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Consumer perspectives of hydrogen homes

Common but differentiated strategies for supporting residential decarbonisation in the United Kingdom

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Introduction

Cadent Gas Ltd. recently supported Joel Gordon in his PhD at Cranfield University [1], which set out to advance the social science research agenda on hydrogen acceptance [2]. The research project focused on the social acceptance and prospective adoption dynamics of hydrogen-fuelled technologies for domestic space heating, hot water and cooking [3].

With around 21.2 million gas appliances and 12.7 million gas cookers installed across the UK housing stock [4], low-carbon hydrogen could play a critical role in decarbonising the residential sector [5] to support net-zero targets [6]. Supporting this trajectory, the £12 million FutureGrid project led by National Gas [7] is testing the feasibility of converting the gas grid to hydrogen [8]. Ahead of taking a policy decision on the role of domestic hydrogen by 2026 [9], the UK government has recognised the importance of developing a comprehensive understanding of consumer acceptability and behaviour [10].

Public engagement will play a key part in supporting the growth of a national hydrogen economy [11]. This executive summary provides an overview of the key outputs and findings from the research project, which was supervised by Professor Nazmiye Ozkan and Dr. Ali Nabavi. The findings can help inform consumer engagement strategies, deployment pathways and policy making to strengthen opportunities for enacting a socially acceptable transition [12] to zero-carbon homes [13].

1. Funded by the UK Research and Innovation Engineering and Physical Sciences Research Council (EPSRC) Grant EP/TS18104/1 (19/10/2020–18/10/2023). Project title at time of funding: Decarbonisation of gas networks via hydrogen: socially acceptable and fair strategies. PhD Thesis title: Towards a unified theory of domestic hydrogen acceptance: A mixed methods multigroup analysis. **2.** Scott M, Powells G. Towards a new social science research agenda for hydrogen transitions: Social practices, energy justice, and place attachment. Energy Res Soc Sci 2020;61:101346. **3.** Scott M, Powells G. Sensing hydrogen transitions in homes through social practices: Cooking, heating, and the decomposition of demand. Int J Hydrogen Energy 2020;45:3870–82. **4.** Frazer-Nash Consultancy. Appraisal of domestic hydrogen appliances. Prepared for the Department of Business, Energy & Industrial Strategy: 2018. **5.** Smith C, Mouli-Castillo J, van der Horst D, Haszeldine S, Lane M. Towards a 100% hydrogen domestic gas network: Regulatory and commercial barriers to the first demonstrator project in the United Kingdom. Int J Hydrogen Energy 2022;47:23071–83. **6.** Government Office for Science. Net Zero Society: Scenarios and Pathways Report. 2023. **7.** Powell E. National Gas pipeline switches to hydrogen in net-zero trial. The Times 2024. https://www.thetimes.co.uk/article/national-gas-hydrogen-pipelines-blending-bz3fhx92t. **8.** Rattan C. UK National Gas pipeline switches to hydrogen in net-zero trial. Energy Central 2024. https://energycentral.com/c/og/national-gas-pipeline-switches-hydrogen-net-zero-trial. **9.** Department for Energy Security & Net Zero. Hydrogen heating: overview 2024. **10.** HM Government. Net zero strategy: Build back greener. 2021. **11.** HM Government. UK Hydrogen Strategy. 2021. **12.** Almaraz S, Kocsis T, Azzaro-Pantel C, Szántó ZO. Identifying social aspects related to the hydrogen economy: Review, synthesis, and research perspectives. Int J Hydrogen Energy 2023;49:601–18. **13.** Alanne K, Cao S. Zero-energy hydrogen economy (ZEH2E) for buildings and communities including personal mobility. Renewable and Sustainable Energy Reviews 2017;71:697–711.

Background to the online survey

The PhD project involved three main phases, contributing towards an integrated mixed-methods research design [14]: (1) Literature review and theory development (2) Qualitative analysis based on data from online focus groups (3) and quantitative modelling based on results from an online survey. This executive summary reports key results from the final project phase and synthesises the presented evidence base.

Prior to launching the online survey in October 2022, in-depth literature reviews on hydrogen acceptance studies [15] and associated socio-technical barriers to domestic hydrogen futures [16] resulted in two conceptual contributions: the Five Dimensions of Domestic Hydrogen Acceptance Framework (5D-DHAF) [17], followed by the unified theory of domestic hydrogen acceptance [18]. The second phase of the research project was motivated by the need to gather in-depth qualitative insights on the topic, ahead of developing survey instruments for deploying an online questionnaire.

Ten semi-structured, online focus groups were conducted between February and April 2022 (N = 58), leading to three research outputs.

The first output of the final phase addressed a knowledge gap by examining consumer preferences and visions for low-carbon cooking and heating technologies [19].
The follow-up analysis investigated public perceptions of the twin-track production strategy and related attitudes towards deploying and scaling up hydrogen homes [20].
The final output highlighted specific causal mechanisms underlying potential social resistance towards hydrogen homes, which include a lack of trust in the government and energy industry, cost concerns related to the purchasing of hydrogen boilers, alongside perceptions of equity-related risks for local communities and vulnerable households [21].

14. Kurtaliqi, F., Lancelot Miltgen, C., Viglia, G., & Pantin-Sohier, G. (2024). Using advanced mixed methods approaches: Combining PLS-SEM and qualitative studies. Journal of Business Research, 172, 114464. **15.** Gordon J, Balta-Ozkan N, Nabavi SA. Homes of the future: Unpacking public perceptions to power the domestic hydrogen transition. Renewable and Sustainable Energy Reviews 2022;164:112481. **16.** Gordon JA, Balta-Ozkan N, Nabavi A. Socio-technical barriers to domestic hydrogen futures: Repurposing pipelines, policies, and public perceptions. Appl Energy 2023;336:120850. **17.** Gordon JA, Balta-Ozkan N, Nabavi SA. Beyond the triangle of renewable energy acceptance: The five dimensions of domestic hydrogen acceptance. Appl Energy 2022;324:119715. **18.** Gordon JA, Balta-Ozkan N, Nabavi A. Towards a unified theory of domestic hydrogen acceptance: An integrative, comparative review. Int J Hydrogen Energy 2024;56:498–524. **19.** Gordon JA, Balta-Ozkan N, Nabavi SA. Divergent consumer preferences and visions for cooking and heating technologies in the United Kingdom: Make our homes clean, safe, warm and smart! Energy Res Soc Sci 2023;104:103204. **20.** Gordon JA, Balta-Ozkan N, Nabavi SA. Gauging public perceptions of blue and green hydrogen futures: Is the twin-track approach compatible with hydrogen acceptance? Int J Hydrogen Energy 2024;49:75–104. **21.** Gordon JA, Balta-Ozkan N, Nabavi S. Price promises, trust deficits and energy justice: Public perceptions of hydrogen homes. Renewable & Sustainable Energy Reviews 2023;188:113810.

Research outputs from the online survey

Following research outputs from literature review and focus groups analysis, a nationally representative online survey (N =1845) ran between October and December 2022[22]. Several outputs were consolidated from the retrieved data, which facilitated opportunities to model the dynamics of social acceptance and perceived adoption potential for hydrogen homes.

The survey included questions on specific areas of hydrogen acceptance, as reflected within the following categories: knowledge and awareness; production perceptions; technology perceptions (i.e. hydrogen boilers and hobs); financial perceptions; safety perceptions; perceived socio-economic costs; perceived risks (i.e. disruptive impacts); perceived community benefits; facilitating conditions; social trust factors; attitudinal preferences; emotional response; social acceptance; behavioural acceptance (i.e. willingness to adopt domestic hydrogen); and finally, willingness to pay for the domestic hydrogen transition[23].

All survey items were measured using a five-point or eleven-point Likert scale. As part of the questionnaire, participants were also given a series of information provision items on hydrogen production methods, hydrogen activities in the UK and hydrogen homes, including specific information on hydrogen boilers and hobs[24]. The survey also included an open-ended question, which invited participants to explain more about their attitudes towards the domestic hydrogen transition[25]. Close to two-thirds of the sample provided a response (N = 1213; 65.7%), facilitating significant scope to explore qualitative data on the topic.

22. Gordon JA, Balta-Ozkan N, Nabavi SA. Qualitative responses to Hydrogen Homes (H2H) Online Survey 2022.docx. Cranfield Online Research Data (CORD). Online resource.https://doi.org/10.17862/cranfield.rd.23585166.v1. **23.** Gordon JA, Balta-Ozkan N, Nabavi A. Hopes and fears for a sustainable energy future: Exploring the hydrogen acceptance matrix. Int J Hydrogen Energy 2024;60:1170–91. **24.** Gordon JA, Balta-Ozkan N, Nabavi SA. Divergent consumer preferences and visions for cooking and heating technologies in the United Kingdom: Make our homes clean, safe, warm and smart! Energy Res Soc Sci 2023;104:103204. **25.** Overall, the survey duration was approximately 15–20 min.

The Domestic Hydrogen Acceptance Model

The first model examines the factors shaping social acceptance for hydrogen homes, as identified during preliminary [26] and subsequent rounds of literature review [27]. In total, the Domestic Hydrogen Acceptance Model (DHAM) includes ten factors spanning multiple dimensions [28], as illustrated in Figure 1: awareness of low-carbon technologies; subjective knowledge of hydrogen; public trust in key actors and stakeholders [29]; perceptions of hydrogen production pathways vis-à-vis the twin-track approach [30]; safety perceptions; perceived disruptive impacts of the hydrogen switchover; perceived socio-economic costs [31]; perceived community benefits [32], and emotional response (positive and negative emotions).

The modelling results indicate that perceived community benefits is the most significant predictor of domestic hydrogen acceptance, followed closely by positive emotions, production perceptions and public trust. Moreover, perceived environmental benefits has the strongest influence on social acceptance, followed by social and economic benefits. Survey participants proved more supportive of a green hydrogen production pathway in the context of the twin-track approach, as also reported during online focus groups [33]. Consequently, prospects for deploying hydrogen homes at scale may rest with coupling renewable-based hydrogen production to environmental and socio-economic benefits.

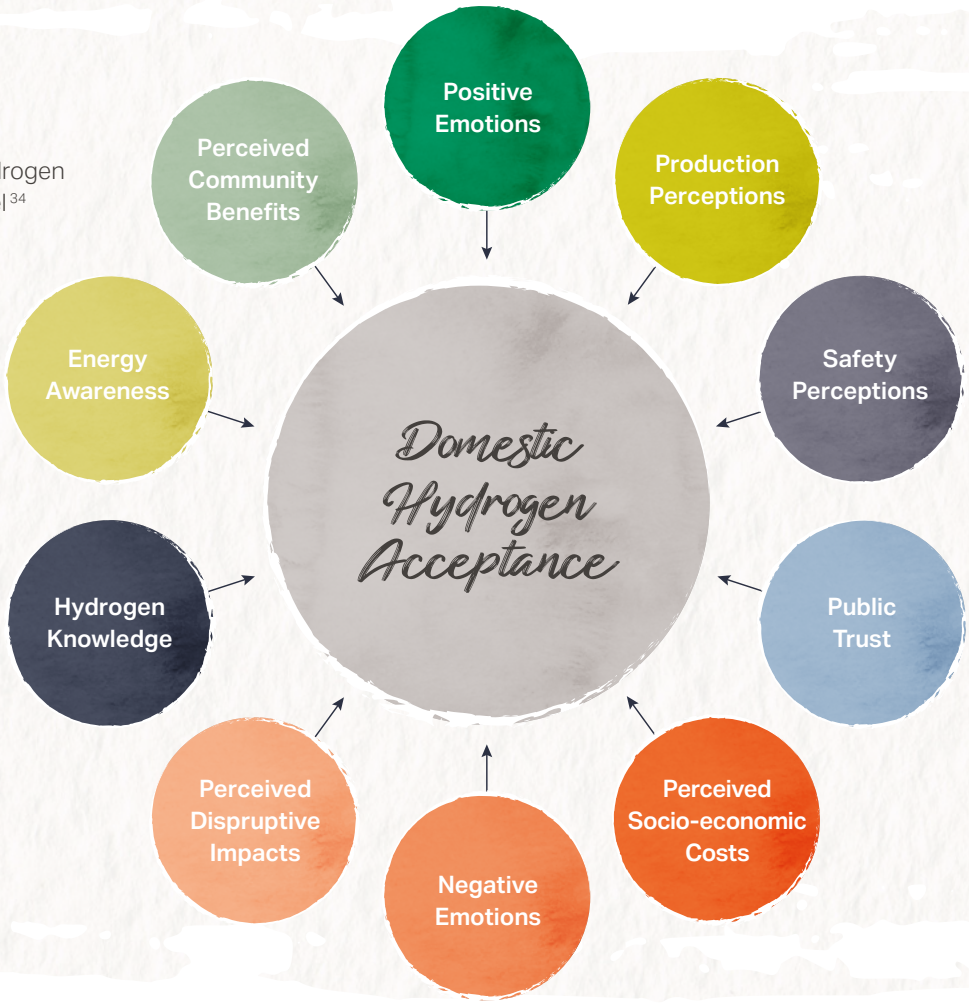


Figure 1:
The Domestic Hydrogen Acceptance Model [34]

26. Gordon J, Balta-Ozkan N, Nabavi SA. Homes of the future: Unpacking public perceptions to power the domestic hydrogen transition. Renewable and Sustainable Energy Reviews 2022;164:112481. **27.** Gordon JA, Balta-Ozkan N, Nabavi A. Towards a unified theory of domestic hydrogen acceptance: An integrative, comparative review. Int J Hydrogen Energy 2024;56:498–524. **28.** Gordon JA, Balta-Ozkan N, Haq A, Nabavi SA. Coupling green hydrogen production to community benefits: a pathway to social acceptance. Energy Res Soc Sci 2024;110:103437. **29.** Gas Distribution Network Operators, the Office of Gas and Electricity Markets (Ofgem); renewable energy producers; financial institutions; and the media. **30.** HM Government. UK Hydrogen Strategy. 2021. **31.** Impacts of fuel poverty and energy security. **32.** Economic, social and environmental. **33.** Gordon JA, Balta-Ozkan N, Nabavi SA. Gauging public perceptions of blue and green hydrogen futures: Is the twin-track approach compatible with hydrogen acceptance? Int J Hydrogen Energy 2024;49:75–104. **34.** Gordon JA, Balta-Ozkan N, Haq A, Nabavi SA. Coupling green hydrogen production to community benefits: a pathway to social acceptance. Energy Res Soc Sci 2024;110:103437.

The dynamics of domestic hydrogen adoption potential

To develop a better understanding of how perceptual and emotional factors may shape consumer behaviour, a subsequent model was developed to examine the perceived adoption potential of domestic hydrogen, as evaluated through the eyes of consumers. The 'Safety-Technological-Economic-Environmental-Emotional -Perspectives' (STEEEP) Framework provides a multi-dimensional lens into the critical success and resistance factors shaping adoption prospects for hydrogen homes [35] (see Figure 2).

In addition to being an imperative from a technical standpoint [36], the analysis demonstrates that consumer confidence in hydrogen safety is a prerequisite for deploying hydrogen homes. Currently, most respondents perceive hydrogen to be at least marginally safer than natural gas when considering home appliances, pipeline transport and underground storage, leading to a positive effect in the model. However, the importance of safety perceptions in shaping perceived adoption potential is especially pronounced among young female mortgage owners (aged 18–34 and living in homes with three or more occupants), which is consistent with observations from online focus groups [37].

Substantial evidence indicates that consumers have an expressed preference for hydrogen heating over hydrogen cooking. From a safety perspective, it should be acknowledged that hydrogen cooking typically arouses stronger concerns than hydrogen heating [38]. Interestingly, female respondents proved less optimistic about the cooking control and maintenance aspects of hydrogen hobs than males, which could impede consumer support. Consequently, more questions marks arise over the role of hydrogen cooking when evaluating socially acceptable decarbonisation pathways for the residential sector.

The literature suggests males usually have stronger positive feelings about gas-based energy futures [39], which proved the case in this analysis and prior hydrogen studies conducted in Australia [40] and Norway [41]. It follows that when objective knowledge of hydrogen fuel is low and consumer experience is absent, the emotional dimension plays a fundamental role in shaping perceived adoption potential. At this stage, in navigating hypothetical market choices that involve multiple variables, consumers are more likely to allocate higher importance to salient factors such as technology performance as opposed to unknowns such as energy consumption costs [42].

35. Gordon JA, Balta-Ozkan N, Haq A, Nabavi SA. Necessary and sufficient conditions for deploying hydrogen homes: A consumer-oriented perspective. Int J Hydrogen Energy 2024;69:982–1021. **36.** Azadnia AH, McDaid C, Andwari AM, Hosseini SE. Green hydrogen supply chain risk analysis: A European hard-to-abate sectors perspective. Renewable and Sustainable Energy Reviews 2023;182:113371. **37.** Gordon JA, Balta-Ozkan N, Nabavi SA. Divergent consumer preferences and visions for cooking and heating technologies in the United Kingdom: Make our homes clean, safe, warm and smart! Energy Res Soc Sci 2023;104:103204. **38.** Scott M, Powells G. Sensing hydrogen transitions in homes through social practices: Cooking, heating, and the decomposition of demand. Int J Hydrogen Energy 2020;45:3870–82. **39.** Visschers VHM, Siegrist M. Find the differences and the similarities: Relating perceived benefits, perceived costs and protected values to acceptance of five energy technologies. J Environ Psychol 2014;40:117–30. **40.** Lozano LL, Bharadwaj B, de Sales A, Kambo A, Ashworth P. Societal acceptance of hydrogen for domestic and export applications in Australia. Int J Hydrogen Energy 2022;47:28806–18. **41.** Bentsen HL, Skiple JK, Gregersen T, Derempouka E, Skjold T. In the green? Perceptions of hydrogen production methods among the Norwegian public. Energy Res Soc Sci 2023;97:102985. **42.** Bull J. Loads of green washing-can behavioural economics increase willingness-to-pay for efficient washing machines in the UK? Energy Policy 2012;50:242–52. https://doi.org/10.1016/j.enpol.2012.07.001. **43.** Scott M, Powells G. Towards a new social science research agenda for hydrogen transitions: Social practices, energy justice, and place attachment. Energy Res Soc Sci 2020;61:101346. **44.** Gordon JA, Balta-Ozkan N, Haq A, Nabavi SA. Heterogeneous preferences for living in a hydrogen home: An advanced multigroup analysis. Sustainable Energy & Fuels 2024. **45.** Cadent Gas. HyNet North West: From vision to reality. 2018. **46.** Gough C, Mander S. CCS industrial clusters: Building a social license to operate. International Journal of Greenhouse Gas Control 2022;119:103713.

At this moment in time, consumers generally have negative expectations for cost-related factors but other aspects of the STEEEP Framework are more prominent in shaping perceived adoption potential. Most consumers acknowledge the perceived environmental value of switching to hydrogen [43], albeit to varying degrees depending on their level of climate change engagement and knowledge of renewable energy technologies [44]. It follows that allocating resources towards improving hydrogen production perceptions is a recommended course of action for supporting the transition to hydrogen homes. In response, government representatives, gas distribution network operators, and other agents of the domestic hydrogen transition should foster stronger public engagement in the industrial north of England and parts of Scotland, where hydrogen hubs are currently envisioned [45] in conjunction with carbon capture and storage clusters [46].

Figure 2:
The Safety-Technological-Economic-Environmental-Emotional-Perspectives Framework [47]

43. Scott M, Powells G. Towards a new social science research agenda for hydrogen transitions: Social practices, energy justice, and place attachment. Energy Res Soc Sci 2020;61:101346. **44.** Gordon JA, Balta-Ozkan N, Haq A, Nabavi SA. Heterogeneous preferences for living in a hydrogen home: An advanced multigroup analysis. Sustainable Energy & Fuels 2024. **45.** Cadent Gas. HyNet North West: From vision to reality. 2018. **46.** Gough C, Mander S. CCS industrial clusters: Building a social license to operate. International Journal of Greenhouse Gas Control 2022;119:103713. **47.** Gordon JA, Balta-Ozkan N, Haq A, Nabavi SA. Necessary and sufficient conditions for deploying hydrogen homes: A consumer-oriented perspective. Int J Hydrogen Energy 2024;69:982–1021.

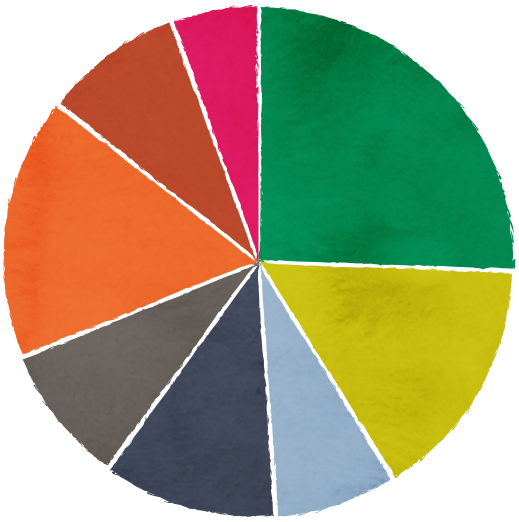
Hydrogen related emotions and emerging consumer perspectives

In-depth analysis of qualitative data further validates the multi-dimensional nature of domestic hydrogen acceptance [48]. Hydrogen-related emotions span optimism, hopefulness, curiosity, cautiousness, scepticism and pessimism, with many respondents also sharing a combination of feelings as well as more neutral perspectives (see Figure 3) [49].

For example, a given consumer may express optimism about the environmental aspects of transitioning to hydrogen homes, while carrying concerns over financial implications and perhaps questioning safety aspects. Additionally, statistical results suggest interest and engagement with environmental issues, knowledge and awareness of renewables, and consumer innovativeness (i.e. interest in being an early adopter) strengthen domestic hydrogen acceptance.

Analysing the patterns in individual responses reveals a specific typology of domestic hydrogen acceptance demarcated according to primary, secondary and tertiary-level factors [51]. Eight sub-factors explain a high proportion of responses, as presented in Figure 4. As drivers of social acceptance, respondents identify environmental benefits, positive feelings, a desire for more information, alongside belief in the promise of hydrogen as a 'fuel of the future' and the underlying notion of a hydrogen economy as critical factors. At the same time, social resistance may stem from a prevailing hydrogen knowledge deficit and financial concerns over hydrogen homes, in addition to associated negative emotions.

Figure 3:
Consumer perspectives towards domestic hydrogen across sample [50]



23%	H2 Optimist	**8%**	H2 Neutral
14%	H2 Hopeful	**15%**	H2 Cautious
7%	H2 Hopeful yet cautious	**8%**	H2 Sceptical
10%	H2 Curious	**5%**	H2 Pessimist

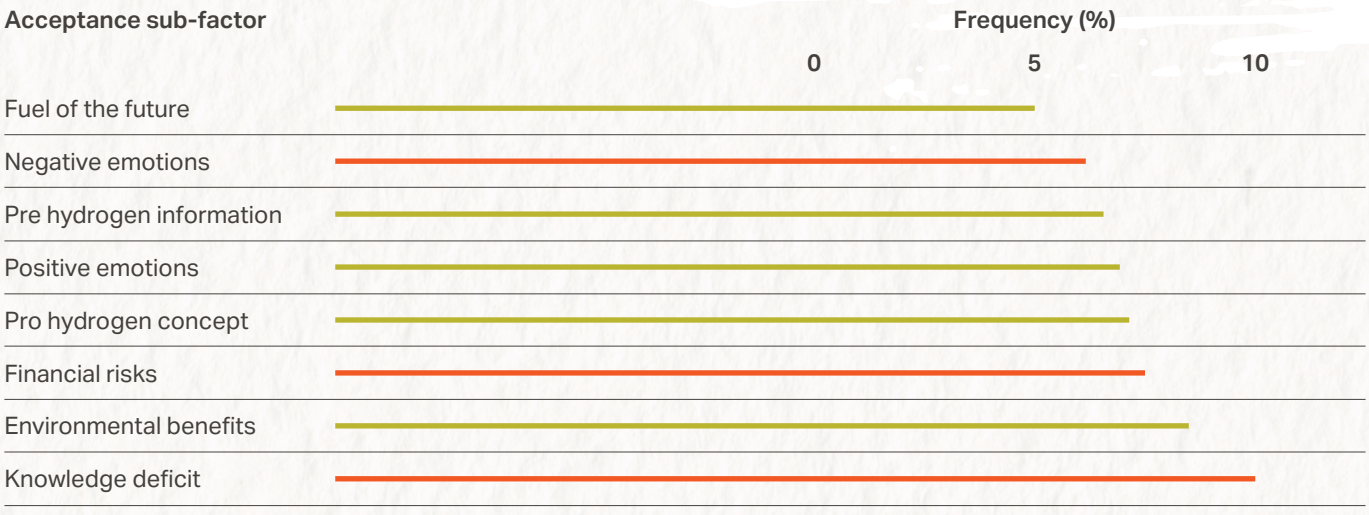


Figure 4: Primary sub-factors of domestic hydrogen acceptance [52]
Positive sub-factors Negative sub-factors

48. Gordon JA, Balta-Ozkan N, Nabavi SA. Beyond the triangle of renewable energy acceptance: The five dimensions of domestic hydrogen acceptance. Appl Energy 2022;324:119715.
49. Gordon JA, Balta-Ozkan N, Nabavi SA. Hopes and fears for a sustainable energy future: Exploring the hydrogen acceptance matrix. Int J Hydrogen Energy 2024;60:1170–91.
50. Gordon JA, Balta-Ozkan N, Nabavi SA. Hopes and fears for a sustainable energy future: Exploring the hydrogen acceptance matrix. Int J Hydrogen Energy 2024;60:1170–91.
51. Gordon JA, Balta-Ozkan N, Nabavi SA. Exploring the contours of consumer heterogeneity: towards a typology of domestic hydrogen acceptance. Energy Res Soc Sci 2024;108:103401.
52. Gordon JA, Balta-Ozkan N, Nabavi SA. Exploring the contours of consumer heterogeneity: towards a typology of domestic hydrogen acceptance. Energy Res Soc Sci 2024;108:103401.

Conclusion

This research project set out to enrich conceptual and empirical understanding on the dynamics of domestic hydrogen acceptance and adoption in support of securing a socially acceptable transition pathway for residential decarbonisation. Through a multi-stage empirical analysis, the presented evidence base highlights that hydrogen-based futures for the residential sector are currently compromised by a pronounced deficit in public awareness and engagement. Notably, objective knowledge of hydrogen remains markedly low across the population, with limited understanding of its technical properties and applications in the energy sector [53]. Regarding consumer reservations, financial risks and equity-related concerns associated with perceived socio-economic costs currently constrain public support for hydrogen homes. At the same time, positive drivers such as public trust and perceived environmental and socio-economic benefits must be strengthened to support prospects for deploying hydrogen homes. Foremost, segment-specific strategies should be embedded into national and regional policy making to steer progress towards realising a net-zero society, recognising that households will have 'heterogenous preferences for living in a hydrogen home' [54]. In response, the notion of common but differentiated consumer engagement strategies should be adopted to strengthen progress on residential decarbonisation. Increasing the observability and trialability of domestic hydrogen remains a pressing priority and challenge, foremost in proximity to industrial clusters and hubs; wherein emissions reduction remains pressing and the stakes for consumer acceptance are likely to be highest.

In conclusion, this report highlights several important findings on the critical success and resistance factors shaping the domestic hydrogen transition, as communicated by existing users of natural gas heating and cooking living in properties owned outright or with a mortgage [55]. Policy makers and stakeholders can take stock of the following key takeaways to support imminent decisions on the role of hydrogen in the UK's energy future:

- Community acceptance for hydrogen homes will hinge strongly on perceptions of environmental and socio-economic benefits
- An underlying deficit in public trust, especially towards the government and energy sector, threatens to undermine socio-political acceptance for the domestic hydrogen transition
- Public support for the twin-track hydrogen production approach should not be taken for granted, motivating the need for clearer communication campaigns and local engagement with citizens in industrial locations
- Confidence in the safety credentials of hydrogen homes must be firmly established to encourage technology acceptance among households with young families or vulnerable members
- Hydrogen cooking may prove more susceptible to consumer resistance than hydrogen heating, with the safety and maintenance aspects of hydrogen hobs raising potential concerns
- Financial perceptions associated with converting to a hydrogen home may prove less influential in shaping initial attitudes towards the transition, but will invariably take on increasing importance as the deployment timeline progresses
- While knowledge and awareness levels remain relatively low, consumers are likely to hold conflicting emotions towards the advent of domestic hydrogen and cooking technologies
- Enhancing the status of hydrogen as critical fuel for securing a net-zero future and accelerating wider progress on the national hydrogen economy will help consolidate the necessary enabling conditions for deploying hydrogen homes

Given the UK's ambitions for developing a national hydrogen economy and accelerating residential decarbonisation, the transition to hydrogen homes will need to be governed in sync with a range of key stakeholders including gas distribution network operators, energy companies, appliance manufacturers, trades bodies and research organisations. Fundamentally, realising visions for domestic hydrogen futures will necessitate both techno-economic feasibility and social acceptability, wherein the interplay between perceptions, emotions and rational decision-making will shape consumer response, as the supply chain and market develops.

Through high-level engagement with the social aspects of hydrogen homes, this research supports the premise that residential decarbonisation should be consumer led, while taking into account the replacement cycles of existing appliances.

53. Gordon JA, Balta-Ozkan N, Nabavi SA. Hopes and fears for a sustainable energy future: Exploring the hydrogen acceptance matrix. Int J Hydrogen Energy 2024;60:1170–91.
54. Gordon JA, Balta-Ozkan N, Haq A, Nabavi SA. Heterogeneous preferences for living in a hydrogen home: An advanced multigroup analysis. Sustainable Energy & Fuels 2024.
55. Gordon JA, Balta-Ozkan N, Haq A, Nabavi SA. Necessary and sufficient conditions for deploying hydrogen homes: A consumer-oriented perspective. Int J Hydrogen Energy 2024;69:982–1021.

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