Supplementary Information

Methodology

A Rapid Evidence Assessment (REA) has been undertaken in order to identify existing studies on heating with hydrogen. REA is an established method to systematically identify and assess existing research in a particular area, establish what is already known about a topic, and support policy decision-making.[1] REA has been used repeatedly in energy research and this paper follows the guidelines for REA developed by the UK Energy Research Centre (UKERC).[2]

The online databases Web of Science and Academic Search Complete have been used to screen the academic literature for relevant papers. In order to also identify grey literature Google Scholar was used but only the first 200 results were analysed for each combination of search terms. The search was conducted by using Boolean combinations of relevant terms (Table 1).

Table 1: Boolean operators used in REA

hydrogen AND	"space heating"
	"home heating"
	heating AND buildings
	heating AND homes
	"heat pumps"
	electrification AND heating

The following constraints have been applied:
- only evidence published since 01 January 2019 was considered;
- only English and German language publications were reviewed due to language skill limitations; and
- publications carried out by or on behalf of a specific industry have been excluded.

It is evident from the identified studies that national-level analysis is highly concentrated in a few countries such as Germany and the UK. This is likely at least partly a result of the REA not considering languages other than English and German, but also partly because a lot of research on heating with hydrogen was produced in those countries.

In order to determine relevance returned results were filtered based on the title and abstract initially. Where this was insufficient the main text was interrogated. The criteria for establishing relevance included:

- research on using hydrogen to provide space and/or hot water heating in buildings;
- modelling of system and/or consumer costs of using hydrogen to provide space and/or hot water heating in buildings versus alternative technologies; and
- evidence reviews on using hydrogen to provide space and/or hot water heating in buildings.

Following the filtering of retained search results, key descriptive information of each of the results was captured:

- geography;
- type of analysis (energy systems modelling, consumer cost modelling, and evidence reviews);
- year to which findings apply (if applicable);
- findings on relative costs of heating with hydrogen versus alternative technologies;
- findings on efficiency of heating with hydrogen versus alternative technologies; and
- findings on environmental impacts of heating with hydrogen versus alternative technologies.

All studies identified are listed in Table 2-5 below.

Table 2: Energy systems modelling studies on heating with hydrogen identified

Type of study	**References**	**Geographical focus**	**Year to which findings apply**	**Findings**
Energy systems modelling	[3]	UK	2050	Modelling least-cost pathway to achieve 100% decarbonisation does not include hydrogen for heating.
	[4]	UK	2050	Hydrogen-dominated heating would cost consumers 73% more compared to pathways relying on district heating and heat pumps.
	[5]	Global	2050	Least-cost pathway includes <2% hydrogen for decarbonising buildings.
	[6]	Germany	2050	Energy efficiency and electrification associated with significantly lower costs than hydrogen pathways.
	[7]	EU	2030, 2040, 2050	Best-case scenario (lowest system cost) contains no hydrogen used for heating.
	[8]	Global	2050	In least-cost pathway majority of heating systems in 2050 are assumed to be heat pumps.
	[9]	Germany	2050	Modelling a 95% carbon emission reduction pathway results in 5% hydrogen share of final energy demand for space and hot water heating in residential buildings.
	[10]	California	2019	In California hydrogen would cost 3-10 times more than electrification of heating mainly through heat pumps.
	[11]	Sao Paulo, Brazil	2050	In 2050 modelled cost-optimal heat decarbonisation pathways most heating is supplied via electrification.
	[12]	UK	2050	CO2-neutral production of hydrogen via renewable electricity and electrolysis is not cost-competitive to the direct use of electricity in ASHP. Use of hydrogen only to complement heat pumps which are modelled to deliver the bulk of heating.
	[13]	UK	2050	Under tight emission limits and cost optimisation almost all domestic heating is provided by electric heat pumps, except for 1% of heating that is provided by hydrogen by converting a portion of the natural gas grid.
	[14]	EU+UK	2050	The main strategies are for decarbonisation of heating are electrification. District heating uses waste heat from hydrogen production.
	[15]	Netherlands	2050	Between 1% and 9% of heating provided by hydrogen. Data underlying analysis obtained from [16].
	[17]	Global	2050	Electrification accelerates to an 88% share in the 1.5C-Elec scenario with almost no hydrogen used for heating.
	[18]	Global	2050	Hydrogen for heating is negligible (close to zero) across all scenarios modelled for cost optimisation.
	[19]	EU	2050	EU electrification of buildings energy demand increases above 65% in 2050 in all scenarios with a limited role for hydrogen supply up to about 10% of final energy demand in 2050 in the hydrogen scenarios.
	[20]	Hamburg, Germany	2050	Analysis finds that even under very optimistic price reduction pathways for green hydrogen heating with hydrogen is more expensive for final customers than heat pumps.
	[21]	UK	2035	Total system cost per household associated with hydrogen boilers equate to £1,600/year compared to £860/year for heat pumps.

Table 3: Consumer cost modelling studies on heating with hydrogen identified

Type of study	References	Geographical focus	Year to which findings apply	Findings
Consumer cost modelling	[22]	EU	2050	Hydrogen for heating at least twice as expensive as heat pumps.
	[23]	Spain, Italy, Czechia, and Poland	2040	Across the four countries investigated, using hydrogen boilers for heating in single-family homes is estimated to be 60-120% more costly than using heat pumps and 50-80% more costly in multi-family homes.
	[24]	Germany	2025, 2035	Hydrogen heating significantly more expensive than electrification even before reform of electricity levies. Very few use-cases where hydrogen makes economic sense in buildings.
	[25]	Germany	n/a	Hydrogen heating 5 times less efficient than heat pumps regarding the required amount of electricity.
	[26]	Netherlands	2050	All hydrogen scenarios are at least twice higher in cost than heat pumps.
	[27]	UK	2050	Heating with hydrogen from steam methane reforming with carbon capture and storage is twice and heating with hydrogen from electrolysis three times more expensive compared to an air source heat pump.
	[28]	Germany	2050	Air-source heat pumps are the most cost-effective residential heating technology in 2050 and are at least 40% lower cost than the hydrogen-only technologies.
	[29]	Germany	2030	Hydrogen heating technologies 1.4-2.1 times more expensive than heat pumps.

Table 4: Environmental impact assessments on heating with hydrogen identified

Type of study	References	Geographical focus	Year to which findings apply	Findings
Environ-mental impact assess-ments	[30]	UK	2035, 2050	Boilers using hydrogen (from electrolysis and steam methane reforming) have the highest impacts in all of the 19 impact categories (due to high electricity and resource use) including primary energy demand, metal depletion, freshwater consumption, fine particulate matter, photochemical ozone formation ecosystems/human health, ozone depletion, freshwater ecotoxicity, marine eutrophication, terrestrial acidification, human toxicity cancer and non-cancer, ionising radiation, and fossil depletion. Heat pumps are the lowest environmental impact option to decarbonise heating.

Table 5: Evidence reviews on heating with hydrogen identified

Type of study	References	Geographical focus	Year to which findings apply	Findings
Evidence reviews	[31]	EU	n/a	Heating with hydrogen is identified as a niche solution and analysis suggests there is no credible route where hydrogen enters the residential heating sector.
	[32]	Global	n/a	Low confidence and lowest readiness level of hydrogen for heating.
	[33]	Global	2050	Concludes that cost of heat from hydrogen would be much higher than from heat pumps and assumes close to 0% of heating buildings provided by hydrogen.
	[34]	Global	n/a	Residential heating assigned the lowest priority of hydrogen applications.
	[35]	Global	2020-2050	Hydrogen not recommended for heating due to inefficiencies and higher costs.

References

1. Fell, M.J. (2019). The Economic Impacts of Open Science: A Rapid Evidence Assessment. Publications *7*. 10.3390/publications7030046.
2. Speirs, J., Gross, R., and Heptonstall, P. (2015). Developing a Rapid Evidence Assessment (REA) Methodology A UKERC TPA Technical Document.
3. Broad, O., Hawker, G., and Dodds, P.E. (2020). Decarbonising the UK residential sector: The dependence of national abatement on flexible and local views of the future. Energy Policy *140*, 111321. https://doi.org/10.1016/j.enpol.2020.111321.
4. Cassarino, T.G., and Barrett, M. Meeting UK heat demands in zero emission renewable energy systems using storage and interconnectors. Appl Energy *306*, 118051.
5. IEA (2021). Net Zero by 2050. A Roadmap for the Global Energy Sector.
6. ifeu, Fraunhofer IEE, and Consentec (2019). Building sector Efficiency: A crucial Component of the Energy Transition.
7. Kranzl, L., Fallahnejad, M., Büchele, R., Müller, A., Hummel, M., Fleiter, T., Mandel, T., Bagheri, M., Deac, G., Bernath, C., et al. (2022). Renewable space heating under the revised Renewable Energy Directive : ENER/C1/2018-494 : final report (Publications Office of the European Union) doi/10.2833/525486.
8. McKinsey & Company (2022). The net zero transition. What if would cost, what it could bring.
9. Simon, S., Xiao, M., Harpprecht, C., Sasanpour, S., Gardian, H., and Pregger, T. (2022). A Pathway for the German Energy Sector Compatible with a 1.5 °C Carbon Budget. Sustainability *14*. 10.3390/su14021025.
10. Sheikh, I., and Callaway, D. (2019). Decarbonizing Space and Water Heating in Temperate Climates: The Case for Electrification. Atmosphere (Basel) *10*. 10.3390/atmos10080435.
11. Jalil-Vega, F., García Kerdan, I., and Hawkes, A.D. (2020). Spatially-resolved urban energy systems model to study decarbonisation pathways for energy services in cities. Appl Energy *262*, 114445. https://doi.org/10.1016/j.apenergy.2019.114445.
12. Aunedi, M., Yliruka, M., Dehghan, S., Pantaleo, A.M., Shah, N., and Strbac, G. (2022). Multi-model assessment of heat decarbonisation options in the UK using electricity and hydrogen. Renew Energy *194*, 1261–1276. https://doi.org/10.1016/j.renene.2022.05.145.
13. Quarton, C.J., and Samsatli, S. (2020). Should we inject hydrogen into gas grids? Practicalities and whole-system value chain optimisation. Appl Energy *275*, 115172. https://doi.org/10.1016/j.apenergy.2020.115172.
14. Victoria, M., Zeyen, E., and Brown, T. (2022). Speed of technological transformations required in Europe to achieve different climate goals. Joule *6*, 1066–1086. https://doi.org/10.1016/j.joule.2022.04.016.
15. Scheepers, M., Palacios, S.G., Jegu, E., Nogueira, L.P., Rutten, L., van Stralen, J., Smekens, K., West, K., and van der Zwaan, B. (2022). Towards a climate-neutral energy system in the Netherlands. Renewable and Sustainable Energy Reviews *158*, 112097. https://doi.org/10.1016/j.rser.2022.112097.
16. Scheepers, M., Palacios, S.G., Janssen, G., Moncada Botero, J., van Stralen, J., Machado dos Santos, C.O., Uslu, A., and West, K. (2022). Towards a sustainable energy system for the Netherlands in 2050 – Scenario update and analysis of heat supply and chemical and fuel production from sustainable feedstocks .
17. Luderer, G., Madeddu, S., Merfort, L., Ueckerdt, F., Pehl, M., Pietzcker, R., Rottoli, M., Schreyer, F., Bauer, N., Baumstark, L., et al. (2022). Impact of declining

renewable energy costs on electrification in low-emission scenarios. Nat Energy *7*, 32–42. 10.1038/s41560-021-00937-z.
18. Oshiro, K., and Fujimori, S. (2022). Role of hydrogen-based energy carriers as an alternative option to reduce residual emissions associated with mid-century decarbonization goals. Appl Energy *313*, 118803. https://doi.org/10.1016/j.apenergy.2022.118803.
19. Capros, P., Zazias, G., Evangelopoulou, S., Kannavou, M., Fotiou, T., Siskos, P., de Vita, A., and Sakellaris, K. (2019). Energy-system modelling of the EU strategy towards climate-neutrality. Energy Policy *134*, 110960. https://doi.org/10.1016/j.enpol.2019.110960.
20. Röben, F., Kicherer, N., Jürgens, L., Decher, S., Schäfers, H., and Düsterlho, J.-E. (2022). Decarbonization of the Heating Sector in Hamburg - Grid Constraints, Efficiency and Costs of Green Hydrogen vs. Heat Pumps.
21. Olympios, A. v, Aunedi, M., Mersch, M., Krishnaswamy, A., Stollery, C., Pantaleo, A.M., Sapin, P., Strbac, G., and Markides, C.N. (2022). Delivering net-zero carbon heat: Technoeconomic and whole-system comparisons of domestic electricity- and hydrogen-driven technologies in the UK. Energy Convers Manag *262*, 115649. https://doi.org/10.1016/j.enconman.2022.115649.
22. Baldino, C., O'Malley, J., Searle, S., and Christensen, A. (2021). Hydrogen for heating? Decarbonization options for households in the European Union in 2050.
23. Element Energy (2022). The Consumer Costs of Decarbonised Heat.
24. Matthes, F., Braungardt, S., Bürger, V., Göckeler, K., Heinemann, C., Hermann, H., Kasten, P., Mendelevitch, R., Mottschall, M., Seebach, D., et al. (2021). Die Wasserstoffstrategie 2.0 für Deutschland.
25. Thomas, S., Bierwirth, A., März, S., Schüwer, D., Vondung, F., von Geibler, J., and Wagner, O. (2021). CO2-neutrale Gebäude bis spätestens 2045. Ein Diskussionsbeitrag für eine ambitionierte und sozialverträgliche Politikstrategie. Zukunftsimpuls Nr. 21.
26. Baldino, C., O'Malley, J., Searle, S., and Christensen, A. (2021). Hydrogen for Heating? Decarbonization Options for Households in the Netherlands in 2050.
27. Baldino, C., O'Malley, J., Searle, S., and Christensen, A. (2020). Hydrogen for heating? Decarbonization options for households in the United Kingdom in 2050.
28. Baldino, C., O'Malley, J., Searle, S., and Christensen, A. (2021). Hydrogen for heating? Decarbonization options for households in Germany in 2050.
29. Meyer, R., Herkel, S., and Kost, C. (2021). Analyse: Die Rolle von Wasserstoff im Gebäudesektor – Vergleich technischer Möglichkeiten und Kosten defossilisierter Optionen der Wärmeerzeugung.
30. Slorach, P.C., and Stamford, L. (2021). Net zero in the heating sector: Technological options and environmental sustainability from now to 2050. Energy Convers Manag *230*, 113838. https://doi.org/10.1016/j.enconman.2021.113838.
31. Agora Energiewende, and Agora Industry (2021). 12 Insights on Hydrogen.
32. Energy Transitions Commission (2021). Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy.
33. IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change P. R. Shukla, J. Skea, R. Slade, A. al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, et al., eds. (Cambridge University Press) 10.1017/9781009157926.
34. IRENA (2022). Geopolitics of the Energy Transformation: The Hydrogen Factor.

35. Ueckerdt, F., Bauer, C., Dirnaichner, A., Everall, J., Sacchi, R., and Luderer, G. (2021). Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat Clim Chang *11*, 384–393. 10.1038/s41558-021-01032-7.