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Social science for a hydrogen energy future

A review of existing knowledge, potential risks from society's response, and science pathways for social responsibility

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Executive summary

Hydrogen fuels could become a reliable part of a future low emission energy mix. Australia has many potential applications for hydrogen energy technologies: from private, public and long-haul transport to household electricity and export. But for hydrogen energy to succeed in Australia and benefit the economy, it is imperative to gain public acceptance and for the technology to be adopted.

It is difficult to know how the public will respond to hydrogen energy technologies, because relevant research is limited, especially in Australia. Today, innovation also needs to be socially responsible. For hydrogen energy, this means the technology must be safe, environmentally friendly, and above all accepted and valued by society, including industry and government.

This report outlines the key issues that could affect the current and future level of acceptance and adoption of hydrogen energy, and presents pathways to address these issues. To do this, we reviewed available studies of the general public's perceptions of hydrogen technology, and interviewed industry and government representatives with a stake in future hydrogen technology.

Overall, we anticipate that the public could have a generally positive attitude towards hydrogen energy. However, the level of awareness of the technology is currently low, and social science research has shown that attitudes formed with low awareness are liable to change. This could pose both risks and opportunities for the reputation of hydrogen energy technologies in Australia. For example, it is known that a negative event early in a technologies introduction can cause public opposition, even when the technology has recognisable benefits. Additionally, considerable growth in understanding may be required to move beyond attitudes based on concerns.

The main influences on future acceptance and adoption of hydrogen energy were found to be perceptions of environmental benefit, especially in regard to renewable versus non-renewable hydrogen production; safety and cost. As communicated by interviewees from industry and government, risks can also arise early, from under-informed attitudes. Early, effective communication is therefore imperative to increase awareness and understanding of hydrogen energy. In the telling words of one interviewee: *"If the public perception is poor, it doesn't matter how good hydrogen is. Perception is reality."*

Keeping in mind the critical need for social responsibility, three research pathways are suggested. First, in order for hydrogen energy technologies to have the best chance of a positive reputation, more social science research is needed to identify early attitudes and concerns, and explore the best ways to communicate hydrogen energy initiatives. Second, to understand the conditions of acceptance, research is required of the perspectives of communities where hydrogen activities are planned. Third, to identify the decisions that lead to adoption, collaborations should be pursued with early adopters, consumer advocacy and industry groups, project proponents and government. The knowledge gained from following these pathways could help guide future decisions of industry, government and the public. This will enable socially responsible practices and policies to be developed that could successfully introduce hydrogen into the Australian energy economy.

1 Introduction

Australia has many potential applications of hydrogen energy technologies: from private, public and long-haul transport to household electricity and export (Commonwealth of Australia, 2018). The benefits of a hydrogen economy are also many, including new industries and jobs, export opportunities and low emission energy options. For hydrogen energy to succeed in Australia, it is imperative to gain public acceptance and for the technology to be adopted.

This report documents the key issues that could characterise the public's response to the introduction of hydrogen energy in Australia. To identify risks to the acceptance and adoption of this technology, we have drawn on a review of existing literature and a series of interviews with industry and government stakeholders. We also outline pathways for applying social science to reduce these risks and to increase the capacity of industry, government and the public to manage this transition.

The report is funded by the CSIRO's Hydrogen Energy Systems Future Science Platform. The Platform is delivering science research and outcomes to underpin hydrogen's emerging role in Australia's energy economy.

1.1 Projections of an increased hydrogen energy presence

Economic analyses signal a positive trajectory for hydrogen energy technologies in Australia.

Examples include the *National Hydrogen Roadmap* (Temminghoff et al., 2018), *Hydrogen for Australia's Future* (Commonwealth of Australia, 2018) and *Opportunities for Australia from Hydrogen Exports* (ACIL Allen Consulting for Australian Renewable Energy Agency (ARENA), 2018). As the presence of hydrogen energy technologies increases, Australia is expected to become part of the global hydrogen economy. Figure 1 provides a snapshot of the type of initiatives and locations in which investment in hydrogen energy has commenced or is planned. As reflected in the mapped examples, these initiatives are likely to facilitate export, transport and household electricity applications. Increased public awareness of these technologies seems inevitable.

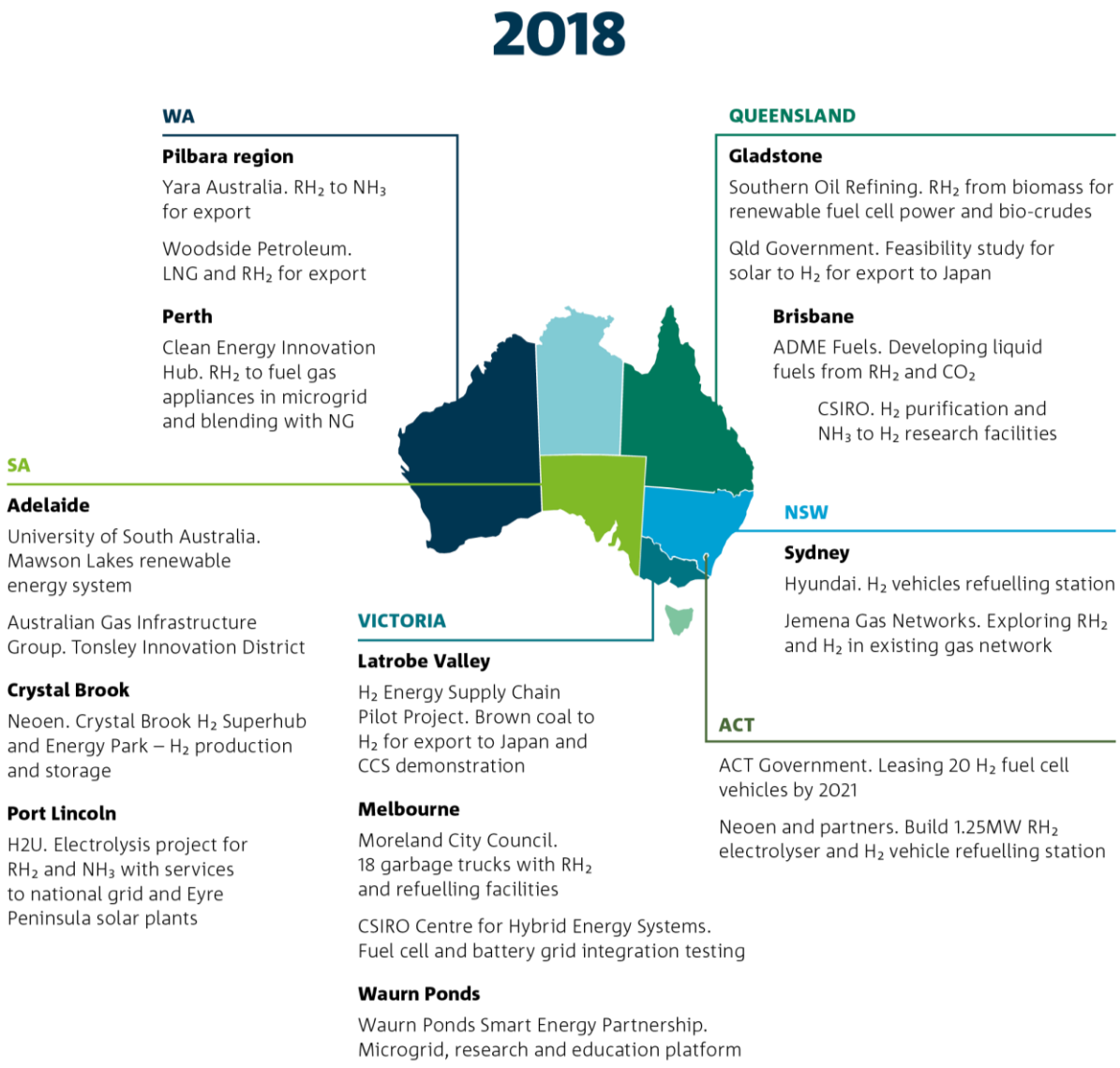

Figure 1. Examples of existing or planned hydrogen energy-related initiatives across Australia, LNG is liquid natural gas, NG is natural gas, and CCS is carbon capture and storage

Sources: Commonwealth of Australia (2018) and Temminghoff et al. (2018)

1.2 Socially responsible research and technology

This report outlines pathways for how social science can be applied to deliver science research and outcomes, such as new technologies, in a socially responsible way.

When scientific research institutions, such as CSIRO, develop technology, they must be aware of and responsive to any societal changes the technology might generate. This approach has been termed responsible innovation (see CSIRO, 2018a; 2018b). To take this approach, the people who develop the technology and the people responsible for making it available, work together with stakeholders, to find out if the technology is sustainable, acceptable and wanted by society. They must determine if the technology is safe, what impacts it might have on people and the environment, and if the overall positive impacts outweigh the negative.

Despite the importance of a formal and applied understanding of responsible research and innovation, such an understanding – specific to hydrogen energy and in the Australian context – is still emerging. In contrast, the economic and technical aspects of the emerging role of hydrogen in Australia's energy economy are well established, and have been documented through reports such as:

- CSIRO's *National Hydrogen Roadmap* (Temminghoff et al., 2018)
- *Hydrogen for Australia's Future* (Commonwealth of Australia, 2018), a briefing paper for the Council of Australia Governments Energy Council led by the country's Chief Scientist
- *Opportunities for Australia from Hydrogen Exports* (ACIL Allen Consulting for ARENA, 2018), a report prepared for ARENA on export opportunities.

The first two reports cited above did consider some aspects of the social response to these technologies. CSIRO's *National Hydrogen Roadmap* described the importance of a social licence, while *Hydrogen for Australia's Future* offered a current, detailed analysis of the Australian public's perceptions of emerging technologies. The analysis was also extended through a national survey, reported in *The Australian public's perception of hydrogen for energy* (Lambert and Ashworth, 2018).

To further understand the potential social response and emerging social responsibilities associated with hydrogen energy, we reviewed the current state of knowledge about how the Australian public perceives hydrogen as part of Australia's energy system. In addition to analysing existing literature, we interviewed key industry and government representatives to make up for the scarcity of studies specific to Australia.

Next, Section 2 of this report presents the results of our literature review, while insights gained from interviews with industry and government representatives are given in Section 3. Based on our research, we identified barriers to the effective adoption of hydrogen energy technology. In Section 4 we outline suggested pathways for applying social science to mitigate these risks and increase the capacity of industry, government and the public to manage the transition to a hydrogen energy future.

2 Society's perceptions of hydrogen energy technologies

As outlined in Section 1, if hydrogen energy systems are to realise their potential in Australia and globally, they need to be accepted and adopted across the public, industry and government. The main factor considered here is society's perceptions of the technology, and how these perceptions are influenced.

The term 'hydrogen economy' has roots back to the 1970s when the term was coined by John O'M. Bockris, the pioneering electrochemist (Bockris, 2013). However, it did not receive much academic interest until the early 2000s, when a combination of energy security, environmental concerns, and economic possibilities propelled the academic discussion. Accordingly, the number of scholarly articles exploring the key term of 'hydrogen economy' has grown substantially in the past two decades (Figure 2), from fewer than 200 published in the year 2000 to more than 2400 published in 2017, with a 10-fold increase from 2001 to 2007. The rapid growth coincides with a number of hydrogen demonstrations in the early 2000s. While the hydrogen economy had a rapid increase in interest in the early to mid-2000s, 'renewable hydrogen' has had a steadier increase in interest and publications. The economics and fundamental technologies of hydrogen energy are vital to the eventual acceptance and adoption by industry and the general public, and there has also been a growing awareness in academia that social implications of these technologies are worth investigating. Though, the increase in academic publications has been significantly less for 'hydrogen social acceptance'. The slower growth in publications on 'hydrogen social acceptance' in part motivated this review.

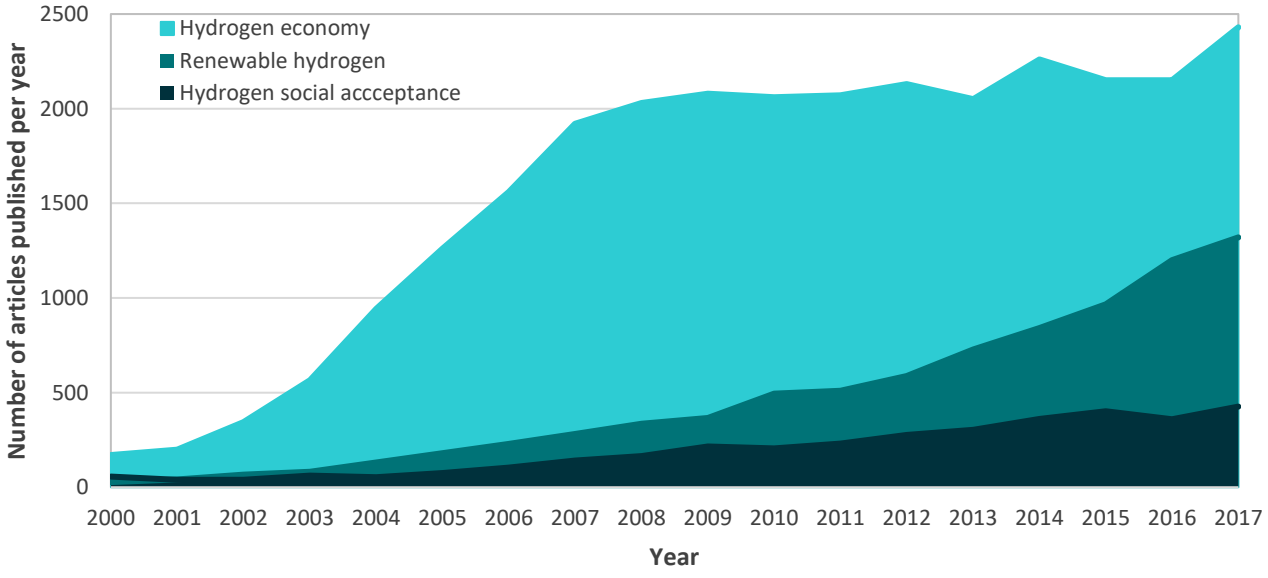

Figure 2. Number of peer-reviewed articles published on 'hydrogen social acceptance', 'hydrogen economy' and 'renewable hydrogen' per year (non-cumulative)
Source: Google Scholar online publications search, 21 August 2018

Research into society's perceptions of hydrogen energy has primarily consisted of studies in relation to trials or demonstrations of hydrogen fuel-cell vehicles and related infrastructure. These have been located around the globe, in locations including:

- Amsterdam (Heinz and Erdmann, 2008)
- Australia (Altmann et al., 2004; O'Garra, 2005)
- Barcelona, Beijing, Berlin (Heinz and Erdmann, 2008)
- Germany (Altmann et al., 2004; O'Garra, 2005)
- Hamburg (Heinz and Erdmann, 2008)
- Japan (Itaoka, Saito and Sasaki, 2017; Ono and Tsunemi, 2017)
- Luxembourg (Altmann et al., 2004; Heinz and Erdmann, 2008; O'Garra, 2005)
- Madrid (Heinz and Erdmann, 2008)
- the Netherlands (Huijts, 2018)
- Norway (Tarigan et al., 2012)
- Reykjavik (Heinz and Erdmann, 2008)
- Spain (Iribarran et al., 2016)
- Taiwan (Chen, Huang and Huang, 2006)
- United Kingdom (Altmann et al., 2004; Heinz and Erdmann, 2008; O'Garra, 2005; Ricci et al., 2010a)
- United States (Altmann et al., 2004; Hickson, Phillips and Morales, 2007; O'Garra, 2005).

Some studies also compared responses to multiple trials (Altmann et al., 2004; Bögel et al., 2018; Heinz and Erdmann, 2008; O'Garra, 2005).

At the time of reporting, in the Australian context, there have been two initiatives: a study of the perceptions of a hydrogen bus trial in Perth, and a report on the Australian public's perceptions of hydrogen for energy.

The Perth bus trial, held from 2003 to 2005, was part of the 'Accept H_2' trial of hydrogen buses, also used in Berlin, California, London and Luxemburg. Publications of findings that included the Perth trial were a conference paper (Altmann et al., 2004) and project report (O'Garra, 2005). Findings specific to the London trial were also published (O'Garra et al., 2005, 2008).

The Perth study involved 300 questionnaires administered before the trial (between July 2003 and February 2004) and six months after the trial commenced (between July 2004 and February 2005). In the initial survey, 49% of respondents were generally bus users (55% in the latter survey). The survey's topics were: bus usage, attitudes towards existing buses in each city, perceptions of the word 'hydrogen', awareness of hydrogen fuel-cell vehicles, and attitudes towards the potential large-scale introduction of hydrogen buses in each city.

The main findings of the Accept H_2 study included the following:

- In the post survey, of all the trials, Perth participants reported the highest levels of awareness of hydrogen vehicles, with 59% of general bus users and 54% of non-bus users being aware. The researchers suggested that the higher levels of awareness may have been due to the visibility of the trial, as Perth is a smaller city compared with other cities in the Accept H_2 trial, and a communications campaign was held to promote 'Accept H_2'.
- The researchers suggested that increased awareness and knowledge over the course of the trial was linked with increased support for the hydrogen technology trial.

- There was a willingness to pay an average of $28.94AUD more in taxes to cover the cost of H_2 powered buses, and this did not change significantly during the trial. However, ~20% of people disagreed with paying more.
- Direct experience of H_2 powered buses did not significantly impact attitudes or preferences towards H_2 powered buses.

The 2018 report entitled *The Australian public's perceptions of hydrogen for energy* (Lambert and Ashworth, 2018) was commissioned by ARENA. The report included a literature review, findings from focus groups with members of the public and a nationally representative survey.

A total of 10 focus groups were held in June, 2018: three each in Adelaide and in Melbourne, and two each in Whyalla (South Australia) and Traralgon (Victoria). Of the 92 participants, 55 were females and 37 were males, with ages ranging from 20 to 76 years with an average 44 years, and employment situations were diverse. The focus group findings were included in a briefing paper, *Hydrogen for Australia's Future* (Commonwealth of Australia, 2018), which was presented to the Council of Australian Governments' Energy Council. In summary, the focus group participants:

- were positive, yet cautious; they sought responses to concerns such as the safety of the proposed technologies
- reported that the consideration of environmental benefits was important, as was the fair sharing of economic benefits
- conveyed a role for government regarding regulation, R&D funding and incentives for early adoption
- expressed the need for more information about the transition to hydrogen energy.

The focus groups, combined with a review of existing literature, informed the development of a national survey (2,785 participants) that explored the Australian public's perceptions of hydrogen for energy. The leading finding was that the public are likely to be supportive of hydrogen for energy across export, transport and household use. The following insights were gained from the national survey:

- The strongest level of support for specific applications was for export and transport (including fuel-cell buses and long-haul trucks), with less support for household use (including hot water heating and on-site electricity generation).
- The strongest level of support for specific production methods was for renewable energy and electrolysis only, with less support for the use of fossil fuels with carbon capture and storage as an intermediate step or indefinitely.
- The leading benefit was perceived to be environmental, including the potential for addressing climate change.
- The leading concern was perceived to be safety, although the majority perceived the existing safety precautions to be adequate.

After reviewing the Australian-specific studies and trials from around the globe, we identified three main concepts that were vital to anticipate or explain the public's responses to hydrogen technologies:

1. initial attitudes and perceptions of hydrogen and its role in the energy system
2. acceptance by citizens and the influences that explain these acceptance levels, such as infrastructure (e.g. fuelling stations) being installed
3. adoption by consumers and the influences that explain adoption of technology applications, such as vehicles for private use and public transport.

For each of these concepts, the contributions and boundaries of existing research follow.

2.1 Initial attitudes and perceptions

The primary social science research approach to gauging reactions to hydrogen, and hydrogen used to fuel transport, has been to measure initial attitudes of early demonstrations through community surveys.

Initial attitudes, which are often also measures of acceptance or adoption, have frequently been summarised as being positive. However, some respondents consistently report less agreement or even opposition to the technology (Altmann et al., 2004; Bögel et al., 2018; Heinz and Erdmann, 2008; O'Garra, 2005; Roche et al., 2010). These initial attitudes are often characterised by low levels of awareness, familiarity with and knowledge of hydrogen technology (Bellaby, Upham, Flynn and Ricci, 2016; Bögel et al., 2018).

The role of familiarity and knowledge in shaping attitudes to technologies is nuanced. For example, knowledge of mining technologies, such as in situ leaching and hydraulic fracturing, are shaped by how people perceive the impacts (Lacey et al., 2019). Attitudes were more accepting towards more established technologies, that people felt familiar with and informed about. Whereas, for emerging technologies, only a little information increased concerns. Considerable growth in understanding may be required to alleviate these concerns, and people who are confident of their views could be more likely to contest information about emerging technologies.

Low knowledge of hydrogen properties and low familiarity with hydrogen energy applications were observed in the national survey of the Australian public's perceptions of hydrogen energy (Lambert and Ashworth, 2018). Knowledge was measured using a series of questions about the properties of hydrogen, to which more correct answers were likely from males, people with university degrees, early adopters and those born overseas.

The perceptions of hydrogen coupled with these initial attitudes are most commonly neutral, for example in relation to water and gas (Altmann et al., 2004; O'Garra, 2005a). Also reported are negative perceptions that are consistent with concerns about safety (e.g. explosive) and positive perceptions, such as environmental benefits.

The Australian national survey in 2018 also reported that neutral perceptions were more frequent than positive or negative perceptions (Lambert and Ashworth, 2018). Specific to hydrogen's role in the energy system, research participants commonly reported positive environmental perceptions (Hickson et al., 2007; Zachariah-Wolff and Hemmes, 2006). However, concerns about safety were also expressed (Ricci, Bellaby and Flynn, 2010b). For example, in the 2018 survey of the Australian public, the leading benefit was environmental, including the potential for climate change mitigation and the leading concern was safety, although the majority thought the precautions would be adequate (Lambert and Ashworth, 2018). Emotional reactions, both positive and

negative, have also been identified as an important part of acceptance of hydrogen energy technologies (Huijts, 2018).

2.2 Influences on citizen acceptance

Citizen acceptance reflects the public's response to technologies, such as hydrogen refuelling stations or buses, placed in their environment at the discretion of others (Huijts et al., 2012). Studies of citizen acceptance have most commonly involved surveys of hydrogen energy technologies in private vehicles and public bus transport, with only a minority considering how the method of producing hydrogen is perceived (Zimmer and Welke, 2012) or a wider range of applications (Lambert and Ashworth, 2018).

As for initial attitudes, citizen acceptance was commonly reported to be positive (Altmann et al., 2004; Bögel et al., 2018; Hickson et al., 2007; Iribarren et al., 2016; O'Garra, 2005; Ono and Tsunemi, 2017; Tarigan et al., 2012; Thesen and Langhelle, 2008). However, the size of the supportive majority did vary substantially, and in the case of the Perth bus trials, 94% thought it a good idea to trial the buses but only 42% where supportive of the broad scale introduction of hydrogen vehicles, with most people wanting more information (Altmann et al. 2004). Whereas, in the recent Australia-wide study (Lambert and Ashworth, 2018):

- 72% of survey participants supported the export of hydrogen for energy
- ~70% were supportive of fuel-cell buses, and 65% of fuel-cell long-haul trucks
- ~60% supported use in the energy supply (hot water heating, on-site electricity and with natural gas)
- 57% agreed and 7% disagreed with hydrogen being produced using renewable energy and electrolysis only, 38% agreed and 19% disagreed with the use of fossil fuels with carbon capture and storage as an intermediate step, 25% agreed and 33% disagreed to such use indefinitely
- support for hydrogen as an energy solution was strongly dependent on knowledge of hydrogen energy technologies.

Several influences on citizen acceptance have been demonstrated across the world. Proximity (or location) had a complex influence, which may be shaped by trust in the safety of the technology. This has implications for perceptions of the benefits and risks (Montijn-Dorgelo and Midden, 2008) and support for local refuelling options (Tarigan et al., 2012).

For example, some studies reported that despite trust in the technology to store hydrogen, there was scepticism about storage near or in residential areas (Zaunbrecher et al., 2016). Conversely, there were at least two locations where closer proximity to vehicle refuelling technology was linked with increased acceptance (O'Garra et al., 2008; Tarigan et al., 2012; Thesen and Langhelle, 2008). Although the different distances tested in each study make comparison difficult, closer proximity may have been linked with a sense of ownership, when participants were informed and trusting, especially of the safety conditions and environmental benefits.

In the 2018 survey of the Australian public, most participants agreed with refuelling stations being located closer to residential areas; this convenient refuelling was also linked with purchase

intentions (Lambert and Ashworth, 2018). The majority also agreed there would be adequate safety precautions around the development of a hydrogen economy, despite some safety concerns. Tarigan et al. (2012) identified that the public's willingness to pay more for hydrogen fuel also increased the likelihood of acceptance. In the Australian national survey, 36.8% of participants reported being willing to pay more (Lambert and Ashworth, 2018). More information on proximity of refuelling stations to residential areas and the influence of willingness to pay is reported in Section 2.3.

Acceptance generally, not just acceptance of the location of activity, is also reported to be influenced by knowledge, and perceived benefits, risks and impacts of the technology/process.

Knowledge, perceived benefits and impacts were also themes in the recent focus groups reported on in *Hydrogen for Australia's Future* (Commonwealth of Australia, 2018). Fairness was another dominant theme, which is consistent with the technology acceptance framework (Huijts et al., 2012). For instance, unfairness was linked to feelings of anger and fear in the context of the first hydrogen fuel station in the Netherlands (Huijts, 2018). In the 2018 Australian survey, the main reported benefit was to the environment, particularly through reduced greenhouse gas emissions (Lambert and Ashworth, 2018). Leading concerns were safety, costs, and environmental impacts, including pollution, emissions and water use.

Research has also revealed socioeconomic influences on acceptance. The most consistent result has been for gender; males were likely to be more supportive (Hickson et al., 2007; Ono and Tsunemi, 2017) or report to be more informed (Altmann et al., 2004; Tarigan et al., 2012). In the 2018 survey of Australians, males were also more likely to be supportive and informed (Lambert and Ashworth, 2018).

Most of the above influences have already been identified as important for explaining the acceptance of energy technologies (Huijts, 2012). Additionally, most of these influences – specifically impacts, benefits, fairness and trust – have also been demonstrated to relate to the community acceptance of mining (Moffat and Zhang, 2014) and other industries. This concept is increasingly known as a 'social licence to operate' and can refer to a community's acceptance of an operation, but also acceptance at different scales such as regional, national and international (Moffat et al., 2018).

2.3 Influences on consumer adoption

Consumer adoption incorporates the notion of acceptance, but usually involves a choice to demonstrate a behavioural response, such as to purchase and use the technology or product (Huijts et al., 2012). Although some studies have focused on adoption (Brey, Brey and Carazo 2017), citizen acceptance has most commonly been measured, or both concepts have been combined (Iribarren et al., 2016; Kang and Park, 2011; Lambert and Ashworth, 2018). Additionally, some reviews present frameworks to explain acceptance and adoption (Huijts et al., 2012; Shaw and Mazzucchelli, 2010), including comparisons with other technology, such as liquefied petroleum gas (LPG; Hu and Green, 2011).

Like the studies that considered initial attitudes, perceptions and citizen acceptance, most studies of consumer adoption have focused on the use of hydrogen energy in transport systems. This reflects how hydrogen fuel-cell vehicles are increasingly available globally (The International

Council on Clean Transportation, 2017). The exception to this trend was the 2018 Australian survey, which asked participants not only about their perceptions of hydrogen vehicles, but also of applications that could be relevant as an Australian hydrogen energy system emerges, such as hydrogen export and use in electricity generation (Lambert and Ashworth, 2018). Across these applications, the report noted the importance of safety, cost, and environmental benefits (except for long-haul trucks).

There were reports of willingness to pay more for hydrogen energy technologies and environmental benefit: 36.8% of participants reported to be willing to pay more if there were clear environmental benefits, 39.4% were unsure and 23.8% were not willing to pay more (Lambert and Ashworth, 2018). This trend was also apparent in the context of comparable costs being described as important.

In relation to hydrogen-fuelled private vehicles, influences on adoption often include environmental benefit, which in the Australian context referred to reduced air pollution and reduced greenhouse gas emissions (Lambert and Ashworth, 2018). Other studies report the importance of perceived environmental benefits in different ways. For example, in a study of citizens in Spain, this importance was expressed as a personal commitment to the environment (Iribarren et al., 2016), while in Korea, it was expressed as being respected as someone who was contributing to conservation (Kang and Park, 2011).

Cost also includes both the cost to purchase the vehicle and refuel, compared with existing vehicles (Lambert and Ashworth, 2018). Both purchase price (Iribarren et al., 2016) and running costs influence adoption (Hardman et al., 2016), notably more so if consumers are not motivated by environmental benefits (Kang and Park, 2011). The importance of costs has also been compared with the adoption of LPG as a transport fuel (Hu and Green, 2011). Modest levels of willingness to pay for hydrogen vehicles and refuelling stations have also been observed, although these studies have sometimes lacked direct comparison of hydrogen with conventional options (Tarigan et al., 2012; Yang, Cho and Yoo, 2017).The 2018 survey of Australians (Lambert and Ashworth, 2018) and other studies reported that general vehicle performance was also important (Kang and Park, 2011), as was convenient refuelling (Brey, Brey and Carazo, 2017; Hardman et al., 2016).

A final factor noted by the research related to transport were bus fares of hydrogen-fuelled buses. On average, there was some support for willingness to pay more, though this was rarely tested in direct comparison to conventional buses (Altmann et al., 2004; Bigerna and Polirnori, 2015). An important consideration for perceived cost of hydrogen-fuelled public transport is its comparison to other emerging alternative technologies, such as electric vehicles (Lambert and Ashworth, 2018).

For household applications, the Australian national survey identified the cost of hydrogen being comparable to gas as important to the public (Lambert and Ashworth, 2018). Other factors of note were the impacts on household appliances (e.g. whether new appliances would need to be purchased).

All the influences mentioned in this section centre on individual consumers. To facilitate adoption beyond the scale of the individual, the support of local authorities and alignment with the interests of community are important (Lambert and Ashworth, 2018; Shaw and Mazzucchelli, 2010). For this reason, it's important to understand the insights that Australian government

organisations and industry can offer towards the potential for acceptance and adoption of hydrogen energy technologies. The next section describes the results from interviews with industry and government representatives involved in the hydrogen industry about their expectations and experiences of public responses to hydrogen energy technologies.

3 Insights from industry and government

The review in Section 2 highlights that further insights into the Australian context are required, as limited local studies have been conducted. Also highlighted is the lack of perspective from industry and government, both of which are instrumental to the early development of the industry in Australia.

To complement our literature review, we therefore interviewed industry and government representatives about their knowledge, experience and perspectives of how hydrogen energy technologies are accepted and valued by society, including how they are likely to be received by Australians. Interviewees were identified through referral from hydrogen industry experts. We used a semi-structured approach to support our focus on predetermined topics while also inviting unanticipated perspectives to emerge (Brinkmann, 2018).

Overall, we conducted 14 interviews. The average time taken for each interview was 59 minutes; the shortest was 23 minutes and longest 90 minutes. To welcome varied views, we sought interviewees from across the hydrogen energy value chain: from production, storage and transport, markets and different areas of government.

Consistent trends in participants' responses began to emerge after seven interviews. Further interviews were conducted, including with stakeholders recommended by earlier interviewees, which clarified the general trends and themes. The themes were primarily analysed by one researcher, using the qualitative analysis software NVivo. The reliability of the analysis was confirmed by a second researcher through repetition of analysis and comparison with previous results, and a third briefly checked the analysis. The next five sections summarise the leading insights from interviewees, which fell into the following themes:

- Hydrogen energy is an emerging technology, unknown to most
- Anticipation that awareness will bring mixed perceptions
- Perceived risks to acceptance
- Perceived risks to adoption
- The comparative importance of public perceptions.

In each section below, summarised are the common trends in responses, including the percentage of interviewees who held the same view and selected representative quotes from interviewees.

3.1 An emerging technology, unknown to most

Theme (percentage of interviewees)	**Representative quotes**
The public are likely to have no awareness (57%) or nearly no awareness (64%) of current activity in Australia to advance hydrogen as an energy carrier	"*On a scale of 1 to 10, 1 being the least (awareness) and 10 being the most, I would say 0.5 to 1.*" "*I think there's been a lot of ongoing debate about our mix of generation because there is very good*

	understanding of wind, solar, coal, gas and now battery storage, but I don't think there's a good understanding of hydrogen technology."
The public are likely to have no or nearly no awareness of the potential role of hydrogen in Australia's energy future (50%)	*"…no awareness of the technology and no awareness of the opportunities that it presents."*
The Australian public have no awareness (50%) or nearly no awareness (43%) of activities overseas	*"…very unaware of what's happening around the world."*
There is likely to have been a recent rise in awareness with the increase in activities such as demonstrations, science breakthroughs, reports and related communications (64%)	*"In terms of Australia's awareness of hydrogen and exploration of it as a topic, I'd say there's been an explosion in the last three to six months."*
Low awareness of hydrogen technology is both a risk and opportunity (36%), and industry/government has a role in facilitating direct engagement and informed decision-making (43%)	*"I think that awareness is low and unless there's vision that actually highlights this as an opportunity and something that people hear about, once that happens I think people will start to understand a bit better."*

3.2 Anticipation that awareness will bring mixed perceptions

Theme (percentage of interviewees)	**Representative quotes**
Awareness will come with acceptance (64%)	*"People that drive into a refuelling station and see, '…it just came in and charged up with hydrogen. Wow. Who knew? Cool.' So I think in those instances there's probably more awareness and acceptance."*
Some concern for safety will be raised (86%). These mainly involved the potential for accidents, explosion and leaks	"*…Hindenburg, concerns around vehicles on the roads with tanks of hydrogen gas within them… having some concerns around the handling of hydrogen, should it escape."*
Positive perceptions included attitudes relating hydrogen to school chemistry (28%) and those from 'techies' or 'early adopters' (14%)	*"…the majority, at least are able to define that it's an element that we have in the environment."* *"People with a technical bent would understand what hydrogen means…"*
Negative perceptions could include the potential for confusion with other energy technology (21%) or about the sources of energy involved in a hydrogen energy system, for example, that while renewable sources are a likely source, so are fossil fuels (14%)	"*If you are interested in developing a hydrogen economy, it needs to be a story about a clean, green future for fuel. But I also understand that it needs to be, in the first instance, because of the reality, to be brown. Then there should be objectives in place to transition towards 100% clean hydrogen."*

3.3 Perceived risks to acceptance

Theme (percentage of interviewees)	Representative quotes
Most often cited was the risk of safety (43%) and benefit of renewable energy (36%)	*"…once people start seeing that it's safe and it is decarbonised, it's a good news story and if we can export it and it becomes a provider of net jobs for the country then I think everyone will get on board..."*
Different energy sources could introduce the potential for confusion and reduce acceptance (14%)	"*People can understand the green side of solar and wind and splitting water…the social licence on either you know, gasification of coal, in particular the gasification of coal and capturing the carbon and sequestering it, as I said, big social license question there…"*
Cost competitiveness (28%)	"*It's still quite expensive. Acceptance also relates to economics. So that's going to be challenging going forward, but we have to invest, we have to start somewhere to ensure the prices start dropping."*
Require supporting infrastructure (21%), usability (14%), negative development impacts (e.g. noise) and general potential for misinformation (14%)	"*Depending on what your production system is there might be some impacts … one thing I did notice actually…is how noisy the hydraulic compressors are… if you need to have those as part of a fuelling station or a production plant that's quite a disruptive noise for anyone who's nearby."* *"…whether it's deliberate misinformation or just pure misunderstanding, … there is a knowledge gap for the general public with regards to hydrogen, particularly related to safety, but also related to utilisation and source."*
Widespread level of engagement needed to increase acceptance (21%), including roles for industry (14%), industry perceptions (7%), government (14%) and media (14%)	"*…we're talking about starting a whole new industry in Australia based on a technology which people aren't familiar with, then I think engagement has to be much more widespread to get people comfortable."*
Importance of recognising what stakeholders, particularly people most impacted, consider as fair process and procedures for decision making: • when used for exporting energy, fair process would be less central to acceptance as the public would be generally unaffected (7%) • transport affords choice of many products and companies, so the need for fairness in processes is perhaps limited (14%) • if used in the domestic gas and electricity network, the benefits may be	*"…I think that we actually have a role to play in improving choice rather than denying consumer choice."* "*…hydrogen is going to provide services and benefits to the electricity network, which benefits effectively everyone in the country. Whereas, people who are likely to pay for the infrastructure to support that are the gas users. So it's a very difficult one to figure out how fairness would work…"* *"10% injection of hydrogen into the grid shouldn't theoretically have any impact on appliances or people's experience of cooking or heating."*

derived by users that do not necessarily pay for the full costs (14%) • if used in the domestic gas network, procedural fairness could be influential at a concentration of H_2 greater than 10%, as anything less would generally not affect current domestic appliances (36%)	

3.4 Perceived risks to adoption

Theme (percentage of interviewees)	Representative quotes
Risks to consumer adoption (of hydrogen vehicles): most often cited was accessibility (28%) and cost competitiveness (28%). Others included safety (14%) and the benefits (14%) of renewable sources, and useability, as in functional for the purpose (7%)	*"I suspect at the end of the day, like everything, it has to make economic sense for individuals before they make investment decisions."* *"They're developing these vehicles to use them. So because of that, if nothing else, I think we're going to have a situation where with great ease we can have people driving these vehicles."*
Risks to industry adoption: most often cited was cost, specifically commercial viability at scale (50%). (Note that comments on cost were often generalised and not specific to any one application, though some references were made to transport costs.) Other influences were: • reliability, in the context of transport and electricity supply (21%) • policy signals that support investment (21%) • investment generally (21%) • the presence of demand (14%) • risk diversification (14%)	*"The technologies are there, it's putting together a solution that makes financial sense or you can see it will make commercial sense in the future…"* *"…if I can't find ways to refuel my vehicle along the way that's going to be a problem for me."* *"I think the models that have worked quite well in other parts of the world are everybody has got to have skin in the game...the whole supply chain, including governments, needs to throw their hat in the ring through some capital and take some risk in the early stages and you can de-risk projects by having some government support."*

3.5 The comparative importance of public perceptions

Theme (percentage of interviewees)	Representative quotes
Public perceptions are of similar importance to other aspects of the technology (72%) Other factors deemed important were: • the combination of adoption and economic feasibility (43%)	*"…if you don't have consumers on board and happy with hydrogen, and providing a social license for hydrogen within our cities, you could actually have people stopping development in these early stage projects that are required to actually prove the technology to build an export market."*

• education of both public and government (21%) • market value proposition (28%) • cost competitiveness (14%) • market demand (14%)	"*If the public perception is poor it doesn't matter how good hydrogen is. Perception is reality."* *"I think all these companies are doing it because they're seeing a future where carbon is constrained…so they need to, they need to diversify their risk."*
Other aspects of public perceptions, which were deemed as critical (72%), included: • social licence • the need for a general respect for the public • the challenge of delivering all the elements of a new energy system together • the potential for education to play a leading role	"*…out of respect, if nothing else, communicating with the public, explaining things is absolutely critical...but also then as well, you'd want Australia to be behind an Australian technology…in my view it is more critical than anything else."* "*…the technology is just as important as government support, education, having a vehicle on the ground and having the opportunity to utilise it…it all needs to happen at the same time in order to make the energy system work. The challenge lies in…which one do you start first and my general opinion is that education plays that major role."*

4 Discussion

This report set out to define the existing state of knowledge and the issues that could characterise the Australian public's response to hydrogen energy technologies. Here, we summarise the findings from our literature review and interviews. We then discuss the barriers to meeting the social responsibilities of the energy transition to hydrogen, along with pathways for applying social science to mitigate these risks and increase the capacity of industry, government and the public to navigate the journey towards a hydrogen energy future.

4.1 State of knowledge

In our review, we identified that a major limitation is the lack of mature social research about how people are likely to respond to hydrogen energy technologies. Research specific to the Australian context is particularly lacking.

There has been some research of how citizens and specific consumers respond to hydrogen energy technologies and related infrastructure, particularly international trials (Altmann et al., 2004; Bögel et al., 2018; Heinz and Erdmann, 2008; O'Garra, 2005). However, the volume of this literature is small in comparison with that published on aspects such as the hydrogen economy.

Consistent with hydrogen energy technologies yet to reach at-scale deployment in Australia, the opportunity to research the response of general citizens or adoptees has been limited to the Perth (and international) bus trial (Altmann et al., 2004; O'Garra, 2005), and the more recent ARENA-commissioned study of the Australian public's perceptions (Lambert and Ashworth, 2018). The latter is the only Australian study and one of few internationally to consider the applications and production methods that are likely to be trialled in Australia. This includes the acceptance of export, transport and household uses, and attitudes to both renewable and fossil-fuel production.

Adding to the lack of Australian-specific social research is the emerging nature of the technology transition, and what social responsibility will mean during this transition. This is important as we know attitudes are liable to change (Allansdottir, Pellizzone and Sciullo, 2018; Devine-Wright et al., 2017; Huijts, 2012), and some of this change is defined by how people form their knowledge of the technology (Lacey et al., 2019).

Despite the limits of our existing understanding, we have identified three main concepts that have been used to describe and explain responses to hydrogen energy technologies:

1. initial attitudes to and perceptions of hydrogen and its role in the energy system
2. influences that explain citizen acceptance of hydrogen developments, such as fuelling infrastructure
3. influences that explain consumer adoption of hydrogen applications, such as hydrogen fuel-cell vehicles for private use.

Tables 1 to 3 summarise the current understanding from existing research and insights gained from informed interviewees for each of these three sets of concepts.

Table 1. Current understanding of initial attitudes and perceptions

Existing research	Insights from interviews
• Attitudes are commonly positive, though there can be opposition, and awareness or knowledge is frequently reported as low • In response to 'hydrogen', neutral perceptions are most common, followed by negative perceptions (including safety concerns) and positive perceptions • Positive environmental perceptions are common in response to hydrogen when described as part of the energy system	• Public perceptions and influences such as economic feasibility are important for the increasing demonstration of hydrogen energy technology at scale • The concept of hydrogen energy technologies being unknown to most is both a risk and an opportunity. Increased awareness could bring a mix of positive perceptions, concerns and confusion • Environmental benefits and safety concerns are anticipated to be common themes in early perceptions

Table 2. Current understanding of influences on citizen acceptance

Existing research	Insights from interviews
• Knowledge, perceived benefits (environment), risks (safety) and impacts are the leading influences on acceptance of vehicles for private use, public transport and related infrastructure • Often related to these is the influence of infrastructure location and familiarity with the technology, with the public's safety concerns conflicting with their preferences for conveniently located fuelling infrastructure • In the Australian context, export activities, long-haul trucks**,** domestic use and production methods also influence acceptance • Production methods that link to environmental benefit have received limited research; in the Australian context, research suggests there is more support for production that uses renewable sources	• Applications extend beyond vehicles for private use and public bus transport to industrial or commercial transport, household use and export • The most common potential influences on acceptance are environmental benefits and safety • There is a need for engagement and fair process, and to determine how this may need to vary according by application

Table 3. Current understanding of influences on consumer adoption

Existing research	Insights from interviews
• Most contributions focus on adoption of vehicles for private use or the use of public buses. Australian research also gives insight into factors important for adoption of long-haul trucks and domestic use • Cost and safety are important factors for the adoption of all applications • For private vehicles, environmental benefit, access to infrastructure and usability is also important • For domestic use, the need for choice is also important • Some people are willing to pay more for hydrogen fuel and bus fares, although across all applications, comparative costs are important	• Accessibility and cost competitiveness of hydrogen vehicles are the most commonly acknowledged influences on adoption for private use • In commercial use, cost at scale is the most important influence • Reliability of both transport and electricity applications is an important influence • For domestic applications, the need for choice is important

The two major findings applicable to the Australian context are:

- initially, positive attitudes are likely, but these coincide with low awareness
- leading influences on acceptance and adoption are likely to be environmental benefit, safety and cost.

Most studies, internationally and in Australia, identified that perceptions of hydrogen were frequently neutral or positive towards hydrogen as part of the energy system, and the majority of people generally indicated acceptance. These positive attitudes co-occurred with low awareness, knowledge or familiarity. The likelihood of a generally positive response and low levels of awareness was also reflected by interviewees. However, attitudes are more accepting towards established technologies, that people feel familiar with and informed about (Lacey et al., 2019). Whereas, attitudes formed through limited experience and knowledge are liable to change in the face of increased exposure and information, so increased awareness can generate negative perceptions (Bögel et al., 2018; Devine-Wright et al., 2017; Huijts et al., 2012). Additionally, for some only a little information can increase concerns and people who are confident of their views may contest information, suggesting considerable growth in understanding may be required to move beyond attitudes informed by concerns (Lacey et al., 2018).

Although implemented differently across studies, environmental benefits were identified as the primary driver of both positive attitudes and acceptance, and one of the leading drivers of adoption. Safety, which also varied in its definition, was a common driver of negative attitudes and a condition of acceptance and adoption. Cost was consistently reported as the leading influence on preferences to adopt.

Other frequently reported important influences were:

- for acceptance, the location of infrastructure, trust in the technology and fairness of decisions (Huijts et al., 2012; Lambert and Ashworth, 2018; Tarigan et al., 2012)
- for adoption, the presence of supporting infrastructure and expectations about usability (Brey, Brey and Carazo, 2017; Hardman et al., 2016; Lambert and Ashworth, 2018; Kang and Park, 2011).

Many of these studies focused on a narrow range of hydrogen energy technologies: hydrogen fuel-cell vehicles for private use, hydrogen fuel-cell public bus transportation and the related infrastructure such as fuelling stations. The 2018 Australian study considered a wider range of applications, including export, household use, long-haul trucks, and both fossil-fuel and renewable production methods (Lambert and Ashworth, 2018). The interviewees in the current study gave similar insights to those gained from that report.

4.2 Risk implications and social science pathways

Our review identified that the introduction of hydrogen into Australia's energy economy could be well received. Evidence of this positive sentiment was reported most recently and specific to Australia by Lambert and Ashworth (2018). However, as identified in that report and in research of the acceptance of energy technologies generally, there can be risks to the acceptance and adoption of even the most beneficial of technologies (Devine-Wright et al., 2017; Huijts, 2012).

The current literature and insights from informed stakeholders suggest the leading risks are:

- early reputational risks from initial attitudes and perceptions
- risks to acceptance, adoption and realisation of benefits.

The risks from influences on early attitudes, acceptance and adoption can also be interrelated. For instance, transport applications could need to face wider community acceptance of hydrogen vehicles and related infrastructure as well as adoption by consumers. Citizen and consumers might also factor their awareness of different hydrogen production methods into their acceptance and likelihood to adopt. Also, the benefits and impacts of one application, such as export infrastructure, might influence the acceptance of other applications, such as hydrogen vehicles.

The implications of these potential risks present a constructive challenge for the emerging hydrogen energy economy. This is especially so in the current era, when society now expects corporate social responsibility from emerging industries and companies, and when the definition of responsible research and innovation is being deliberated (Allansdottir, Pellizzone and Sciullo, 2018).

Early reputational risks and opportunities

The positive, initial attitudes to hydrogen energy combined with low levels of awareness is a dynamic often observed across emerging energy technologies. While not problematic in itself, this can have implications for attitudes towards the technology, potentially shifting them to negative if an early event, such as a hydrogen gas explosion, raises concern (e.g. Devine-Wright et al., 2017; Huijts, 2012; Lacey et al., 2018). To move beyond attitudes informed by concerns, considerable growth in understanding may be required.

The industry and government stakeholders we interviewed knew and understood the potential risks arising from under-informed early attitudes. They were also aware that early communication is an opportunity to establish understanding, and with it the reputation of hydrogen energy. Table 4 describes a possible social science research strategy, or social science pathway, to identify in the Australian context early attitudes and their propensity for change. This could be done through representative surveys that test the effectiveness of different communication approaches.

Table 4. Social science pathway for early reputational risks and opportunities

Design	Application	Users

• Identify early attitudes; explain changes and preferences for communication of emerging initiatives, such as proposed export developments
• Sample would need to be representative of the general public or specific groups (e.g. communities where early demonstrations are planned)
• The research method would depend on the context:
  ○ initial interviews or focus groups in the early stages of actual demonstrations
  ○ online questionnaires to compare either hypothetical or actual experiences of communication approaches over time
	• Inform early communications of hydrogen's role in Australia's energy system generally, and of proposed specific demonstrations and trials	• Early interest groups such as:
		  ○ consumer, advocacy and industry groups
		  ○ project proponents
		  ○ government

Risks to acceptance and adoption

As explored by Lambert and Ashworth (2018) and highlighted by our interviewees, Australia has a range of potential hydrogen energy applications:

- private and public transport
- long-haul transport
- household electricity applications
- export to other countries for their transport and electricity use.

Additionally, the production methods of hydrogen can be both renewable and non-renewable. This has implications for the actual and perceived environmental benefit of these technologies.

Beyond Lambert and Ashworth (2018) there is a lack of research on the different influences on acceptance and adoption in the Australian context on topics which have also lacked inquiry internationally. As a result, there are many fruitful targets for new social science research into both acceptance and adoption. The social science pathway to identify influences on acceptance using stakeholder workshops and surveys is described in Table 5, while Table 6 details the pathway to identify the decision-making of those who may adopt the technology.

Table 5. Social science pathway to identify and reduce risks to acceptance

Design considerations	Application	Users
• Run stakeholder workshops and surveys, such as online questionnaires, to identify how influences such as environmental benefit, safety and location of infrastructure manifest in the Australian context, particularly for initiatives that have lacked research generally, such as export and different production methods	• Inform the co-design of stakeholder and community engagement and consultation for demonstration and trial initiatives • Include a set of best practice principles that companies and governments can use when considering hydrogen developments at a local or national level	• Project proponents • Regulating governments • Involved communities

Table 6. Social science pathway to identify and reduce risks to adoption

Design considerations	Application	Users

• Identify the decision-making processes that characterise adoption
• Run focus groups and surveys with early adoptees, and if applicable, with adoptees of varying demographic profiles, across a range of applications
	• Inform the design of applications for the Australian context and related communication materials and campaigns	• Organisations developing applications and enabling their adoption, such as:
		  ○ industry associations
		  ○ manufacturers
		  ○ regulators
		  ○ adoptees

4.3 Conclusion

The emerging role of hydrogen in Australia's energy economy could afford considerable benefits for society, including the potential to reduce greenhouse gas emissions, increase renewable energy exports, and assist in providing baseload power from renewable resources. However, despite these benefits and the potential for the technologies to be well received, the acceptance and adoption of these technologies cannot be assumed.

This report has documented the key issues that could characterise the public's response to the introduction of hydrogen energy technologies in Australia, drawing on a review of existing literature and a series of interviews with industry and government stakeholders. Based on this research, risks to the effective adoption of this technology were identified. We also outlined pathways for applying social science to mitigate these risks and to enhance the capacity of industry, government and the public to manage this transition.

Based on a review of studies of international trials, and interviews with industry, our principal conclusions are that:

1. Initially, positive public attitudes with low awareness are likely. Attitudes from a base of low awareness are liable to change, which could have implications in the form of both early risks and opportunities for the reputation of hydrogen energy in Australia.
2. Perceptions of environmental benefit, safety and costs are likely to be leading influences on attitudes, acceptance and adoption; these perceptions will have implications for realising benefits of hydrogen energy technologies.

Building a positive reputation through early communication and engagement will be important, as previous experiences with emerging technologies has shown that there is a pattern of initial positive attitudes combined with low awareness that leads to unstable attitudes, where minor events can change public opinion substantially. The stakeholders we interviewed from industry and government were cognisant of the potential risk arising from under-informed early attitudes, and were aware that early communication is an opportunity to establish the reputation of hydrogen energy. To our knowledge, no existing research provides guidance on the best communication and engagement processes to support growing awareness and understanding of hydrogen energy. Thus, for understanding **early reputational risks and opportunities** a valuable social science research pathway is to:

- Identify early attitudes, concerns, and explore preferences for communication about hydrogen energy technology initiatives. To assess these early attitudes, the sample could either be representative of the general public or drawn from specific groups (e.g. communities where early demonstrations are planned). The research method would depend on the context. For example, interviews or focus groups with potentially affected people would be relevant in the early stages of actual demonstrations where more in-depth insights may be needed. In other contexts, it may be appropriate to conduct online questionnaires with a broader sample of the general public, to assess general attitudes towards hydrogen energy technologies (including how these attitudes change over time).
- Draw on existing evidence on effective communication and engagement in other energy technology domains (e.g., wind farms, carbon capture and storage, nuclear energy and coal

seam gas) to inform the design and delivery of early and ongoing communications (and public engagement strategies) about hydrogen's role in Australia's energy system generally and of proposed specific demonstrations and trials.

- Seek engagement with and utilisation by early interest groups such as consumer advocacy and industry groups, as well as project proponents and government representatives.

Building on the limited evidence of influences on acceptance and adoption in the Australian context, social science research could be conducted to identify the strongest drivers of both acceptance and adoption.

Specifically for **acceptance**, the social science pathway could:

- Utilise stakeholder workshops and surveys (such as online questionnaires) to identify how influences such as environmental benefit, safety and location of infrastructure manifest in the Australian context, particularly for initiatives like export and different production methods (areas which have received little research attention to date).
- Inform the co-design of engagement and consultation for demonstration and trial initiatives, including a set of best practice principles, which companies and governments can use/implement when considering hydrogen developments at a local level and national coordination of such.
- Be implemented by project proponents, regulating governments and involved communities.

The social science pathway regarding the explicit behaviours of **adoption** could:

- Identify the decision-making factors that underpin adoption through focus groups and questionnaires with early adoptees (and if applicable, adoptees of varying demographic profiles), across a range of applications. This work could also include experimental work (e.g., surveys or field trials with embedded experiments) to identify causal effects.
- Inform the design and delivery of applications for the Australian context and related communications.
- Be applied by organisations developing applications and enabling their adoption, such as industry associations, manufacturers, regulators and adoptees.

Combined, these science pathways can provide an evidence base to guide the decisions of industry, government and the public. The ideal effect of this shared evidence base is to enable practices and policies that are responsive to the social responsibilities of introducing hydrogen into the Australian energy economy. This is a constructive approach to the overarching social risk, which this interviewee quote goes some way to summarising:

"If the public perception is poor it doesn't matter how good hydrogen is. Perception is reality".

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