Here we have examined what has been learnt about public perceptions of risk of leakage from geological storage of CO_2, to apply these learnings to the geological storage of hydrogen. From this, we raise the following recommendations:

- *Early engagement*: Successful projects have early and high-quality engagement programmes to open channels of communication between stakeholders and which can help to build trust, deepen understanding (both the publics of the process, and also the developers understanding around concerns). They are also informed by a good understanding of the project context, including familiarity with energy or resource industries.

- *Address the unknown:* New technologies or changes, such as using hydrogen for distributed power, generating hydrogen from renewable-powered electrolysis, or storing hydrogen in rocks underground are relatively new. This means that many of the concepts may be unfamiliar. It is important that hydrogen stakeholders do not assume a level of knowledge from non-expert stakeholders, for the misunderstanding that this can propagate can be problematic risk acceptability, and also difficult to reverse.

- *Complex concepts*: Some aspects of new technologies introduce complex concepts which might affect perceived risks. For example, regarding the perceived risk of gas leakage, conceptualising the subsurface is unfamiliar to many people, and is therefore particularly challenging. There is much scope to develop better understanding of how best to communicate or build dialogue around such topics, otherwise there can be a barrier to communication or risk assurance than is difficult to manage.

- *Material evidence*: There is value in demonstrator projects: whether these are field trials, pilot scale projects or commercial scale operations. The generate evidence. And without evidence, beliefs may be built on own experience or on rumour [21]. Further, to quote Reiner [47:710] "…it is difficult to engage in a serious public debate over risks or to develop an effective risk communications strategy if there is no actual project on which to present information."

- *Trust in operators and regulators:* As for any emerging technology or any new development, whether or not communities accept the risks associated with a project will be affected by trust in the governing stakeholders. But of particular relevance for gas storage underground is how the public view how risks will be managed and allayed. Risks become more acceptable if there is the perception that regulation will protect, monitoring will be robust, and that operators will be genuinely operating to maximise safety. Experiences from analogue technologies suggest that these perceptions will vary with scale and context, for example, at the local level the operator might be considered to be a trustworthy given they have a track record or doing things safely in the local area, whereas at a national level the operator may be deemed to be not trustworthy because for example they are linked to a gas leak that occurred elsewhere in the world.

- *A useful gas*: Hydrogen is a useful fuel. It can be used as a chemical feedstock as well as for power. This is likely to be an advantage for public acceptance of the hydrogen sector, particularly where it is widely believed that fossil fuels are in decline.

- *Blue, green or black*: Public attitudes may be more positive or hostile depending on the hydrogen source. The risks related to the underground storage of hydrogen generated from renewables (green hydrogen) or biofuels will likely be much more widely accepted than the storage of hydrogen generated from fossil fuels (black hydrogen).

Finally, research on the public acceptance of CCS finds that support for the technology is dependent upon the acknowledgement that climate change is real, and must be mitigated. It is very likely that this will also apply to the public acceptability of underground hydrogen storage, and the hydrogen economy more generally.

5. CONCLUSIONS

The review of existing scholarship around CCS and underground hydrogen storage in this paper illustrates the importance of early and thorough consideration of societal issues prior to deployment of hydrogen storage in support of the hydrogen economy. Risk perception is of course just one factor among many driving societal views towards new and potentially unfamiliar technologies such as hydrogen storage. Experiences with CCS show the importance of considering new technologies in context, and of understanding how place history and prior experience can drive risk perception. There is a concomitant need to develop communication resources for stakeholder, community and general public engagement on hydrogen storage, underpinned by rigorous and context-specific research. Moreover, experiences with CCS also illustrate there can be a difference between considering the technology in the abstract versus a 'real-world' project in a specific locale. In this regard, pilot projects offer a valuable opportunity to understand what informs societal responses in practice, and to generate evidence of new technology. Once projects commence, it is also important to remember that stakeholders and communities will require ongoing engagement and monitoring data, hence there is value in considering now questions such as the relative ease of monitorability of hydrogen leakage. Whilst it is too early to pinpoint specific issues which may arise for societal support of underground hydrogen storage, it is fair to say that site-specific communication and engagement strategies, underpinned by broad-based principles covering the entire span of the project, will aid the likelihood of underground hydrogen storage gaining societal acceptance, as well as the broader expansion of the hydrogen economy

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