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Communicating leakage risk in the hydrogen economy: Lessons already learned from geoenergy industries

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Hydrogen is set to play a part in delivering a net zero emissions future globally. However, previous research finds that risk perception issues are particularly challenging for emerging and potentially unfamiliar technologies. Hydrogen as a fuel falls into this category. Thus, while the hydrogen value chain could offer a range of potential environmental, economic and social benefits, it is imperative that the roll-out of hydrogen fits with societal expectations of how risk ought to be managed—and by whom. Communication and engagement are critical to ensure 1) communities and stakeholders are able to come to informed decisions on hydrogen and 2) developers, operators and regulators are able to respond to societal concerns and adapt practices appropriately. Within the hydrogen value chain, geological storage may be an important step, but could present challenges in terms of perceived safety. 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 power respectively] which may be relevant to hydrogen storage in salt caverns or porous sandstones. We draw on these analogues to present potential societal risk perception issues which may arise for geological storage of hydrogen. We argue that site-specific communication and engagement strategies, underpinned by broad-based principles covering the entire span of the project and a clear rationale for how hydrogen benefits the climate and the most vulnerable members of society under an energy crisis, will be critical to fostering societal support for geological hydrogen storage.

KEYWORDS

geological carbon storage, energy transition, societal acceptance, underground storage, hydrogen safety

1 Introduction

The use 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. Within broader consideration of the place of hydrogen within an increasingly electrified and net-zero society [e.g., the UK's Committee on Climate Change (Climate Change Committee, 2021) report on hydrogen in a low carbon economy], governments and regulators are turning attention to issues of storage and safety around hydrogen. This is happening around the globe, for example, The Council of Australian Government's hydrogen strategy working group states "The primary consideration in delivering hydrogen is attention to safety and community awareness" (Commonwealth of Australia, 2018). There is a large body of research which indicates that societal views of energy technologies such as new applications of hydrogen are not homogenous, and ought to be considered within a much wider picture of what constitutes a fair and just transition to a net-zero society (e.g., Upham, et al., 2019; Scott and Powells, 2020). Negative public views and responses can also challenge other emerging technologies, including utility-scale renewable projects such as solar farms. Siting solar farms have key technical requirements (e.g., solar resource, proximity to transmission infrastructure, slope, aspect/elevation) but may be impacted by lack of support, uncertainty, opposition, or outright resistance (Sward et al., 2021). This range of sentiment has also been seen in new nuclear and wind installations and resulting in projects being moved or terminated.

Societal responses to energy-related developments can operate at different scales. Host communities immediately adjacent to developments may have concerns relating to the physical characteristics of the development, potential risk, or perceived fairness in consultation and engagement processes. At a wider societal level (e.g., national or regional level), publics and opinion-shapers (e.g., non-governmental organisations, NGOs) may express broader concerns about the appropriateness of different energy technologies under a climate emergency, or the general direction of national energy policy. However, site-specific controversies can also become focal points for broader societal concerns about energy policy or climate responses. For instance, a small-scale exploratory shale gas study at Balcombe in the United Kingdom became the focus of protest for national NGOs, media and celebrities concerned over the potential for shale gas exploration in the United Kingdom more broadly (Hilson, 2015).

Nonetheless, a key issue driving societal support across these scales is that of trust in operators to have the competence to deploy technologies safely and securely, including—for new subsurface technologies which may enable a net-zero

society—being able to understand geological complexity and work with uncertainty to avoid leakage (Gough and Boucher, 2013; Mabon and Shackley, 2015). These concerns are relevant both for communities adjacent to infrastructure, who may bear the greatest physical exposure to any risks; and also for societal actors operating at a national or regional level, who may use issues of safety to judge whether an operator and/or a technology can be trusted to operate safely and quickly enough to support net-zero targets. While acceptance of new technologies is challenging at both a community and wider societal level, it is possible to draw parallels from other relevant technologies and developments such as the implementation of carbon capture and storage (CCS) and underground (natural) gas storage (UGS). CCS and UGS industries demonstrate successes and failures that can provide lessons learned for future proponents of a hydrogen economy. As hydrogen is rarely found as a free gas in "reservoirs" like natural gas resources (Prinzhofer et al., 2018; Zgonnik, 2020; Stalker et al., 2022), other methods have been developed to isolate or generate hydrogen.

A range of countries are considering becoming hydrogen exporters, such as Australia, Norway, Brunei, and Saudi Arabia (Commonwealth of Australia, 2018). 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, so addressing all aspects of safety for the full value chain is becoming increasingly urgent, especially in the light of announcements by the Japanese government to not only become carbon neutral by 2050, but also commit to a 46% reduction in its greenhouse gas emissions by 2030. Similar targets have also been proposed by over 130 countries (UN, 2022). Therefore identifying, understanding and communicating the perceived risks of storage as part of hydrogen utilisation 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 for insight into the potential societal attitudes around the development and adoption of storage as part of the hydrogen chain. Scovell (2022) in a recent review notes that a large focus of past research on the role of hydrogen as a low emissions energy technology, has mainly focused on the role of this energy vector for transport applications (e.g., passenger transport). Scovell points out the vast array of uses of hydrogen for electricity, domestic heating, manufacturing and feedstocks, and notes that understanding all the aspects of the hydrogen value chain and how they are perceived will be important for uptake and acceptance (Figure 1). For this paper we focus and 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.

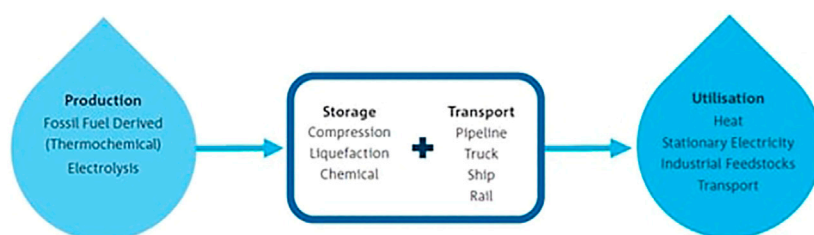


FIGURE 1

Simplified summary of the range of hydrogen technologies, including forms of hydrogen production, storage, transport and use (from Bruce et al., 2018). In this paper, we focus on underground hydrogen storage.

1.1 The hydrogen technology and value chain

The emerging hydrogen industry is anticipated to be a large-scale business. Goal setting for use as energy, fuel or feedstocks include 5 GW hydrogen production capacity by 2030 for the United Kingdom (Climate Change Committee, 2021). Japan's Sixth Basic Energy Plan likewise aims to increase hydrogen supply from approximately 2 million tons per year in 2021, to up to 3 million tons/year in 2030, and 20 million tons/year by 2050 (METI, 2021).

There are a range of hydrogen technologies, including forms of hydrogen production, storage, transport, and use, each of which will have different associated risk perception issues (Figure 1). The production of hydrogen for feedstock is a long-established technology, however, the novelty of hydrogen for energy is its widespread application for greenhouse gas emissions reduction. There are different hydrogen feedstocks and processes to produce hydrogen. The most common production technology is 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 reduced or mitigated via CCS to reduce its carbon intensity (Volsund et al., 2016). There is potential for hydrogen generation via electrolysis using renewable energy (green hydrogen), offering hydrogen fuel with a low carbon footprint.

The temporary storage of hydrogen is likely to become a limiting factor for large scale hydrogen projects. Storage is particularly relevant where large volumes of hydrogen are being produced by electrolysis using excess renewable electricity during periods of low demand, thus requiring temporary storage to be later recovered for use or export. 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 (e.g., large vessels) gas storage. Small volumes could also be stored in the domestic distribution pipeline networks (Panfilov, 2016). Underground geological formations, in

contrast, can offer capacity to hold significant volumes of hydrogen. Two primary types of geological hydrogen stores are anticipated: salt caverns (whereby gas is injected into a series of natural or engineered small, but discrete cavities in thick salt formations), and larger-scale 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 typically capped by an impermeable seal, not dissimilar to the characteristics of geological CO₂ stores. Individual salt caverns may be small in capacity, but multiples can be used for commercial operations; four hydrogen storage projects are operational; three in the US and one plant in the United Kingdom (Zivar et al., 2021), though more are in planning. Some operations manage a large number of caverns which may have a range of different gases or materials present. Hydrogen storage in reservoir-caprock systems is more attractive owing to the larger size and scale of the potential store (Heinemann et al., 2018), but there are currently no commercial projects injecting hydrogen into porous media (Kruck, 2014; Heinemann et al., 2021).

There are similar challenges relating to surface operations of gas-filled pipelines. Transport of CO₂ requires the additional management of high-pressure gas as a dense or supercritical phase. Irrespective of the type of gas, hazards relating to mechanisms, consequences and probabilities of damage or failure of pipelines can result in similar responses to risk perceptions and risk acceptability around the development of other new technologies, for example, managing large volumes of (unfamiliar) gas. Understanding these different risks can advise the appropriate development of a hydrogen economy. To this end, we consider the similarities and differences between hydrogen storage and other geenergy technologies such as CO₂ and natural gas storage to clarify where the similarities and differences between these technologies may lie (Section 2). We then review findings relevant to hydrogen storage from analogues such as advances in leakage risk perception, and communication and risk management (Section 3), and then consider what these could mean for societal and community

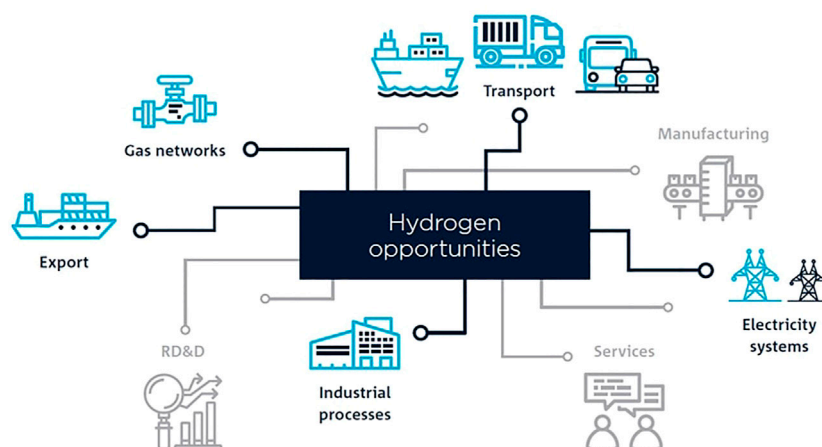


FIGURE 2

The range of role and use of hydrogen across the energy and transport sector (from Srinivasan et al., 2019).

acceptability of hydrogen deployment including storage 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 (Figure 2). 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 publics will tolerate, accept, or support. At a community level, resistance to planning decisions has delayed or terminated a range of different energy developments and has long been recognized as a risk to deploying energy infrastructure which may form part of the low-carbon energy transition (Strachan and Lal, 2004; Van Os et al., 2014; Fast and Mabee, 2015; Temper et al., 2020). At a wider societal level, energy projects which could otherwise have been argued to support the net-zero transition have been delayed or cancelled due to national-level campaigning on broader issues such as biodiversity protection or questions over what constitutes appropriate climate action. Examples include RSPB Scotland's opposition to offshore wind in Scotland on grounds of potential impacts on bird populations (RSPB, 2022); and the John Muir Trust's opposition to the Beaulieu-Denny power

line upgrade in Scotland on grounds of landscape and biodiversity impact despite the renewable energy potential the line could unlock (Tobiasson et al., 2016).

Within this landscape, the perceived safety of the technology chain is known to be a strong component shaping public attitudes. Societal acceptability of new technologies interweaves issues of technical complexity, procedural, recognition and distributive justice, risk perception and governance of developments (Huijts et al., 2012), and depends on several factors, including perceived risk and benefits, and trust in risk management (Breakwell, 2014). As well as psychometric approaches to risk perception which emphasise perceived uncontrollability and affect from "dread factors" as explanatory factors (e.g., Alhakami and Slovic, 1994); cultural approaches to risk argue that trust in decision-makers, fit with world views and perceived fairness in decision-making processes can all shape people's risk perceptions (Kasperson, 2014). Common across these approaches, however, is the idea that a broad range of social and cultural factors can influence what people consider to be an acceptable level of risk. Accordingly, providing more or better "evidence" alone will not necessarily lead people to believe that a risk is acceptable for a range of reasons, including perceptions of controllability (risks that are perceived to be uncontrollable are much less tolerable) and trust in the evidence-provider or other actors (Flynn et al., 2006).

Societal acceptance is particularly relevant to technologies that need public funding to support pre-commercial development (Lambert and Ashworth, 2018). In such cases, publics' views can influence market preference and 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 decisions about technology development, siting, and monitoring, and can

shape community engagement processes to be fair and effective and increase the likelihood of getting support from stakeholders including local communities. Therefore, with anticipated growth of a global hydrogen market, there is a growing need to map and understand public attitudes towards hydrogen technologies at this nascent stage of technology development. This is especially important when it comes to hydrogen storage, as relatively few studies exist on public attitudes towards risks of hydrogen storage (Scovell, 2022). Much work that has been done on the societal dimensions of hydrogen has focused on hydrogen as a fuel for transportation (e.g., Itaoka et al., 2017); or on the place of hydrogen in the energy system in broader terms (e.g., Lambert and Ashworth, 2018). However, studying public perception is particularly challenging for emerging, highly technical, sensitive, uncertain or unfamiliar technologies; and exploring lay perceptions of geological hydrogen storage could be additionally confounded by the unfamiliarity of the subsurface (Ashworth et al., 2015).

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

A breadth of studies on new and unfamiliar energy technologies such as CCS have illustrated that public opinions are driven by a much broader range of factors than simple cost-benefit analyses or narrow perceptions of “safety,” both for host communities close to developments and also the wider public (e.g., Terwel et al., 2012; Mabon and Shackley, 2015). In their review of 14 studies of public perception of hydrogen, Ricci et al. (2008) noted that findings from free word association methods (used in six out of ten quantitative studies) found that hydrogen safety is not a major concern, though safety is found to be a primary concern in three of these studies and is raised as a key issue in all four qualitative studies included in their review (Ricci et al., 2008). Qualitative research found that 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 (Ricci et al., 2006). Sherry-Brennan et al. (2010) investigated host community attitudes to a hydrogen-wind project on Shetland (Scotland) using free-association methods integrated into a survey. They 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 (Itaoka et al., 2017) indicated that there was a much larger increase in awareness of hydrogen for energy use, but perception of risks and benefits remained from the previous observations discussed earlier.

A study in Australia which used mixed methods approach combining a literature review, ten focus groups ($N = 92$) and a

nationally representative online survey ($N = 2,785$) Lambert and Ashworth (2018) found that the public attitudes towards hydrogen were generally neutral. The level of perceived or actual knowledge positively correlated with participants' overall attitude to hydrogen technology, and the main perceived benefits related to the environment and include reduced greenhouse gas emissions and other pollutant emissions. Most people preferred hydrogen production from renewable sources, and there was some concern around using coal (a fossil fuel) or water (a scarce resource in Australia) as the fuel with which to generate hydrogen. A more recent review of 43 studies by Emodi et al. (2021) found that prior knowledge, perceived cost, risk and benefits were critical factors that contributed towards increased acceptance of hydrogen technologies.

Framing is known to be important in shaping public attitudes to emerging technologies (Hilson, 2015). The early generally positive attitude towards hydrogen noted in Ricci et al. (2008) was 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 Ricci et al., 2008; Bögel et al., 2018). A study of how attitudes influence technology acceptance by Bögel and co-authors (2018) noted that this was limited by lack of knowledge and awareness of the technology in question. Their study on the use of hydrogen fuel cells in Europe (they surveyed nationally-representative samples of approximately 1,000 adults from 7 countries in Europe) found that information campaigns would have maximum effect at the early stage of new technology introduction in the sphere of hydrogen. The attitude of individuals with respect to technology, climate change, fuel cells and their specific applications were compared, and it was noted that prior attitudes had a strong influence on how new information on hydrogen was perceived (Bögel et al., 2018). In cases where there were positive attitudes, these were easily eroded and lacked intensity.

Trust—or more correctly, distrust—was also identified as a key driver of public beliefs, attitudes and expectations (Ricci et al., 2008). 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. As noted previously, few studies have explored public attitudes to hydrogen storage. Lambert and Ashworth (2018) 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 (Lambert and Ashworth, 2018). While publics may

TABLE 1 A comparison of the CO₂, hydrogen and natural gas geological 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	Gas (compressed)	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	Geological hydrogen storage first proposed in 1970s, (Amid et al., 2016). Salt cavern storage operating since 1970s	Operating since 1915 (Evans, 2009)	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 (Panfilov, 2016)	United Kingdom stores 3–4%, Germany 19%, France 24% and United States 18% of annual consumption (Matos et al., 2019)	In 2021, there were 27 commercial CCS CO ₂ injection projects, a further 4 in construction, and 58 in advanced development worldwide (Global CCS Institute, 2021). Current capture capacity of 36.6 Mt annually (Global CCS Institute, 2021)	
	Forecast by (2050)	Global demand for hydrogen anticipated to be 530 million tonnes (Commonwealth of Australia (2018).	Likely increase, in the medium term. Could be overtaken by hydrogen by 2050.	Abatement options evolving from storage to include utilisation, direct air capture.	

have a neutral or even positive attitude towards hydrogen, given the limited—and mixed—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) have all been argued to be suitable analogues (Itaoka et al., 2017) (Table 1). However, we do not consider CAES in this work because the technology is in very early development, like hydrogen storage. Demonstration projects that do exist for CAES at present are small-scale and within the grounds of research facilities, and hence are not close to communities or in the general public domain. As such, the kinds of CAES facilities that currently exist are unlikely to be understood, let alone a source of concern, for publics; and may offer limited insight to managing risks associated with storage from a technical perspective. This is different to CO₂ storage and natural gas, where there have been medium-to large-scale demonstrators (e.g., Tomakomai in Japan, Ketzin in

Germany), commercial-scale CCS operations of millions of tonnes per annum (e.g., Gorgon in Australia, Boundary Dam in Canada or Sleipner in Norway) and a long history of storage (natural gas) in the lived environment, and hence examples of deployment that lessons for hydrogen can be drawn from.

2.1 Carbon capture and storage and natural gas storage analogues

CCS includes geological storage of CO₂ that is intended to be permanent. Globally, there are currently 27 active commercial-scale CCS projects (Global CCS Institute, 2021; Table 1). While gas processing and handling (i.e., akin to capture), pipeline transport of gases and geological assessment of the subsurface for volumes of hydrocarbons in place (i.e., carbon geological storage) are all well understood, joining these pieces up together for CCS is still regarded as somewhat of an emerging technology. However, all the components of the CCS value chain have been technically feasible for decades, and there is a reasonably lengthy history of activity. The first CO₂ injection project (unconnected to enhanced oil recovery (EOR) processes) is

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 CH₄.¹Pidwirny (2012), ²Cape Grim Data (2022); ³IPCC (2013); ⁴Warwick et al. (2022).

Stored medium		H ₂	CH ₄ (+ LHCs)	CO ₂
Atmospheric concentration (ppm)		0.5 ¹	1.847 ²	413.122 ²
Global warming potential (GWP) ³		11 ± 5 ⁴	36	1
Toxic		No	No	Yes
Natural odour		No	No	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

LEL/LFL—lower explosive limit/lower flammable limit.

UEL/UFL—upper explosive limit/upper flammable limit.

Sleipner. The Sleipner CCS Project is located in the Norwegian North Sea and 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 (Preston et al., 2018). Geological storage of CO₂ is fundamental to the delivery of net zero emissions by 2050 (Alcalde et al., 2018), but many challenges have hindered CCS development. These have tended to be economic and financial rather than technical or procedural and had up until recently related to a lack of economic viability (Alcalde et al., 2018). The design and development of hub and cluster models such as Northern Lights, Acorn, or Net Zero Teeside have reframed the technoeconomics (e.g., Alcaldé et al., 2019).

UGS refers to temporary, cyclic, storage of methane. UGS is a well-established technology that has been used as an economical method for managing gas delivery for over 90 years. In total 630 facilities were in operation in 2009 (Evans, 2009) with 317 active commercial projects in the US in 2017 (Michanowicz et al., 2017). UGS 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 (Evans, 2009), however in recent years there have been some incidences of gas leakage in the US, including the well failure at the Aliso Canyon gas storage facility in Los Angeles in 2015 (Pan et al., 2018). The paper by Pan et al. (2018) notes that the researchers had previously developed coupled well-reservoir simulators for modelling behaviour of CO₂ leakage in wells, which was then adapted for methane leakage. The modelling software was then able to predict possible outcomes from remediation and kill procedures to mitigate the leakage of large amounts of methane from the UGS facility, demonstrating the benefits of considering analogues.

Key properties and behaviours of each of these gas storage types, summarized in Table 1, illustrate how comparable these industries are.

2.2 Comparing analogues

Reservoirs for hydrogen and UGS tend to be shallower than CO₂ storage [>800 m to maintain supercritical CO₂ phase (Chadwick et al., 2008)]. Hydrogen storage depth is shallower (~200 m below surface at typical geothermal gradient; Heinemann et al., 2018). 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.

A 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, unimaged faults etc., (Chadwick et al., 2008), the impacts of leakage will be different owing to the properties of the three gases. While hydrogen might be more mobile in the subsurface relative to natural gas and CO₂, other processes, such as increasingly tortuous pathways for smaller molecules (Carrigan et al., 1996) could have counterintuitive influences. At surface, 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 larger range of flammability introduces different and potentially greater risks to that of methane and CO₂ (Table 2). Further points of similarity and difference between hydrogen and other gases can be found in Schmidtchen (2009).

3 The perceived risks of underground storage

As illustrated in Section 2, UGS offers insights into the management of risks related to gas storage from a technical perspective, which can help to identify potential risk perception and management issues that could arise for hydrogen. However, there are very few modern academic studies specific to the social perception of risks associated with UGS. This likely reflects that

UGS is a widespread and widely accepted energy technology, and therefore has been in little need of research around public perceptions, even following a series of events in the US where several thousand people were displaced from their homes over several months following the Aliso Canyon underground gas storage well blowout and subsequent kill operations (Pan et al., 2018). As such, much of this section focuses on public perception of leakage from CO₂ stores. We return to UGS in Section 4, where we draw out potential risk issues for hydrogen storage identified in our analogues and reflect on with this means for societal risk perception and engagement on risk for hydrogen storage.

3.1 Perceived risk of gas leakage

Whilst it is true that a wide range of factors shape public perceptions of new subsurface energy technologies, L'Orange Seigo et al. (2014) 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. As CO₂ is regarded as a pollutant, it also has associations with toxicity. Publics can express fear of over-pressurization and may 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 (L'Orange Seigo et al., 2014). Shackley and Gough (2006) 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. However, the perceived risk of CCS is also negatively related to the trust in stakeholders (Terwel and Daamen, 2012) and in acceptability of the technology (Wallquist et al., 2012). Public perception of risk is reduced if monitoring approaches are trusted (Terwel and Daamen, 2012), and detailed monitoring is deemed to be beneficial in terms of public acceptability of the technology and trust in the regulation (Feitz et al., 2014; Waarum et al., 2017). Conversely, in the case of Tomakomai, Japan, Mabon et al. (2017) found that fishers' initial apprehensions towards sub-seabed CO₂ storage were driven in part by previous negative experiences with poorly managed industrial activities in the bay. Both at the community and wider societal levels, therefore, although safety and storage integrity concerns are often discussed by publics and stakeholders, these discussions are heavily influenced by issues of trust and perceived competence of operators and regulators.

Public support for CCS is dependent upon the acknowledgement that climate change is real and must be mitigated (Mabon and Shackley, 2015). However, publics and stakeholders may also view CCS as an unsustainable or undesirable mitigation strategy, even if they acknowledge the reality of climate change and trust in the safety of the technology. CO₂ storage space is finite, and the technology is associated with power stations and heavy industry. CCS has been critiqued for its potential to allow fossil fuel energy operators to continue

environmentally harmful practices such as oil recovery and hydrogen production from methane without fully deploying CCS to capture associated emissions. This may become especially problematic if CCS is perceived as diverting attention and research and development effort away from renewable energy sources (Mabon and Shackley, 2015); or comes to be viewed as “subsidising” fossil fuel industries through the use of public funds to support operators to implement CCS projects (Stephens, 2013). In short, public and opinion-shaper support for CCS—which is critical to sustain support from policy makers and legislators—may depend not only on the perceived safety of the technology, but on a much wider suite of factors relating to the political economy of who ought to benefit from the deployment of net-zero technologies (Markusson et al., 2020).

Scepticism towards CCS may hence be strong at the national scale. Yet at a local level 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 by the technical or political-economic risks outlined above. Operators involved in CCS activities are likely to have prior experience of working in a locality through, for example, extracting oil or gas from reservoirs that are now considered storage sites, or running power stations/refineries that are suitable for CO₂ capture (Alcade et al., 2019). It may thus be the case that operators come to be viewed as good and trusted employers with a long history of managing their operations safely and bringing employment and economic benefit to host communities. Whilst it should not be assumed that this means a social licence to operate can be transferred to CCS activities, good relations established during prior activity may well help to maintain community support for new developments such as CCS (Mabon et al., 2017; Gough et al., 2018).

3.2 Conceptualizing leakage

For many, geoenergy technologies such as CCS can appear largely “imaginary” (Reiner, 2015). 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, research into the subsurface more broadly has found that publics without in-depth or specialised knowledge can find the nature of the subsurface hard to conceptualise (Gibson et al., 2016). In turn, this difficulty in conceptualising the subsurface can lead to concerns 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 (Shackley et al., 2004). Further, given that the most publicised forms of leakage from UGS are uncontrolled blowouts, it is reasonable for publics to assume that leakage of hydrogen or CO₂ from geological stores might occur in a similar dramatic manner.

3.3 Communicating leakage

The need for effective engagement and communication around CCS, and the role of such communication in risk perception and management, is well recognised and can offer insights for hydrogen storage. CCS communication and engagement has been the subject of extensive study, especially as some projects have been terminated due to societal concerns (e.g., Ashworth et al., 2010; Van Os et al., 2014; Xenias and Whitmarsh, 2018). These, and other studies provide a gateway into planning and consideration for the emergence of hydrogen technology use and deployment. Reflecting our points above about the breadth of factors that can shape societal attitudes to CCS and other novel uses of the subsurface, it is vital that engagement and communication does not tend towards ‘information deficit’ models where the end goal is to lead host communities and wider society to “accept” new energy or emissions-related technologies. It is also important that engagement and communication respects the breadth of issues that may be of concern to publics, rather than closing down engagement to narrow discussions on risk and safety. Nonetheless, for technologies like CCS, UGS, and hydrogen where public understanding is low and real-world examples may (in the case of CCS and hydrogen) be limited (Reiner, 2015; Perdan et al., 2017), it is true that some level of communication and engagement may be required to enable communities, less-informed stakeholders and publics to come to an informed decision on whether or not they deem these technologies to be appropriate.

Several studies have found that as public participants gained more information about CCS, group discussions became increasingly complicated, and the opinions of participants negatively affected (e.g., Upham and Roberts, 2011). However, more recent work from Dowd et al. (2014) 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. This may directly relate to the lack of flammability or explosive behaviour of CO₂ relative to other gases such as hydrogen (Table 2).

Significant efforts have been undertaken to develop materials that have helped to inform a range of stakeholders about CCS concepts (Ashworth et al., 2015). Community engagement has been conducted—and evaluated—for CO₂ storage-related

activities across a range of scales. One example of this is the QICS (Quantifying and Monitoring Potential Ecosystem Impacts of CO₂ Storage) project, which released CO₂ from below the seabed into a bay in the west of Scotland under experimental conditions, to assess potential ecosystem impacts of leakage from storage site (Mabon et al., 2015). Another is the Tomakomai CCS Demonstration project in Japan, which injected 300,000 tonnes of CO₂ into subsea geological formations *via* a subsea pipeline from an onshore capture plant to demonstrate the viability of CCS technologies in Hokkaido, northern Japan (Mabon et al., 2017). The peer-reviewed research into both of these examples illustrates the importance of early and prolonged engagement and of projects being able to adapt their communication and engagement approaches in response to what communities and stakeholders say they want to know. While the emerging CCS industry can provide case studies and potential roadmaps for community engagement, there are mixed results reported in the literature regarding the effect that information and tools used by these communication programmes has had on risk perceptions (L’Orange Seigo et al., 2014).

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 (Feenstra, 2012). The role of the subsurface geology, and its depiction, is a key part in not only CCS but also in underground hydrogen (and gas) storage. In 2010, Wallquist et al., 2010 and co-authors noted that “CCS communication should focus on information and images that quickly help nonexperts 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 visuals 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 widespread, and have been studied around the globe to understand the surface expression of leakage. There is hence a case for making these images and data more widely available to enhance communication of leakage risk (Roberts and Stalker, 2017; Stalker et al., 2018). At the same time, however, the ability of publics to quickly grasp complex issues and to engage in-depth with questions of risk and uncertainty should not be underestimated. Graphics that appear over-simplified, or indeed engagement approaches that are viewed as patronising or overly confident in the capabilities of CCS, may have the effect of reducing public support for CCS if they create the impression the presenter is trying to convince the public of the technology (Howell et al., 2014). These are important lessons to be considered as part of the development of a hydrogen industry.

4 Translating these learnings to hydrogen storage

We have presented learnings about the perceived risks around gas leakage from CO₂ storage and from UGS and experiences of communicating these risks, to identify potential risk perception issues that may arise in relation to the geological storage of hydrogen. We now consider the differences between CO₂, natural gas, and hydrogen storage which could limit how translatable or applicable these learnings are, and then 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 has long been considered as a pollutant, a waste product and a cost. However, this perception is in transition as more countries declare their net zero targets and their related mechanisms for crediting emissions avoided. If hydrogen is used for domestic power, 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. However, there may be nuance in perception depending on the nature of the hydrogen produced. ‘Green’ hydrogen (i.e., hydrogen produced through renewable energy) will likely be viewed more favourably than hydrogen derived from fossil fuels, given that this will reduce the CO₂ emissions associated with hydrogen production and remove the need for CCS, which is viewed by more sceptical voices as unproven or unfeasible (e.g., [Toke, 2020](#)). This reflects results of research conducted for CCS in the context of CO₂-Enhanced Oil Recovery, which found that public and opinion-shapers perceived storage less positively when it was viewed as enabling an activity regarded as harmful to the climate ([Mabon and Littlecott, 2016](#)). Indeed, reflecting CCS research e.g., [Stephens, \(2013\)](#) and [Mabon and Shackley, \(2015\)](#), evidence from Scotland suggests that NGOs view hydrogen production as allowing fossil fuel operators to give the impression of taking positive climate action and hence perpetuating harmful activities elsewhere ([Dixon, 2019](#)). In 2020, Friends of the Earth Scotland branded hydrogen as a “false solution” to climate change ([Friends of the Earth, 2020](#)). Similarly, empirical research has questioned the necessity of hydrogen in the UK’s heating goals, and positioned the technology as being pushed by a coalition of incumbent actors including the gas industry ([Lowes et al., 2020](#)). At a national level, it may thus be the case that public and

stakeholder perceptions of hydrogen storage are driven not only by views on safety concerns, but on the necessity and propriety of hydrogen in a net-zero energy system more broadly.

The gases we consider here for geological storage gases (CO₂, H₂, and CH₄) are all 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 ([Upham and Roberts, 2011](#)). 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. Nonetheless, initial research ([Mouli-Castillo et al., 2021](#)) indicates that people can identify escaping odourised hydrogen at regulatory thresholds.

As for leakage from geological formations, hydrogen is a smaller and lighter molecule than natural gas and CO₂ and could buoyantly leak more readily ([Heinemann et al., 2018](#)). 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 ([Heinemann et al., 2018](#)). That said, from a technical perspective, UGS and hydrogen storage could be regarded as 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 ([Heinemann et al., 2021](#)). Understanding deliverability (i.e., cycles of injection and withdrawal) and impacts from the interplay of water drainage and replacement by gas, types of cushion gas, buffering and repressurisation are complex and still subjects of research into performance and financial viability of UHS ([Muhammed et al., 2022](#)). However, these geological complexities are unlikely to be a major influence on public perspectives of leakage risk ([Ricci et al., 2006](#)). 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 concentrations 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, where variations in background concentration due to natural processes can be problematic ([Blackford et al., 2015](#)). Reflecting on the points raised in [Section 3](#), however, trust in the institution

providing the data to “tell the truth” and manage a storage site competently is likely to have a significant influence on whether communities and stakeholders engage with and trust the outputs of monitoring and measurement. The ease of monitorability may alter risk perception. There are other learnings beyond leakage risk to be translated between the technologies. For example, there may be parallels with regards to the political narrative or messaging regarding CO₂ storage and hydrogen. In the United Kingdom, [Turner et al. \(2019\)](#) 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 policymakers, businesses and publics. [Swennenhuis et al. \(2020\)](#) similarly suggest that presenting CCS within a narrative of a just transition for workers and communities reliant on carbon-intensive industries may build support, a strategy that could be explored for hydrogen too.

4.2 Messages for the hydrogen storage sector

A nebula of issues surrounds societal and community acceptability of new technologies. What is critical to note is that issues of perceived risk are often closely linked to questions of trust, efficacy, and fairness. Understanding these issues, and what hydrogen developers, regulators and policymakers can do to allay, adapt, or address concerns, will be fundamental to the roll out of hydrogen storage and the wider hydrogen economy. 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 for dialogue with communities and stakeholders proximate to proposed developments; and also with key opinion-shapers (e.g., NGOs, media) at a national or regional level. Such dialogue builds trust and deepens understanding of both publics’ and developers’ understandings, concerns and proposed responses. This dialogue improves understanding of the project context, including familiarity with energy or resource industries. What is especially important, however, is that engagement is not “closed down” to a narrow focus on technical factors, and that industry and governments are able to demonstrate they are able to make tangible changes to projects (or at least to engagement strategies) in response to societal concerns;
- *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. Conversely, it should also be remembered that non-experts can quickly understand and engage with complex issues relating to energy and the subsurface. Engagement and communication that is perceived as overly simplified or patronising may be viewed with suspicion;

- *Complex concepts:* New, complex or unfamiliar concepts can affect perceived risks. For example, risk of gas leakage or conceptualising the subsurface is typically unfamiliar and therefore challenging for non-specialists to conceptualise. Such topics should be identified early so as to enable the design of effective communication tools and approaches. Again, however, the dangers of oversimplifying communication tools or of trying to “oversell” a technology should be borne in mind. It may instead be more effective to aim to empower communities, stakeholders and wider publics with the knowledge they need to come to their own informed standpoint on the merits or otherwise of hydrogen;
- *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 ([Flynn et al., 2006](#)). Further, to quote [Reiner \(2015\)](#):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.” Demonstrator projects can also help to overcome the scepticism that subsurface technologies are unviable or cannot reach deployment stage ([Gonzalez et al., 2021](#));
- *Trust in operators and regulators:* As for any emerging technology or any new development, a project will be affected by trust in the governing institutions. 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 analogous technologies suggest that these perceptions will vary with scale and context, for example having a demonstrable track record. Under a climate emergency and a cost-of-living crisis, the sincerity in the motivations of operators from the energy sector in particular is likely to come under intense scrutiny from NGOs, the media and pressure groups operating at a national or regional level. This is especially so if projects are supported in part by public funds;
- *Blue, green or black:* Public attitudes may be more positive or hostile depending on the hydrogen source. The underground storage of hydrogen generated from

renewables (green hydrogen) or biofuels will likely be much more widely acceptable than the storage of hydrogen generated from fossil fuels (black hydrogen) or fossil fuels with CCS (blue hydrogen). Clarity on the hydrogen source involved in projects, and ideally a clear pathway towards the least carbon-intensive forms of hydrogen, may hence help to build support and demonstrate the climate benefits of a project;

- *Impacts and Benefits:* Societal and community perception will depend on the perceived negative and positive impacts, both to the host community and to the region or country more broadly. These might be in terms of economic or social gains, or environmental fit. For example, 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. More generally, lack of local benefit from investment in infrastructure such as CCS and hydrogen will challenge societal and community acceptability, especially for localities that have been heavily reliant on fossil fuel jobs and who will expect to see local employment and financial benefits as part of a just transition. Examining developments through a social justice lens will reduce risk of developments hindering a just transition to net zero.

4.3 Limitations of technocentric analogues

We have focused in this paper on technocentric analogues for the geological storage of hydrogen, especially CCS and UGS. There are, however, limitations to what can be understood from these analogues. Firstly, as noted by [Esteves et al. \(2012\)](#), the operational and closure phases are an equally important part of community engagement with developments. The lack of large-scale CCS projects (not related to fossil fuel production) that have reached operational yet alone completion stage, and the limited body of literature on the societal aspects of later stages of UGS, mean that there is only limited insight from these analogues as to the broader issues that geological storage of hydrogen projects may face once they are up and running. Indeed, one could argue that the CCS literature in particular has been skewed towards “acceptance” of new CCS projects, and not enough towards what happens once projects are in operation.

Second, although we have previously suggested that a history of an operator working on subsurface energy issues in a locality may make it more likely for communities to engage with new subsurface developments, it must not be assumed that this will always be the case. A social licence to operate

cannot directly be “transferred” from one development to another, even if there may be links ([Gough et al., 2018](#)). This is especially so in the context of an energy crisis and a climate emergency. Oil, gas or coal operations will likely have commenced several decades previous, when community and civil society concerns over climate change were much less visible than they are today. Therefore, it should not be assumed that because an analogous fossil fuel development was able to proceed in the past, that there will be similar support for developments such as hydrogen storage that are happening against much more vocal calls for a just transition and rapid move away from fossil fuels (see e.g., [Swennenhuis et al., 2020](#)).

5 Conclusion

The review of existing scholarship around CCS and UGS illustrates the importance of early and thorough consideration of societal issues prior to deployment of hydrogen storage in support of a potential future hydrogen economy. Risk perception is of course just one factor among many driving societal views towards new and potentially unfamiliar technologies such as geological hydrogen storage. Moreover, risk perception has also been shown to be influenced by a wide range of contextual factors relating to society and culture. 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 and an acknowledgement that communities and stakeholders will expect their own knowledges and concerns to be respected within the engagement and decision-making process. 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 and a clear rationale for how hydrogen benefits the climate and the most vulnerable members of society under an energy crisis, will aid the likelihood of underground

hydrogen storage gaining societal acceptance, as well as the broader expansion of the hydrogen economy.

Data availability statement

This work is a synthesis of research experience and from the intersection of geological experience and research into social license to operate. It has not used specific data sets or generated data.

Author contributions

All authors participated in the development and design of the paper. LS led the writing, JR and LM provided additional material and references on the social aspects. PH provided information and materials on the context of the hydrogen industry and access to the figures.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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