

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

Linda Stalker^{1*}, Jennifer J. Roberts², Leslie Mabon³ and Patrick G. Hartley⁴

¹CSIRO Energy, PO Box 1160, Bentley, WA, 6102, Australia. ²Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, Scotland. ³School of Applied Social Studies, Robert Gordon University, Scotland. ⁴CSIRO Energy, Private Bag 10, Clayton South, VIC 3169, Australia. *Corresponding author: linda.stalker@csiro.au

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.

Geological storage of hydrogen could present challenges in terms of perceived safety. Valuable lessons can be learned from international research and practice of CO₂ 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 electricity, 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) [1]. 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. As hydrogen is rarely present as a free gas in “reservoirs” like natural gas [2], other methods have been 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.

A range of countries are considering becoming hydrogen exporters, such as Australia, Norway, Brunei and Saudi Arabia [1]. Japan and South Korea have developed formal, government led strategies for transition to hydrogen imports (from LNG and other fuels). 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 CO₂. 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, each of which will have different associated safety risks. The production of hydrogen for feedstock is a long-established technology, however, the novelty of hydrogen for energy is its widespread application for emissions reduction. 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 (CO₂) is a significant by-product of fossil fuel derived hydrogen, but could be mitigated via CCS to maintain low carbon footprints [3].

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 but their size is limited due to cost and safety. An overview by Barthélémy, 2012 of industrial storage reinforces the limits of fabricated gas storage [4]. Small volumes could also be stored in the domestic distribution pipeline networks [5]. Underground geological formations, in contrast, can offer capacity to hold significant volumes of hydrogen. It has been noted that quantifying volumes for storage remains challenging for industrial storage of hydrogen in porous media; it would be expected that very large scale geological hydrogen storage would be approximately 1 mega tonne, while medium-scale storage of 2-3 mkg would equate to a large salt cavern or small oilfield [6]. 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. In the latter, 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, 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 [6], but there are currently no commercial projects injecting hydrogen into porous media [7].

Challenges relating to pipelines and transport of hydrogen may lead to similar issues of risk perceptions and risk acceptability around the development of new technologies, 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 CO₂ 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 rapid and widespread technology innovation, scale-up and roll-out. The uptake of hydrogen 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 public 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 [8, 9, 10].

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 [11], and depends on a number of factors, including perceived risk and benefits, and trust in risk management [12]. 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 [13]. When risks are perceived to be high, the associated benefits are perceived to be low, and vice versa [14]. 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 [15].

Public acceptance is particularly relevant to technologies that need public funding to support pre-commercial development [16]. 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 [17]. 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 [16].

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 [15]. In their review of 6 studies of public perception of hydrogen, Ricci et al [18] 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 [19] 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 Japan, a series of more recent surveys [20] indicated that there was much larger increase in awareness of hydrogen energy, but perception of risks and benefits remained unchanged.

In a much more recent study in Australia, Lambert & Ashworth [16] 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 [16]. 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 [16]. Linked to this, most people prefer hydrogen production from renewable sources [16], 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 [16].

Messaging is known to be important in shaping public attitudes to emerging technologies, and the generally positive attitude towards hydrogen in Ricci et al. [18] 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 [18]). Trust – or more correctly, distrust – was identified to be a key factor that shaped public beliefs, attitudes and expectations [18]. 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 [16] 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 CO₂ 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 [16]. While 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 for insight.

2. ANALOGUES FOR THE GEOLOGICAL STORAGE OF HYDROGEN

The geological storage of CO₂ and natural gas (UGS) and compressed air energy storage (CAES) are all suitable analogues [21] (Table 1). However we do not consider CAES in this work because the technology is also emerging.

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 CO₂ injection project, Sleipner, located in the Norwegian North Sea, started injecting CO₂ for storage in 1996. However, it was 18 more years until the first fully integrated CCS project Boundary Dam in Canada, commenced CO₂ injection. Geological storage of CO₂ is considered to be fundamental to the delivery of a net zero emissions by 2050 [22], but many challenges 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 [22]. 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 630 facilities in operation in 2009 [23]. Underground storage presently occurs in salt or rock caverns, depleted hydrocarbon reservoirs or abandoned mines, and saline aquifers. UGS is deemed to have excellent health, safety and environmental record [23]. However there have been some incidences of gas leakage in recent years in the US which have caught global media attention, including the well failure at Aliso Canyon in Los Angeles in 2015 [24]. Key properties and behaviors of each of these gas storage types to illustrate how comparable these industries are (Table 1).

2.2 Comparing analogues

Reservoirs for hydrogen and UGS will tend to be shallower than CO₂ disposal (> 800 m to maintain supercritical phase [25]). Hydrogen storage depth is much shallower (~200 m below surface at typical geothermal gradient [16]). For all gas storage technologies, the surface footprint of the geological store is small, and most visual impacts, if any, would be related to the well head or monitoring of the store.

The primary concern for all forms of geological storage is leakage. While the most likely potential leakage pathways of CO₂, natural gas and hydrogen may be similar (poorly sealed wells, un-imaged faults etc, [6]), the impacts of leakage will be different owing to the properties of the three gases. Light gases like hydrogen readily disperse, whereas CO₂ 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 CO₂ (Table 2).

Table 1: A comparison of the CO₂, 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	<i>Phase</i>	Gas(compressed)	Dense or gas phase natural gas.	Dense phase CO ₂ .
		<i>Geological parameters</i>	Reservoir-caprock systems, or salt caverns	Reservoir-caprock systems, or salt caverns	Reservoir-caprock systems; large saline aquifers.
<i>Injection cycle</i>		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	Geological storage first proposed in 1970s [27]	Since 1915 [23]	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 [5]	Common in salt caverns or saline formations / depleted gas fields. Typically shallow geological depth. UK stores 3-4%, Germany 19%, France 24% and USA 18% of annual consumption [28]	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 [29]. 40 Mt annual capture in 2017 [28]	
	Forecast by (2050)	Global demand for hydrogen anticipated to be 530 million tonnes [1]	Likely increase, in the medium term. Could be overtaken by hydrogen by 2050.	Abatement options evolving from storage to include utilisation, direct air capture.	

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 events in the US [24]. As such, much of this section concerns public perception of leakage from CO₂ stores.

Table 2: Summary of the different properties of H₂, CH₄ and CO₂. Natural gas is normally a blend of light hydrocarbons (LHCs) but is predominantly CH₄.

Stored medium		H ₂	CH ₄ (+ LHCs)	CO ₂
Atmospheric concentration (ppm)		0.5 ^[30]	1.798 ^[31]	405.70 ^[31]
Global warming potential (GWP) ^[32]		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

3.1 Perceived risk of gas leakage

L'Orange Seigo et al. [33] report that the most commonly held concern about CCS is that the injected CO₂ might leak, how this leakage might occur, and the resultant environmental impact. Further, as CO₂ is regarded as a pollutant, it has associations with toxicity. Publics often express fear of over pressurization, and people often believe there might be sudden blowouts or explosions at the surface or deep underground, or that CO₂ injection might cause earthquakes, which might compromise storage integrity [33]. Shackley and Gough [34] 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 CO₂ leakage. The perceived risk of CCS is also negatively related to the trust in stakeholders [35] and in acceptance of the technology [36]. Public perception of risk is reduced if monitoring approaches are trusted [35], and detailed monitoring is deemed to be beneficial in terms of public acceptability of the technology and trust in the regulation [37, 38].

Public support for CCS is dependent upon the acknowledgement that climate change is real, and must be mitigated [39]. However, publics may also view CCS as unsustainable. CO₂ 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 [39] or compete with renewables. 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 and less concerned. 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 [40, 41].

3.2 Conceptualising leakage

For many, geenergy technologies such as CCS can appear largely "imaginary" [42]. 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 [43]. These concerns are wrapped up in misconceptions around the belief that because CO₂ 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 CO₂ 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 [44].

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, sometimes resulting in projects being terminated [e.g. 10, 45, 46]. This is particularly necessary given the low levels of public knowledge about CCS [47], and perhaps more significantly, given the unfamiliarity of the underground geological realm. Several studies, including Upham and Roberts [48] 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. [49] suggests that such problems could arise because of flaws in the assumed public knowledge of CO₂. They found that providing information on the scientific characteristics of CO₂ 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 [17], and there are examples of excellent community engagement ranging from research projects such as QICS [50] to large CCS proposals like those in Tomakomi [41] 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 [33]. Perceived risk could be informed by imagery. It is a well-known proverb that “a picture speaks a thousand words”, however with problems of scale, conventional visualisations of the CCS process generally present overly simplified and highly schematic depictions of the geological subsurface [51]. As expressed by Stewart and Lewis [52] ‘...*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 CO₂ 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 [53, 54].

4. TRANSLATING THESE LEARNINGS TO HYDROGEN STORAGE

We have presented learnings about the perceived risks around gas leakage from CO₂ storage and from UGS 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 CO₂, 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 geological storage.

4.1 How similar might the perceived risks be?

CO₂, natural gas and hydrogen storage follows the same principles - the storage of gas in geological formations. Hydrogen and natural gas are a valuable commodity, while CO₂ is a pollutant, a waste product and a cost. If hydrogen is used for domestic power, the public 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 public than CCS. Renewable hydrogen will likely be more favourable than hydrogen derived from fossil fuels, given that work from CCS shows that public are more accepting of long-term sustainable goals. Learning from CCS [55], 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.

All three gases (CO₂, H₂, and CH₄) are odourless and not visible, and so are difficult to detect with the human senses, but only CO₂ classifies as toxic (Table 2). Humans tend to be more fearful of unseen or undetectable compounds such as gases. Public awareness of the properties of these gases (i.e. whether or not you can smell or see them) is generally quite limited [56]. This low level of knowledge in itself means that it is difficult to predict perception of a hydrogen leak in comparison to CO₂ or natural gas, since the lay public are likely not to know, for example, that hydrogen disperses more readily than CO₂.

As for leakage from the geological formation, hydrogen is a smaller and lighter molecule than natural gas and CO₂, and could buoyantly leak more readily [6]. But the small size of hydrogen molecules could lead to more tortuous pathways through the subsurface thus taking longer to travel. While CO₂ is injected for permanent disposal, hydrogen will have a comparatively short residence time in the subsurface formation, reducing likelihood of significant leakage [6]. That said, from a technical perspective, UGS and hydrogen storage could be considered to be more complex than CO₂ storage. 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.

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 CO₂, for which variations in background concentration due to natural processes can be problematic [57]. The ease of monitorability may alter risk perception. 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 CO₂ storage and hydrogen. In the UK, a recent report by Turner et al [58] indicates that the political narrative of presenting CCS as part of a climate mitigation strategy (i.e. reducing CO₂ 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.

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 the hydrogen economy (including hydrogen storage). Applying learnings from geological storage of CO₂, we propose the following recommendations:

- *Early engagement:* Successful projects have early and high-quality engagement programmes to open channels of communication between stakeholders, building trust and deepening understanding of both publics' and developers' understanding around concerns. This improves 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 and unfamiliar. It is important that hydrogen stakeholders do not assume a level of knowledge from non-expert stakeholders, as misunderstandings can propagate, become problematic and difficult to reverse.
- *Complex concepts:* These might affect perceived risks. For example, risk of gas leakage or conceptualising the subsurface is typically unfamiliar and therefore challenging. Development of better communications or dialogue is essential, otherwise barriers to communication may result.

- *Material evidence*: There is value in demonstrator projects: whether these are field trials, pilot scale projects or commercial scale operations. They generate evidence. And without evidence, beliefs may be built on own experience or on rumour [15]. Further, to quote Reiner [42:710] “...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, a project will be affected by trust in the governing stakeholders. 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 having a demonstrable track record.
- *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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