# HyDelta 2

## WP10 – Social acceptance for hydrogen transport and storage

D10.1 – Overview from the literature / studies on societal support for new energy technologies and hydrogen in particular. An exploration of the aspects that (in similar circumstances) hinder or accelerate societal embeddedness.

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# Document summary

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## Executive summary

Social acceptance is an important aspect in the realization and implementation of various renewable energy technologies. Our main objective with this literature review is to provide insight into public support, social acceptance and societal readiness for new energy technologies in general, and hydrogen, both as an energy carrier and as an application in the built environment, in particular. 110 relevant articles were identified, of which 28 have been included in this literature review, based on relevance and year of publication (2012-2022). Generally, the findings show there is low awareness concerning hydrogen, as well as limited knowledge and familiarity with this new energy technology, especially concerning hydrogen storage. Despite this, there is overall moderate to high willingness to accept hydrogen, which decreases when it comes to the local implementation of hydrogen projects. Safety and affordability were two important characteristic of a hydrogen industry that would motivate people to support this industry, together with climate change mitigation. Safety concerns over the flammability of hydrogen are mostly expressed when used for household activities and storage, and less so when it concerns the use of hydrogen for transportation. Communication about safety and risks, transparent interaction between all parties and the community, as well as giving the community a voice in the decision-making process, will be essential for hydrogen acceptance. Together with the results from five case studies (deliverable 10.3 of the HyDelta 2.0 project), recommendations regarding the elements that should and should not be included in a development and implementation strategy will be given.

## Samenvatting

Sociale acceptatie is een belangrijk aspect in de realisatie en implementatie van diverse hernieuwbare energie technologieën. Het doel van deze literatuur review is om inzicht te geven in publieke en sociale acceptatie en de mate waarin de maatschappij klaar is voor nieuwe energie technologieën in het algemeen, en voor waterstof in het bijzonder. We focussen ons hierbij op waterstof als drager van energie (transport en opslag), en als toepassing in de gebouwde omgeving. 110 relevante artikelen zijn geïdentificeerd, waarvan er 28 zijn gebruikt in deze literatuur review (geselecteerd op basis van relevantie en jaar van publicatie (2012-2022)).

De bevindingen laten zien dat er weinig bewustzijn en kennis is omtrent waterstof, en mensen zijn slechts weinig bekend met deze nieuwe energie technologie, met name wanneer het gaat over de opslag van waterstof. Desalniettemin is er gemiddelde tot hoge bereidheid om waterstof te accepteren, welke echter naar beneden gaat als het gaat over de lokale implementatie van waterstof projecten. Veiligheid en betaalbaarheid zijn twee belangrijke kenmerken van een waterstof industrie die kan rekenen op publieke steun, net als het kenmerk dat waterstof wordt beschouwd als manier om klimaatverandering tegen te gaan. Veiligheidszorgen over de ontvlambaarheid van waterstof worden vooral geuit wanneer het gaat over opslag van waterstof en het toepassen van waterstof in huishoudens, en minder als het gaat over waterstof voor transport doeleinden. Communicatie over veiligheid en risico's, transparante interactie tussen alle partijen en de community, net als het geven van een stem aan de community in het besluitvormingsproces, zijn essentieel voor de acceptatie van waterstof. Samen met de resultaten van vijf case studies (deliverable 10.3 van het HyDelta 2.0 project) zullen aanbevelingen worden gedaan aangaande elementen die al dan niet aanwezig moeten zijn in ontwikkel- en implementatiestrategieën voor waterstof projecten.

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# 1. Introduction

Social acceptance is an important aspect in the realization and implementation of various renewable energy technologies. Research clearly shows that in parallel with overcoming technical and financial challenges towards deployment of a new technology, societal aspects should be considered for creating the optimal circumstances for societal embeddedness of technologies (Geerdink et al., 2020; Duijn & Puts, 2013; Wiekens, 2019). This literature review is conducted to get state-of-the-art insights into the social acceptance and societal embeddedness of hydrogen as an energy carrier in the context of the HyDelta 2.0 project (WP 10). The specific scope addresses the transport / distribution and (subsurface) storage of hydrogen to serve different applications and sectors, and it also takes into account future possibilities, such as fuel for cars (fuel-cells) and hydrogen as a heat source (H2-gas in heating boiler) in the built environment. Such insights can help to develop a risk government strategy that can be incorporated in the planning phase of hydrogen projects to improve societal support and uptake.

A first step towards such insights is to conduct a literature review on this topic. The overarching research question of WP10 is: *What are the main societal challenges for deploying hydrogen transport / distribution, storage, and application within the built environment in the Netherlands and how could these challenges be overcome as part of the development and implementation strategy?*

Our main objective is therefore to provide insight into public support, social acceptance and societal readiness for new energy technologies in general, and hydrogen, both as an energy carrier and as an application in the built environment, in particular. More specifically, the current study aims to explore that hinder or accelerate societal embeddedness of hydrogen as an energy carrier and as an application.

Different theoretical frameworks have been applied. Regarding social acceptance and public support, three dimensions can be distinguished: socio-political acceptance, support within communities and market acceptance (Wüstenhagen, Wolsink, & Bürer, 2007). Socio-political acceptance is the broadest form of support and focuses on governmental frameworks and policies. Support within communities focuses on the attitude and perception of local stakeholders, among which residents. Market acceptance addresses the extent to which the market (producers, consumers, investors) makes use of and invests in the technology. A recent review article (Gordon et al., 2022) additionally shows the complexity of renewable energy acceptance by introducing five dimensions and their interrelatedness (socio-political, community, market, attitudinal and behavioural acceptance).

In the context of new technologies, the identification of risks as well as the development of risk strategies is quite common and an important aspect of societal acceptance and public support. In this regard, the International Risk Governance Council developed a so-called risk governance framework which includes the risk perceptions of different stakeholders and provides a stepwise approach for jointly developing a risk governance strategy. All relevant perspectives and interests could be included in this process.

Finally, there are several frameworks that concern ways of introducing new technology in society, such as the Technology Readiness Level, a commonly used measurement system to assess how mature a technology is to use in its intended operational environment (Sprenkeling, Geerdink, Slob, & Geurts, 2022). As this framework does not take into account societal aspects, another framework was developed, called Societal Embeddedness Level methodology (Geerdink et al., 2020; Sprenkeling et al., 2022). This framework is used to identify the main societal challenges towards deployment of a certain technology, which leads to recommendations on how to overcome these challenges as part of the overall project development strategy. Four levels for societal embeddedness are identified (Exploration, Development, Demonstration and Deployment), and at each level, four societal dimensions are considered (Environment, Stakeholder involvement, Policy and Regulations, and Market and Financial Resources). This method embodies a structured assessment approach to analyse the social embedding stage of a technology or system and the hurdles to overcome before realization of an innovation or system in society can take place. Additionally, it gives attention to setbacks through the entire development process.

The above mentioned theoretical frameworks concerning societal acceptance, risk governance and societal embeddedness have been used as starting points for the current literature review. All in all, it aims to provide more insights into public support, social acceptance and societal readiness for new energy technologies and hydrogen in particular.

# 2. Method

The search inquiry for this review consisted of different phases. First, different electronic databases were used to do an initial search (Google Scholar, and twelve Ebscohost research databases, among which Academic Search Premier, APA PsycArticles, eBook Academic Collection (EBSCOHOST, eBook Collection (EBSCOHOST), eBook Open Access Collection, EconLit, GreenFILE, Psycinfo MEDLINE, Psychology and Behavioral Sciences Collection, and SocIndex). The search query was organized around the two main topics of this literature review (social acceptance and risk management), leading to the following search terms:

H2 OR Hydrogen AND Social acceptance OR public acceptance OR engagement OR societal embeddedness / Hydrogen OR H2 AND Risk management OR risk perception OR governance.

Within the twelve research databases and with the different search strings, this yielded approximately 700 articles. Google Scholar was additionally used to check for new articles (the exact steps can be found in our Information logbook, available upon request at the main author). We also used a snowballing technique after screening the articles. Finally, we looked in the professional literature, and we also used expertise from the field and up to date insights about projects concerning novel (hydrogen-related) energy technologies.

Next, after screening the titles and abstracts of the articles, 110 relevant articles were identified. We then applied as an inclusion criterium the year in which the article should be published (after consideration within WP10, we decided to focus on a ten-year time-frame, which means that articles published between 2012 and 2022 were included). After assessing and reading the articles in more detail, a final selection of 28 articles was used to write this literature review. This selection is to be found in Table 1, see the next chapter.

# 3. Results

Table 1 provides an overview of the literature and studies on societal support for new energy technologies, with a focus on hydrogen. The main output concerns a state-of-the-art exploration of the aspects that hinder or accelerate societal embeddedness. Below the table, there is a review of the articles concerning the three main topics and observed differences between applications and countries.

*Table 1. Articles included in the current literature review.*

| **Authors and year** | **Country** | **Research methodology and sample** | **Application of hydrogen / energy technology** | **Main results and conclusion** |
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| Emodi et al (2021) | 25 European countries, United States of America, Republic of Korea, Japan, Australia, Malaysia and China | Systematic literature review | Hydrogen: diverse applications | Low awareness in 60% of the countries. Important factors related to acceptance are prior knowledge, perceived costs, risks and benefits. |
| Iribarren et al (2016) | Spain | Cross-sectional survey, *n* = 1005. Relatively young [18-35 year] and highly educated respondents.<br><br>HYRREG project | Hydrogen: transport | High level of awareness in this sample, also high support for hydrogen as a transportation fuel. The building of a local hydrogen refuelling station yields strong social support, but preferably away from residential areas. Also strong social support for an affordable tax to implement hydrogen in public transport system. Purchasing a vehicle is motivated by personal environmental commitment, and success of hydrogen vehicles is hindered by costs and technical issues |
| Schönauer & Glanz (2022) | Germany | Cross-sectional, online survey (*n* = 1438) | Hydrogen technology as an energy carrier in general | High general acceptance of hydrogen energy, which decreases when it comes to large-scale infrastructure projects and the implementation of a project in the own |

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| | | | | neighbourhood. Place attachment and trust in (political and scientific) stakeholders can influence acceptance. |
| Ingaldi & Klimecka-Tatar (2020) | Poland | Survey (*n* = 766) | Hydrogen energy in general and hydrogen-powered cars | Knowledge is very low, and people doubt the safety of hydrogen energy in general. This may be due to the finding that new energy technologies are quite unknown in this country. |
| Baur et al (2022) | Germany | Online survey (*n* = 1247, distributed across the three technologies) | Broader: Hydrogen fuel station, stationary battery storage and biofuel production | For all three technologies, general acceptance is higher than local acceptance. Concerns with regard to the technologies differed. For hydrogen fuel stations and stationary battery storage, explosion and fire hazards were most frequently mentioned, whereas smell pollution was a relevant concern in the context of biofuel production plants.<br><br>Across all three technologies, trust in stakeholders was relatively high, as well as attitudes towards financial support. |
| Han, Kim, & Yoo (2022) | South Korea | Survey (n = 1000) | Hydrogen fuel station | Approximately half of the respondents approved of building a hydrogen refuelling station near their homes, which means that the other half was either against or indifferent towards such a project. Income and education were positively associated with acceptance, as was prior experience with hydrogen refuelling stations near respondents' homes or workplace. |
| Zaunbrecher et al (2016) | Germany | Interviews (*n* = 10) and surveys (*n* = | Hydrogen storage | Despite lack of knowledge and information, overall positive attitudes, acceptance of and trust in hydrogen storage. Fear of risks, |

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| | | 141). General public | | especially in residential areas should be addressed adequately. |
| Hienuki et al (2019) | Japan | Survey (*n* = 540 experts / early adopters) | Hydrogen fuel station | Investigation of the effect of initiatives to improve awareness on hydrogen energy technology. Seminars on the topic increased knowledge, whereas participants attending hydrogen energy related events trusted and accepted the installation of hydrogen fuel stations near their own homes more. Increasing familiarity and experience with the technology seems to be important in stimulating awareness on hydrogen-related energy technology. |
| Bögel et al (2018) | Belgium, France, Germany, Norway, Slovenia, Spain and the United Kingdom | Survey with *n* ≈ 1000 respondents per country | Both hydrogen stationary fuel cells, as well as hydrogen fuel cell vehicles | Low levels of awareness and knowledge and positive attitudes towards hydrogen fuel cell technologies were reported across countries. Prior attitudes also strongly affected how information about the topic is processed and evaluated. |
| Ono & Tsunemi (2017) | Japan | Survey, *n* = 2069 (general public) | Hydrogen fuel station | 66% of the respondents scored high on acceptance towards the construction of a hydrogen fuel station nearby home. Explanatory factors were (among others) educational level, prior knowledge about hydrogen, risk perception of hydrogen stations and inherent risk acceptance or avoidance. It is recommended to provide correct and precise information to decrease public fear about hydrogen-related technologies (reliability, and possibility / type of accidents) |
| Itaoka et al (2017) | Japan | Online panel survey (*n* = 3133) | Transport: Hydrogen fuel cell vehicles | In comparison to previous surveys in 2008 and 2009, there is a large increase in awareness and small improvements in knowledge of hydrogen energy |

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| | | | | (due to media publicity). Risk perception, perceived benefits and public acceptance kept relatively stable: one became a bit more positive and more cautious about the risks and benefits, which is interpreted as 'a change in the quality of perception and acceptance' as a rational view rather than a positive prejudice about hydrogen technology. |
| Ono et al (2019) | Japan | Collective interview survey, *n* = 240 | Hydrogen fuel station | Providing risk information increased acceptability, but only in response to a hydrogen refuelling station nearby the homes of the respondents (and not at the nearest gas station). Under this condition, risk information did decrease feelings of fear or uncertainty, leading to higher acceptance. In case of the nearest gas station, respondents did not initially experience hydrogen-related fear, but providing the information on risk or safety measures did evoke such feelings. The findings imply that sharing information among neighbours is helpful, as is the provision of risk information to stakeholders. |
| Zimmer & Welke 2012 | Germany | Interviews (*n* = 30), focus groups (*n* = 12) and telephone survey (*n* = 1011). General public<br><br>HyTrust project | Hydrogen: transport | There is a generally positive view on hydrogen as a transportation fuel, and also high awareness. Knowledge of hydrogen as a transportation fuel is rather low. There is high willingness to use hydrogen as a transportation fuel, preferably when it is produced in an environmentally friendly way. |
| Al-Amin & Doberstein, 2019 | Malaysia | Survey (*n* = 232) & semi-structured | Transport: Hydrogen fuel cell vehicles | Respondents believe that hydrogen fuel cell vehicles contribute to environmental sustainability. Knowledge is |

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| | | interviews (*n* = 48) | | important in influencing purchasing behaviour (e.g., through awareness of the benefits). Adequate management of negative attitudes and acceptance is necessary for the introduction of this technology, with a coordinated (top-down) approach focusing on both demand and supply side. |
| Hardman et al., 2016 | United Kingdom | Survey (n = 30) after fuel cell vehicle trial | Transport: Hydrogen fuel cell vehicles | Purchase costs of a hydrogen fuel cell vehicle are high; therefore relative advantages are important. Perceived functional benefits of hydrogen fuel cell vehicles are related to their environmental impact, fuel economy, performance as high technology and the quietness of the vehicles. The main barriers relate to the high purchase prices and lack of refuelling infrastructure. |
| Oltra et al., 2017 | Belgium, France, Germany, Norway, Slovenia, Spain and United Kingdom | Survey (two versions concerning two different technologies; *n* ≈ 1000) | Fuel cell vehicles, hydrogen fuel stations and home fuel cell technology | In the seven countries, there is low awareness of the existence of hydrogen and fuel cell technologies. Familiarity with the applications is also low. Overall, there is a positive initial attitude, likelihood to accept and support the adoption of residential fuel cells and fuel cell vehicles. Between countries, there are small to moderate differences in awareness and acceptance. Among other aspects, positive and negative affect, perceived benefits and trust are related to acceptance. |
| Huijts & van Wee, 2015 | The Netherlands | Survey (*n* = 1214) | Hydrogen fuel stations | Local implementation of a hydrogen fuel station is investigated (public acceptability). Psychological variables (positive and negative affect, expected local effects and expected societal and |

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| | | | | environmental effects) explain public acceptability better than the socio-demographic and spatial variables, and serve mostly as mediators in the relationship between socio-demographic / spatial variables and public acceptability. Respondents living nearer to a fuel station location indicated lower acceptance than those living further away (in line with NIMBY, but contrary to findings in previous hydrogen-related research). The group living nearby had lower levels of trust in the industry and experienced less strong positive affect when thinking about the hypothetical placement of a local hydrogen fuel station. |
| Huijts et al., 2013 | The Netherlands | Experimental design, information group vs. control group ($n$ = 800) | Hydrogen fuel stations | Investigation of the motivations of citizens to act in favour or against hydrogen refuelling facilities. Intention to act (both in favour or against) was more affected by moral considerations than self-interest. Especially for supporters, self-interest is a secondary goal. |
| Huijts et al., 2014 | The Netherlands | Survey ($n$ = 1214) | Hydrogen fuel stations | Personal norm, affect and perception of the advantages are important determinants in acceptance of hydrogen technology. Distrust in the energy industry is an additional factor linked to rejecting the technology. |
| Apostolou & Welcher (2021) | Denmark | Web-based survey ($n$ = 158), general public | Transport: Hydrogen fuel cell vehicles | Environmental awareness, limited refuelling infrastructure and media support for this market impact willingness to accept or even purchase a hydrogen fuel cell vehicle in the near future. Technology knowledge and familiarity with |

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| | | | | the technology are important parameters towards so-called green mobility. |
| Tarkowski & Uliasz – Misiak (2022) | Poland (no primary scientific research) | Narrative review | Hydrogen storage | Social acceptance can be seen as a barrier to the implementation of underground hydrogen storage, next to technical and safety limitations and legal barriers. Providing reliable knowledge is an important aspect in this regard, as well as gaining more understanding on societal acceptance factors, including the risk perception. |
| Lozano et al (2022) | Australia | National survey (*n* = 2785) | Hydrogen: Domestic use and export | Acceptance of hydrogen in domestic applications was influenced by its relative cost, and perceived benefits: ability to reduce air pollution and associated health benefits. Acceptance of hydrogen as an export industry was influenced by trust in the government (to manage the associated risks) and the industry. Nuanced communication and engagement is needed, as is financial support. |
| Liu et al (2019) | The Netherlands and China | Experimental design (trust and public influence were manipulated in a 2 x 2 design), *n* = 192 in two studies | Broader: renewable energy projects | In China and the Netherlands, trust in responsible agents and public influence affected public acceptability of renewable energy projects. |
| Gordon et al (2022) | United Kingdom | Structured narrative review | Domestic hydrogen | A lack of knowledge and awareness is reported, partly because there is an absence of information dissemination. Consumer engagement and public trust in key stakeholders are important factors that can stimulate social acceptance. The most critical barrier is |

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| | | | | affordability and distributional injustice is a key concern. |
| Dumbrell et al (2022) | Australia | Survey (*n* = 1824), general public | Hydrogen energy in general | The importance of six characteristics of a hydrogen industry in supporting the development of such an industry was assessed, showing that safety was rated as the most important characteristic, followed by climate change mitigation and affordability. This information can be used to 'align policy and investment decisions with public expectations for the further development of the hydrogen industry in Australia'. |
| Chen et al (2016) | Taiwan | Survey (*n* = 858) | Hydrogen energy in general | Development of a questionnaire to assess acceptance of hydrogen energy and public perceptions. Specific perceptions that positively influenced acceptance were: the public perception of hydrogen energy as a green energy, public belief in domestic hydrogen industries being able to conform to international safety standards and public perception of the cost advantage. There are concerns about the safety of hydrogen, but this does not relate to acceptance in this study. |
| Lee et al (2021) | South Korea | SWOT analysis (20 experts) and focused group interview | Hydrogen fuel stations | Among the assessed strengths of hydrogen fuel stations are the response to climate change and driver convenience. Safety, accessibility and location are among the weaknesses, whereas opportunities lie in government policy, a global market and education. A threat can be seen in competition with other industries. It is recommended to focus on maximizing the strengths, for instance by informing the public about the |

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| | | | | benefits of hydrogen and hydrogen fuel stations. |
| Wiekens et al (2016) | The Netherlands | Longitudinal context analysis, discourse analysis and survey (*n* = 61) and interviews (*n* = 12) | Biogas installation | There was no social support for biogas installations in two cases, as they are perceived as unreliable and unsafe installations, and there is low trust in the government and initiators of such projects. There has been no public debate about the installations and the concerns (e.g., smell) and questions of residents near the biogas installations. |

## 3.1 General view

As can be seen in table 1, the reviewed articles are from Western European countries (12 primary research articles), but also Asian research into hydrogen and societal acceptance is reported quite frequently (9 primary research articles). The Western European originated articles are mostly dominated by articles concerning the German energy transition.

A review article from 2021 (reviewing 43 articles) indicates there is low hydrogen awareness in more than half of the countries included (Emodi et al., 2021). Yet, within certain samples of younger and higher educated respondents, there are studies that report higher levels of awareness (e.g., Iribarren et al., 2016). Awareness might depend on the application of hydrogen too, as high levels of awareness of hydrogen have often been found concerning hydrogen as a transportation fuel in multiple studies, possibly by the investment in hydrogen buses (Emodi et al., 2021; Iribarren et al., 2016; Oltra et al., 2017; Zimmer & Welke, 2012). Additionally, general knowledge about hydrogen and how it works seems to be fairly low (e.g., Zaunbrecher et al., 2016; Zimmer & Welke, 2012), and familiarity with hydrogen technology is low as well (e.g., Oltra et al., 2017).

Despite this, there is overall moderate to high willingness to accept hydrogen (Schönauer & Glanz, 2022), more specifically to accept it as a 'key energy carrier within the energy and transport sector' (Iribarren et al., 2016) or to introduce hydrogen based cars (Zimmer & Welke, 2012). Yet, it has to be taken into account that this general acceptance decreases when it comes to local acceptance (Baur et al., 2022), as illustrated with the infrastructure implementation in residential areas (Iribarren et al., 2016) or in the own neighbourhood (Schönauer & Glanz, 2022). For instance, 48% of the respondents approved of the building of a hydrogen fuel station nearby their home, which was slightly higher than twice the percentage of people who were against this, but still more than half of the people did not express support or were explicitly against this solution (Han et al., 2022).

Generally, people view the use of hydrogen as environmentally friendly (Emodi et al., Iribarren et al., 2016; Zaunbrecher ; Itaoka; Achterberg 2014; Hienuki et al 2019 ; Al-Amin & Doberstein, 2019). For instance, this can be seen as a motivating factor to choose a hydrogen-based car (Iribarren et al.,

2016) and the notion that the use of hydrogen contributes to climate protection is related to overall support (Lozano et al., 2022). Hydrogen being associated with health effects was more related to the use of hydrogen in domestic applications (Lozano et al., 2022). Related to this, moral considerations are found to be important in explaining the intention to act (both in favor or against) hydrogen refuelling facilities (Huijts et al., 2013). For the general public, the notion that hydrogen needs to be produced with renewable energy is also an important condition (as this would reduce feelings of shifting the problem and feelings of guilt for using a car), even when the consumer price would then be higher (Han et al., 2022; Zimmer & Welke, 2012).

Besides the overall low awareness and knowledge levels, positive attitude and relatively high willingness to accept hydrogen as a new technology, there is another component that is shining through multiple publications: the 'uncertainty with regard to possible risks and security issues' (Zaunbrecher et al., 2016), especially when hydrogen is to be stored in or near residential areas and when hydrogen will be deployed more widespread. Then it is important to focus on risk governance and risk communication (also see later in this review).

## 3.2 Psychological indicators of social acceptance and public perception

Socio-economic indicators, such as higher education (Han et al., 2022) and income were positively related to social acceptance of hydrogen (Emodi et al., 2021), but this pattern is not always confirmed (e.g., Schönauer & Glanz, 2022). Additionally, younger respondents are commonly found to be more supportive of hydrogen technology (Emodi et al., 2021). Generally, one can however state that socio-demographic variables or spatial variables (e.g., distance towards hydrogen refuelling stations, infrastructure availability) explained public or local acceptance less well than psychosocial variables (Huijts & van Wee, 2015; Oltra et al., 2017).

From a recent literature review (including 43 articles regarding societal acceptance of hydrogen; Emodi et al., 2021) it is found that environmental knowledge and prior knowledge about hydrogen and familiarity or experience with the technology is positively related to being supportive about hydrogen technologies (Emodi et al., 2021; Zaunbrecher et al., 2016; Ono & Tsunemi, 2017; Hienuki et al., 2019; Hirayama et al., 2021; Han et al., 2022; Lozano et al., 2022). Additionally, technology knowledge and experience with the technology (i.e., in case of hydrogen storage) may contribute positively to the transition towards more sustainable ways of transportation (Apostolou & Welcher, 2021), which can be overcome by providing reliable knowledge (Tarkowski & Uliasz-Misiak, 2022).

It is found that information provision and experiences with the technology are mostly effective for people who are not yet widely familiar with the technology, which is relevant in the early stage of the implementation of hydrogen nation-wide (Bögel et al., 2018). Relatedly, Hienuki et al (2019) also found that reliability of the technology is most important for acceptance of hydrogen technology, which is to be influenced by knowledge about the topic. It is important that people experience the technology in order to make an estimation of the reliability of the technology, for instance at a hydrogen energy technology introduction event. Besides trust, barriers for using hydrogen technology are mostly related to economical (costs of the hydrogen driven vehicle) and technical aspects (e.g., availability of hydrogen fuel stations; Iribarren et al., 2016; Hardman et al., 2016).

In other studies, personal norm, positive affect and the perception of the (local, societal and environmental) effects were also considered important for hydrogen technology acceptance (Huijts

et al., 2013; 2014), whereas negative affect, personal norm and distrust in the energy industry were important factors for respondents to reject hydrogen refuelling stations. Indeed, stronger public trust in key stakeholders is an important factor for public acceptance (Liu et al., 2019; Gordon et al., 2022) and more specifically, trust in both industry and government was identified as an important factor for support for a hydrogen export economy (Lozano et al., 2022).

Safety and affordability were two important characteristic of a hydrogen industry that would motivate people to support this industry, together with climate change mitigation (Dumbrell et al., 2022; Emodi et al., 2021). Socio-economic variables, knowledge about hydrogen and environmental concern influenced such individual considerations, showing the interrelatedness of these factors. Additionally, in the review paper (Emodi et al., 2021) the perceptions from three different stakeholder groups (general public, end users and experts/early adopters) on hydrogen energy technologies were studied. It was concluded that all groups agreed that infrastructure availability, affordability, local community engagement, regional skill capability development, preservation of biodiversity, safety and distributive benefits to the community were essential conditions under which a hydrogen industry can be successful. A key concern for the large-scale application of hydrogen in homes was further recognized as distributive injustice (Gordon et al., 2022), which also can lead to more safety concerns.

## 3.3 Risk perception, safety issues and public perception

Safety is an important topic for various stakeholder groups in hydrogen energy technology projects (e.g., Dumbrell et al., 2022; Emodi et al., 2021), for instance because hydrogen is flammable and several hydrogen-related hazards due to accidents are reported (Moradi & Groth, 2019). Perceived risks were indeed one of the main determinants for societal acceptance of hydrogen technology in a recent review (Emodi et al., 2021) and it is also found that ‘people who think safety is an important consideration are less supportive of a hydrogen facility near them’ (Lozano et al., 2022). General public and potential end users expressed concerns over the flammability of hydrogen when used for household activities (Emodi et al., 2021; Zaunbrecher et al., 2016; Itaoka et al., 2017; Ono et al., 2019) and especially in the case of hydrogen storage, mixed attitudes concerning safety do arise (Zaunbrecher et al., 2016). Such concerns were often related to ‘the near-invisibility and odourless nature of hydrogen flame during combustion’ (Emodi et al., 2021) and more concerns about safety arise are reported in a country with a lack of attention for modern energy technologies (Ingaldi & Klimecka-Tatar, 2020).

Studies also show that respondents do not (or only to a limited amount) express concerns regarding the safety of hydrogen being used as a transportation fuel (Zimmer & Welke, 2012; Iribarren et al., 2016). When safety at hydrogen refuelling stations is in place, both general public and potential end users as well as experts trust that safety measures will be taken before hydrogen vehicles will be used more broadly in the transport sector (Hienuki et al., 2019). Thus, while people do express concern about the safety of hydrogen technologies, the unsafe perceptions are unrelated to hydrogen support (Chen, Huang, & Huang, 2016). ‘In particular, public belief in domestic hydrogen industries being able to conform to international safety standards is a powerful factor that enhances support’ (Chen et al., 2016). With this, safety of hydrogen infrastructures can be seen as an

important precondition for realization and public acceptance of hydrogen technologies (Moradi & Groth, 2019) and it is recommended to provide correct information to decrease public fear and uncertainties about reliability of the associated technology and possible accidents (Ono & Tsunemi, 2017). This will then in turn lead to higher acceptance, especially when initially, there is hydrogen-related anxiety or uncertainty (Ono et al., 2019).

## 3.4 Policy, market and their relations with public perception

As with perceived risks, perceived costs were identified in a recent review as an important determinant of societal acceptance of hydrogen technology (Emodi et al., 2021; Lozano et al., 2022). More specifically, 'the price of hydrogen as a fuel source, hydrogen converting techniques and cost of running hydrogen cars were seen as important factors for the uptake of hydrogen techniques by all three stakeholders groups' (general public, end-users and experts; Emodi et al., 2021). Additionally, experts expressed positive ideas about market development leading to lower costs, but also concerns over the cost of energy needed to produce and transport hydrogen. Other studies found strong social support for the application of hydrogen, if it is an affordable task to implement hydrogen in the public transport sector, and when new direct taxes are avoided (Iribarren et al., 2016). Policy efforts are required to address the main (economic, technological) barriers hindering the success of hydrogen vehicles.

In a recent literature review, it was found that there is 'a lack of government interest and long-term vision for the development of a hydrogen industry' (p. 30689; Emodi et al., 2021), which contributes to low public awareness and negative perceptions of hydrogen-related technologies. This also supports the need to enhance knowledge about hydrogen and its potential application among local governmental parties to support the uptake of hydrogen energy projects (i.e., with start-up funding and market incentives for hydrogen promotion). Additionally, experts think that establishing supportive standards, regulations, and legislations are also important ways to stimulate the development of the hydrogen industry further (Emodi et al., 2021). Examples can be found in policies that encourage the installation of boilers suitable for hydrogen gas in new homes and incentives for hydrogen energy pilots or demonstration projects. As such 'improving public awareness, community engagement and providing the necessary hydrogen support infrastructure will be key for guiding the behaviour of the public in a future hydrogen economy' (p. 30692; Emodi et al., 2021). This also means to adequately manage the existing negative public attitudes and promotion of hydrogen-related technologies in a coordinated approach (Al-Amin & Doberstein, 2019).

In multiple studies, the relevance of dissemination of information about hydrogen-related technologies, and thus, communication and education about these topics and potential risks is emphasized, as knowledge of, and familiarity with hydrogen and the associated opportunities is low (Gordon et al., 2022; Emodi et al., 2021). (Mass) communication and education campaigns, as well as extensive demonstration pilots are needed to build knowledge about and increase familiarity with these topics, especially when trust in the initiators is lacking (e.g., Duijn, Puts, & Boxem, 2013). These campaigns need to include information about the promise of implementation of hydrogen-related technologies for the economy, the environment and for communities (Emodi et al., 2021; Gordon et al., 2022; Lee et al., 2021). Transparent communication would help to prevent misconceptions, for instance about associated costs and risks (Baur et al., 2022). More specifically, Lozano et al (2022)

describe that nuanced communication is needed, with 'a clear focus on clarifying uncertainties around hydrogen technologies, as well as highlighting the benefits it brings' (p. 28816). Information about safety, for instance, may increase trust in the technology, which can then lead to more support (Lozano et al., 2022). Especially for first-time users of hydrogen, who may associate it mainly with explosions and hazards, it is important to be engaged in demonstration projects and to have addressed cost and safety concerns (Emodi et al., 2021). Indeed, it was shown that economic benefits of hydrogen were related to overall support, which leads to recommendations to focus on these benefits (Lozano et al., 2022). These results additionally showed that different factors influenced acceptance depending on the proposed hydrogen application. For instance, this implies that projects considering domestic use of hydrogen would benefit more from engagement campaigns and specific communication about the health benefits of hydrogen (e.g., reducing air pollution). Trust in both industry and government (i.e., 'to act in the best interest of consumers and to manage the associated safety elements') was found to be related to support in hydrogen as an export industry. Hence, transparent interaction between these parties and the community, as well as giving the community a voice in the decision-making process, will be essential (Lozano et al., 2022). A public and content-related discussion about the concerns and questions people have is an important condition for societal support and embeddedness, as was found in a project concerning biogas installations (Wiekens et al., 2016).

All in all, it can be concluded that 'hydrogen is yet to permeate the public consciousness' (Gordon et al., 2022). Consumer engagement and stronger public trust in key stakeholders will help support social acceptance as the hydrogen transition unfolds. Affordability and knowledge and awareness are seen as the most critical barriers to the large-scale adoption of hydrogen homes, whereas distributive injustice and the disruptive impact of the switchover are key concerns as well (Gordon et al., 2022). These findings have implications for the development of information and education campaigns, while at the same time it is important to realize that this would not necessarily be sufficient for public acceptance or support. For instance, it is recommended that 'policy-makers and practitioners should refrain thinking of energy infrastructure plans as "top-down" processed that the public should seemingly accept. On the contrary, if valid public concerns exist, these should be taken seriously" (Baur et al, 2022). That is, higher acceptance may exist if people believe that the decision-making process was fair, and if they feel their considerations have been taken seriously.

## 3.5 Differences between applications of hydrogen

*Transport / distribution*

In line with the review article of Scovell (2022), it was observed that most articles focused on hydrogen fuel stations and hydrogen cars (here treated as an application within the transport domain).

Safety is identified as an especially important aspect in transport applications (e.g., fire, explosion and toxicity; Najjar, 2013). Nevertheless, several studies additionally showed that there is willingness to accept hydrogen in the domain of transport (Iribarren et al., 2016). There are indications that public awareness was highest for hydrogen fuel cell vehicles, especially when directly compared to fuel cell residential applications (Oltra et al., 2017). For instance, it was found that people generally

were likely to purchase a hydrogen car in the near future if price, features and brand are the same as conventional cars, but not necessarily to pay more for hydrogen as domestic use (Emodi et al., 2021). Key barriers for the success of hydrogen vehicles are related to current costs and technical aspects such as the availability of refuelling stations. 'Mass market penetration, leading to affordable vehicle prices is also seen as a key social requirement for purchasing a hydrogen vehicle' (Iribarren et al., 2016). Reliability and range were considered important aspects for hydrogen vehicles (Emodi et al., 2021).

Ono et al (2019) found that 'the provision of respondents with risk information and risk acceptance criteria increased acceptability of hydrogen refuelling stations in proximity to the homes of the respondents, but decreased the acceptability of it at the nearest gas station'. This shows that even within a certain domain and application of hydrogen technology, acceptance can be very nuanced and is not an easy-to-answer question in the social domain of hydrogen technology.

*Hydrogen storage*

Hydrogen storage and how this exactly works is typically a topic that the general public has low knowledge about (Zaunbrecher et al., 2016), which is essential for public acceptance (Tarkowski et al., 2022). Specific knowledge gaps existed around the processes before and after the storage, hydrogen generation and electricity generation from hydrogen (Zaunbrecher et al., 2016). Regarding safety, there are potential hazards with hydrogen storage, especially leaking and ventilation issues (Najjar, 2013). Indeed, although acceptance and trust were generally high regarding hydrogen storage, there were more diverse reactions concerning the safety and storage near residential areas (Zaunbrecher et al., 2016). Safety measures are also specifically recommended at storage facilities, for instance to prevent trespassing (Emodi et al., 2021). Current barriers that have been identified in the implementation of hydrogen storage facilities are: geological and reservoir constraints, technical and safety limitations, legal barriers, conflicts of interest and social acceptance of underground storage of hydrogen. It is recommended to adequately communicate general knowledge and address the fear of risks in this regard, especially when hydrogen storage is planned in or near residential areas, while taking into account the knowledge level of the respondents and focusing on the trust in the technology (Zaunbrecher et al., 2016).

*Other (future) applications of hydrogen*

Besides relative costs, ability to reduce air pollution and provision of health benefits were important factors that influenced acceptance of hydrogen in domestic applications in Australia (Lozano et al., 2022). This means that the framing of such information is relevant when a project refers to domestic use of hydrogen.

*Other new energy technologies*

In a recent article (Baur et al., 2022), social acceptance concerning three key technologies in the German energy transition were examined, which were hydrogen refuelling stations, grid-scale stationary battery storage and biofuel production. Worries that people had differed across technologies; for instance, the most frequently reported worries about hydrogen fuel stations were explosion hazards and fire hazards, which is consistent with previously mentioned concerns (e.g.,

Najjar, 2013). Other concerns were noise pollution and the negative impact on the landscape concerning the hydrogen refuelling stations.

Although trust in stakeholders was generally high across the three technologies (Baur et al., 2022), it is recommended to seriously address the concerns of the general public, for instance during the planning stages of hydrogen-energy related projects. This is also emphasized by the finding that approximately one third of the respondents was undecided in their trust towards the stakeholders (Baur et al., 2022).

*Differences between countries*

Most of the reviewed articles originate from Western countries such as Germany and the Netherlands and from Asia, where measures have been introduced to stimulate the use of hydrogen energy (for instance, in contrast to Poland (Ingaldi & Klimecka-Tatar, 2020)). The general public in Poland was not convinced about the safety levels of hydrogen energy, which may also be related to the fact that hydrogen energy does not receive much attention in Poland (Ingaldi & Klimecka-Tatar, 2020). In a comparison between seven European countries (Oltra et al., 2017), similar attitudes concerning hydrogen were reported, whereas small to moderate differences in awareness and acceptance of hydrogen fuel cell application were reported. In Germany and Norway, respondents showed the highest acceptance, whereas this was lower in Spain, France and the UK. Differences between the applications existed as well, for instance, in Germany, Slovenia and Spain, one was more accepting of the home fuel cells, whereas acceptance of the hydrogen fuel cell vehicles was higher in Norway and Spain (Oltra et al., 2017).

# 4. Conclusion and discussion

Based on the reviewed literature, we generally see that people have a positive attitude towards hydrogen energy technology, although knowledge is relatively low, safety may be questioned and implementation 'in the backyard' may lead to fewer positive reactions. Differences between applications exist, as knowledge levels are, for instance, specifically low when it concerns the storage of hydrogen. Affordability and knowledge seem to be important barriers for making the transition to a large-scale hydrogen industry.

Interestingly, Scott & Powells (2020) suggest a new social science research agenda for the transition to hydrogen energy (especially when it comes to domestic heating), for instance by including more varied research methods (e.g., home-tours, diaries) aimed at capturing the everyday user interaction with hydrogen in households who are or have been in hydrogen pilots. This is in line with a recent systematic review stating that post-hydrogen implementation data often are missing (Emodi et al., 2020). This means there is an opportunity for current hydrogen pilots and projects to ensure more understanding of the everyday consequences of hydrogen when applied in peoples' homes. Another suggestion for future research is to focus on more than one stakeholder group to get an overall impression of societal embeddedness of hydrogen technology (Emodi et al., 2021). Moreover, for collaboration within a project it is important to map all relevant stakeholders from the beginning of the project, invest in professional stakeholders management and be aware that they have different levels of expertise and different perspectives on the matter, while keeping the common mission central (Polycentric, 2022).

It is important to take the perceptions and concerns seriously, for instance when it comes to lack of trust in safety of hydrogen energy technology (Baur et al., 2022). For instance, in communication, it is recommended to focus on the benefits of hydrogen to society and / or the environment (Huijts et al., 2013). In policy, this may mean to set safety standards or require renewable energy sources for the production of hydrogen.

Based on the current review findings, recommendations can be given for developing an approach to increase social acceptance of hydrogen and implement hydrogen technology in a way that it is supported by the general public. Together with the results from five case studies (deliverable 10.3 of the HyDelta 2.0 project), such recommendations (for instance regarding the elements that should and should not be included in such an approach) will therefore be available at the end of January 2023 upon request at the main author.

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