A meta-review of 54 studies on hydrogen heating

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Abstract

In the context of achieving net zero climate targets, heating poses a significant decarbonisation challenge, with buildings contributing substantially to global energy consumption and carbon emissions. While enhancing energy efficiency in building fabric can reduce emissions, complete elimination is not feasible while relying on fossil fuel-based heating systems. Hydrogen has been suggested for decarbonising buildings in recent years as a potential solution for replacing fossil-fuel heating. This paper carries out a meta-review of 54 independent studies to assess the scientific evidence for using hydrogen for heating buildings. The analysis concludes that the scientific evidence does not support a major role for hydrogen in cost-optimal decarbonisation pathways being associated with higher energy system and consumer costs. Electrification and district heating are deemed preferable due to higher efficiency and lower costs in the majority of analysed studies.

1. Introduction

Heating remains one of the most critical decarbonisation challenges in the context of net zero climate targets. Buildings contribute 30% of total global final energy consumption and 26% of global carbon emissions related to energy [1].

The initial and apparent strategy to reduce carbon emissions from buildings involves reducing the heating demand of buildings, primarily accomplished through energy efficiency measures such as enhancing insulation in building fabric. While this can decrease emissions associated with heating, complete elimination is not attainable as long as the heating system relies on fossil fuels [2].

This is why net zero scenarios also involve the decarbonisation the heat supply to buildings, such as transitioning from a fossil gas boiler to a heat pump powered by zero carbon electricity, low carbon district heating, or using low or zero carbon gases. This approach allows for the complete elimination of heating-related emissions, irrespective of whether a building has significantly reduced its heat demand through fabric insulation measures, although more efficient buildings have multiple energy system benefits especially in pathways with a large share of electrification [3,4].

In this context, green hydrogen produced from electrolysis using renewable electricity as well as blue hydrogen from steam methane reforming with carbon capture and storage has been proposed as a drop-in solution for decarbonising buildings currently using fossil gas [5,6], often by gas network operators [7] and heating system manufacturers [8].

In order to assess the scientific evidence base regarding using hydrogen for heating buildings at scale a meta-review of existing studies was carried out in 2022 showing that all 32 independent studies identified concluded that the future role for hydrogen would be limited given the lower efficiency, higher costs and larger environmental impacts [9].

Since then, an additional 22 studies have been published. This updated meta-review includes those new studies and also provides more detailed analysis of studies carried out. Similar to the first meta-review 'independent' was defined as analysis "*not carried out by or on behalf of a specific industry (e.g. gas, oil, electricity, heat pumps, boiler manufacturers)".* The updated meta-review now encompasses a total of 54 studies conducted at international, regional, national, state, and city levels by various organisations, including universities, research institutes, intergovernmental bodies such as the IPCC and the IEA, and consulting firms. Studies funded by industries have been omitted, as these studies are typically conducted to advocate positions aligned with the vested interests of industry groups**.** This does not imply the absence of rigorous analyses funded by industry. However, for the scope of this meta-review focusing on independent evidence, such industry-funded analyses have been omitted to avoid bias.

Overall, this updated meta-review confirms the findings of the 2022 meta review: the scientific evidence does not suggest a major role for hydrogen for heating in cost-optimal pathways and indicates higher system and consumer costs. Alternative pathways such as electrification and district heating are found to be preferrable by the vast majority of studies analysed due to their higher efficiency and resulting lower costs.

1.1. Modelling approaches to assess different heating decarbonisation pathways

A variety of modelling approaches are being used to assess different heating pathways:

1. Consumer cost modelling: Consumer cost modelling is concerned with the final cost to the end-user (measured for example through \$/kWh of heat delivered for different technologies). Modelling focused on energy technologies typically consider the costs of the energy carrier being used (e.g. fossil fuels, hydrogen, electricity), the capital cost of the heating system, maintenance costs, and the technical lifetime of the equipment [10]. More sophisticated consumer cost modelling also models energy system costs further upstream (for example grid expansion in the electricity sector) and builds this into consumer prices.

2. Whole energy system modelling: This approach transcends traditional sectoral boundaries. Unlike conventional models that isolate sectors, these models provide a unified view, acknowledging the dynamic feedback loops and dependencies shaping the modern energy system. By accounting for the interplay of electricity, heat, and transportation, these models facilitate a nuanced understanding of cross-sectoral effects and the potential for integrated solutions. It allows for the comparison of different technology pathways in terms of costs but also other non-monetary parameters [11,12].

3. Cost-optimisation models: The integration of cost-optimisation principles within whole energy system models allows for identifying the least-cost pathway for achieving a specific goal such as a predetermined reduction of carbon emissions from heating [13]. The output typically comprises a mix of technologies and infrastructure compliant with the least-cost pathway.

1.2. Energy supply chain for different forms of heating

In order to assess the technical, economic, and environmental impacts of heating with hydrogen compared to alternatives studies typically consider the energy supply chain, encompassing the entire journey from the primary energy input to the supply system and finally to the end-users of heat. In the case of blue hydrogen systems (based on steam methane reforming using fossil gas and carbon capture and storage), the delineation of the system boundary spans from fossil gas fields to the hydrogen boiler. For renewable energy systems, the system boundary extends from the juncture where renewable power is introduced into the power transmission grid to hydrogen boilers or heat pumps. It is useful to sketch out the energy supply chain related to different heating system technologies and below this is done in an illustrative fashion. The numbers used are not representative of the studies analysed in this paper, do not represent specific units, and only serve for illustrative purposes.

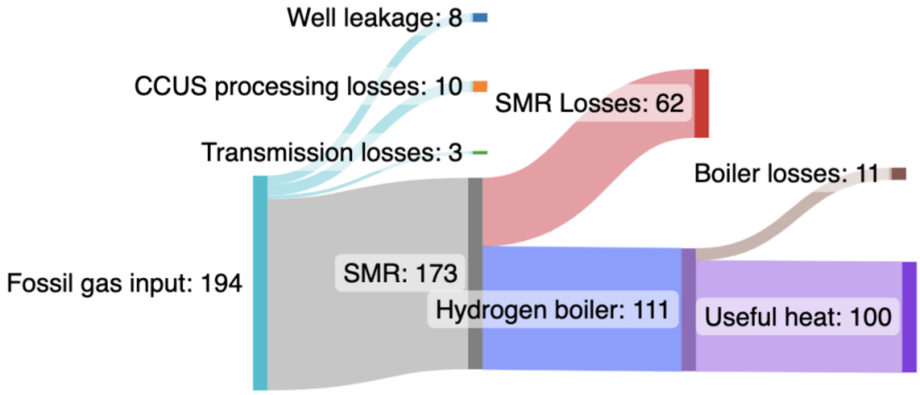
Making the same assumptions as Gudmundsson and Thorsen [14] Figure 1 depicts the energy flow diagram for heating with blue hydrogen:

- Fossil gas is extracted with 4% leakage and processed at 94% efficiency with carbon capture, utilization, and storage (CCUS), to standard fossil gas qualities at the gas reservoir.
- Processed fossil gas is then transported to the periphery of an urban centre through a transmission system with 1.5% transmission losses.
- Hydrogen is produced through steam methane reforming (SMR) with an efficiency of 65%, coupled with 90% efficient CCUS. The hydrogen production is tailored to meet instantaneous demand, eliminating the need for hydrogen storage facilities.
- The hydrogen generated from the SMR plant is at a pressure sufficient for the operation of the hydrogen distribution grid, eliminating the necessity for additional compression.
- Condensing hydrogen boilers operate with an efficiency of 90%.

The overall fossil gas input to useful heat efficiency is 52%.

More optimistic or pessimistic assumptions regarding efficiency can of course be made and the diagram is purely illustrative to explain the steps and conversion losses involved in heating with blue hydrogen from extraction of fossil gas to the hydrogen boiler.

Figure 1: Energy flow diagram for blue hydrogen heating

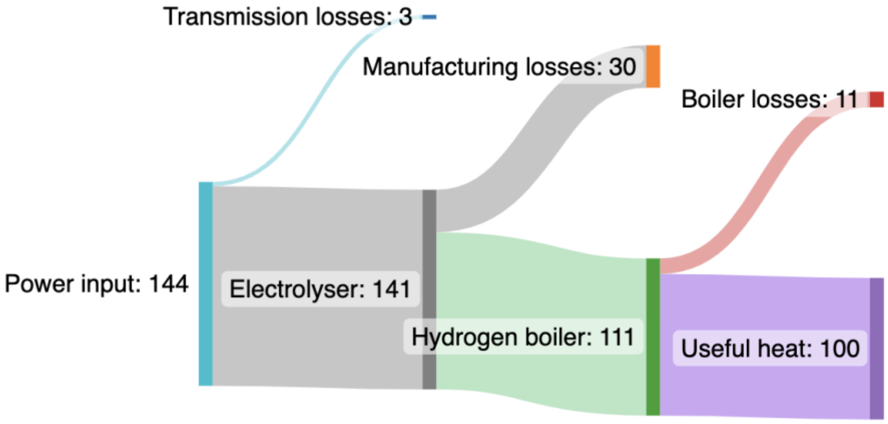


Again following the same assumptions as Gudmundsson and Thorsen [14] the efficiencies in the green hydrogen (hydrogen from electrolysis powered by renewable electricity) scenario are as follows:

- Transmission of power from renewable power generation units to the electrolysis plant is assumed to be 98.3% efficient.
- The manufacturing of green hydrogen utilises an alkaline electrolysis plant with an assumed efficiency of 79%.
- The hydrogen produced by the electrolysis plant is at a sufficient pressure for hydrogen grid operation, eliminating the need for additional compression.
- Condensing hydrogen boilers operate with an assumed efficiency of 90%.

Considering these assumptions, the overall efficiency of the green hydrogen system is approximated at 70%. This implies that, for generating 100 units of useful end-user energy, 144 units of renewable power generation would be required, as illustrated in Figure 2.

Figure 2: Energy flow diagram for green hydrogen heating

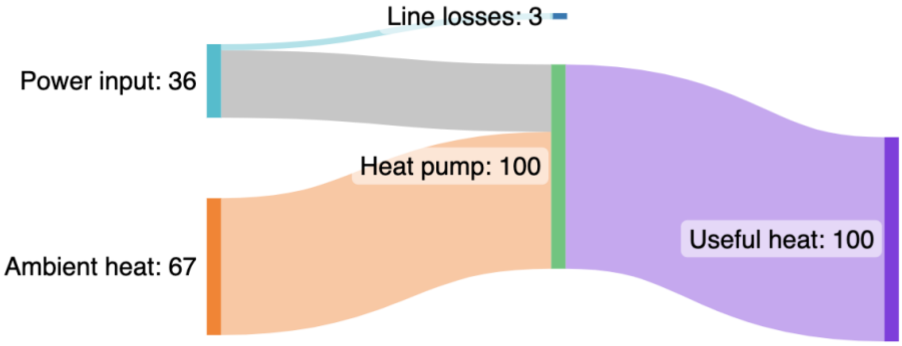


The energy flow for an individual heat pump is depicted in Figure 3. It is assumed:

- Combined transmission and distribution losses of 8%.
- A Seasonal Coefficient of Performance for the heat pump of 3.0.

The overall power input to useful heat efficiency is 278%.

Figure 3: Energy flow diagram for a heat pump

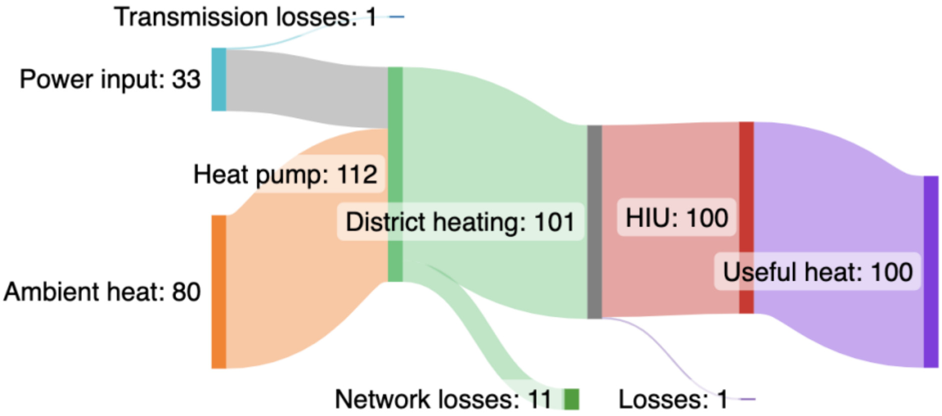


Using the same assumptions as Gudmundsson and Thorsen [14]:

- Renewable power is conveyed from generation units to a large heat pump with an assumed efficiency of 98.3%.
- The generation of heat takes place at a centrally located heat pump plant, utilising ambient heat as a heat source, operating with a Seasonal Coefficient of Performance of 3.5.
- The distribution grid for district heating is presumed to be 90% efficient with 10% losses.
- End-users utilize standard district heating heat interface unit systems with an efficiency of 99%.

The overall power input to useful heat efficiency is 303%.

Figure 4: Energy flow diagram for district heating driven by a heat pump



The diagrams depict the energy supply chain for the different heating technologies in a rather simplistic fashion. Whole energy systems models will account for dynamics regarding power input and the required upstream infrastructure including generation capacity, transmission and distribution, and storage amongst other elements of the energy system at a highly level of spatial and time-dynamic granularity [11,12].

2. Results

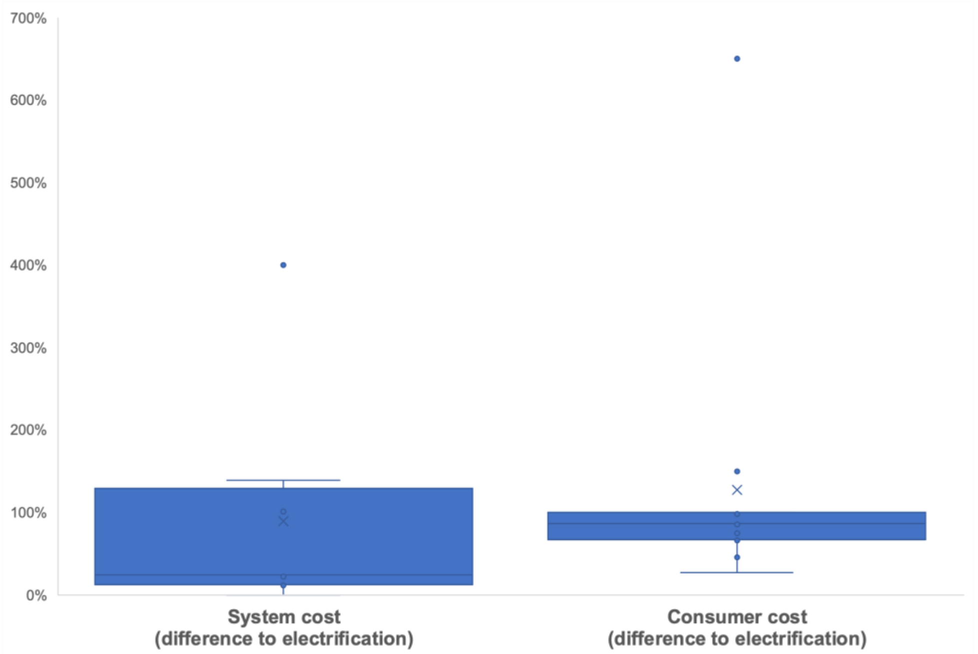
The outcomes of the meta-review are organized into three sections: Initially, a comparison is drawn between the cost estimates of hydrogen pathways and electrification. Subsequently, the representation of hydrogen in cost-optimisation models is detailed. Lastly, the identified studies are listed along with concise summaries for each.

2.1. Cost differences of hydrogen pathways compared to alternative technologies

Figure 5 shows the difference in system costs of hydrogen pathways compared to electrification (either direct or via district heating) and the consumer cost difference between hydrogen and electrification. Any value above 0% indicates a higher cost of the hydrogen pathway and any value below 0% indicates a lower cost of the hydrogen pathway. In other words, a +50% figure suggests 50% higher costs for the hydrogen pathway.

For the energy system costs the median is +24% and for the consumer costs the median is +86%. There is a wide range of cost estimates both for system costs (0%-400%) and consumer costs (27%-60%). Energy system costs are higher for the hydrogen pathway in all but one study [15]. In none of the studies assessed is hydrogen cheaper from a consumer cost perspective than electrification.

Figure 5: Range of hydrogen system cost (n=8) and consumer costs (n=13) compared to electrification

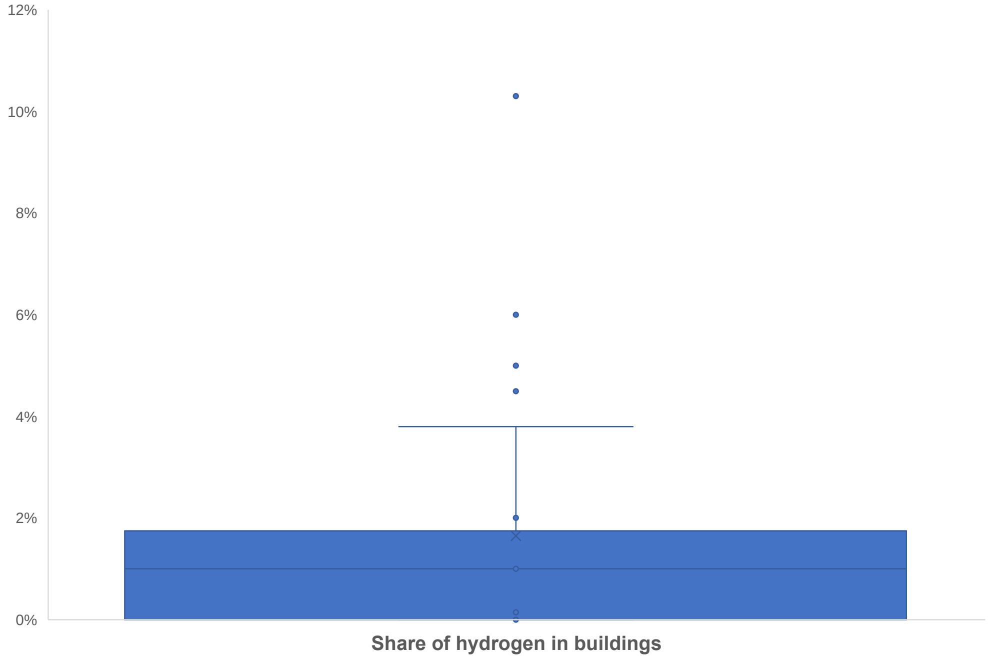


Sources: data from 7 system cost studies [15,16,17 (does not include consumer costs),18 (used WTL scenario),19–22] and 13 consumer cost studies [16,19,23–30,31 (compared to green hydrogen),32,33 (mid-point figure)]

2.2. Cost-optimisation studies and the contribution of hydrogen to heating

Figure 6 depicts the contribution of hydrogen for final energy demand for heating in the different studies. The median of all studies is 1% with a range of 0%-10%. This suggests that there may be some very limited role for hydrogen for heating but only as a complementary technology with the bulk of heating provided by other means.

Figure 6: Contribution of hydrogen to final energy demand for heating (n=24)



Sources: data from 24 studies [34–52,53 (mid-point figure),54–57]

2.3. Summary of all studies identified and analysed

For information, all studies identified and analysed for this review are also presented in the tables below with a brief summary. This table includes studies not referenced in the figures above because they did not provide quantitative figures for the comparative costs or share of hydrogen for heating. Most of these studies are evidence reviews [58–63] except for one analysis of environmental impacts of heating with hydrogen [64].

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	Aunedi et al. 2022	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.
	Aunedi et al. 2022	UK	2030-2040, 2040–2050 and 2050–2060.	In the cost-optimal scenario the bulk of heat demand being supplied by electric heat pumps with hydrogen playing a role for delivering peak heat demand.
	Aurora 2023	UK	2050	Total system costs of the maximum heat pump scenario are lowest of all modelled pathways including hydrogen.
	Beckford et al. 2023	UK	2050	Less than 1% of heating by 2050 is expected to come from hydrogen.
	Billerbeck et al. 2023	EU	2050	Decarbonisation pathways for space and water heating based on large shares of heat pumps have at least 11% lower system costs in 2050 than pathways with large shares of hydrogen or synthetic fuels.
	BNEF 2023	Global	2050	Hydrogen provides 4% in the cost-optimal pathway.
	Broad et al. 2020	UK	2050	Modelling least-cost pathway to achieve 100% decarbonisation does not include hydrogen for heating.

	Capros et al., 2019	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.
	Cassarino and Barrett, 2022	UK	2050	Hydrogen-dominated heating would cost consumers 73% more compared to pathways relying on district heating and heat pumps.
	Committee on Climate Change 2020	UK	2050	Hydrogen provides 6% in the cost-optimal pathway.
	Deloitte 2023	Global	2050	Hydrogen provides 1% in the cost-optimal pathway.
	European Commission 2021	EU	2050	Hydrogen provides 10% in the cost-optimal pathway.
	Giehl et al. 2023	Germany	2050	Total annual energy system cost in the hydrogen scenario is more than four times higher than in the electrification scenario.
	Hoseinpoori et al. 2023	UK	2050	The total system transition cost is relatively close in all scenarios ranging from complete electrification to complete conversion of the gas grid to hydrogen.
	IEA 2023	Global	2050	Least-cost pathway includes 0% hydrogen for decarbonising buildings.
	IEA 2021	Global	2050	Least-cost pathway includes <2% hydrogen for decarbonising buildings.
	ifeu et al., 2019	Germany	2050	Energy efficiency and electrification associated with significantly lower costs than hydrogen pathways.
	IPCC 2022	Global	2050	Concludes that cost of heat from hydrogen would be much higher than from heat pumps and models close to 0% of heating buildings provided by hydrogen.
	IRENA 2023	Global	2050	Hydrogen provides 0.1% in the cost-optimal pathway.
	Jalil-Vega et al., 2020	Sao Paulo, Brazil	2050	In 2050 modelled cost-optimal heat decarbonisation pathways most heating is supplied via electrification.
	Keramidas et al. 2022	EU	2050	Hydrogen provides 1% in the cost-optimal pathway.
	Korberg et al. 2023	EU27+UK	2050	Use of hydrogen for heating, especially in urban contexts where district heating can be a viable alternative, significantly increases the costs of the energy system.
	Kranzl et al., 2022	EU	2030, 2040, 2050	Best-case scenario (lowest system cost) contains no hydrogen used for heating.
	LCP Delta 2023	UK	2050	Hydrogen for heating entails twice as high grid infrastructure costs as electrification. Electrification identified as the cheapest option for all 12 of the defined location archetypes.
	Luderer et al., 2022	Global	2050	Electrification accelerates to an 88% share in the 1.5C-Elec scenario with almost no hydrogen used for heating.
	Martin Scheepers et al., 2022	Netherlands	2050	Between 1% and 9% of heating provided by hydrogen. Data underlying analysis obtained from (M. Scheepers et al., 2022).
	McKinsey & Company, 2022	Global	2050	In least-cost pathway majority of heating systems in 2050 are assumed to be heat pumps.
	Olympios et al., 2022	UK	2035	Total system cost per household associated with hydrogen boilers equate to £1,600/year compared to £860/year for heat pumps.
	Oshiro and Fujimori, 2022	Global	2050	Hydrogen for heating is negligible (close to zero) across all scenarios modelled for cost optimisation.
	Quarton and Samsatli, 2020	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.
	Panos et al. 2023	Switzerland	2050	Least-cost pathway includes 1% hydrogen for decarbonising buildings.

	Röben et al., 2022	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.
	Sheikh and Callaway, 2019	California	2019	In California hydrogen would cost 3-10 times more than electrification of heating mainly through heat pumps.
	Simon et al., 2022	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.
	Victoria et al., 2022	EU27+UK	2050	The main strategies are for decarbonisation of heating are electrification. District heating uses waste heat from hydrogen production.
	Weidner and Guillén-Gosálbez 2023	EU27+UK	2040	Green hydrogen 2–3 times more expensive than electrification while transgressing several planetary boundaries.
	Wietschel et al. 2023	Germany	2045	No demand for hydrogen for heating forecasted in the model.

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	Baldino et al. 2021a	EU	2050	Hydrogen for heating at least twice as expensive as heat pumps.
	Baldino et al. 2020	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.
	Baldino et al. 2021	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.
	Baldino et al. 2021b	Netherlands	2050	All hydrogen scenarios are at least twice higher in cost than heat pumps.
	Element Energy 2022	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.
	Matthes et al. 2021	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.
	Meyer et al. 2021	Germany	2030	Hydrogen heating technologies 1.4-2.1 times more expensive than heat pumps.
	Ryland and He 2022	UK	n/a	Green hydrogen almost 2 times more expensive than heat pumps.
	Thomas et al. 2021	Germany	n/a	Hydrogen heating 5 times less efficient than heat pumps regarding the required amount of electricity.

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	Slorach and Stamford 2021	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	Agora Energiewende and Agora Industry 2021	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.
	EASAC 2023	EU	n/a	Renewable hydrogen identified as uncompetitive for heating buildings compared to heat pumps and district heating.
	Energy Transitions Commission 2021	Global	n/a	Low confidence and lowest readiness level of hydrogen for heating.
	IRENA 2022	Global	n/a	Residential heating assigned the lowest priority of hydrogen applications.
	Riemer et al. 2022	Global	2030, 2040, 2050	The median share is predicted to be less than 2% of final energy demand in buildings in 2050 in all regions.
	Ueckerdt et al. 2021	Global	2020-2050	Hydrogen not recommended for heating due to inefficiencies and higher costs.
	Wietschel et al. 2021	Global, EU, Germany	n/a	Majority of studies reviewed suggest more significant role for electrification.

3. Discussion

This meta-review indicates that the scientific evidence pertaining to hydrogen heating is unambiguous. None of the independent studies analysed in this review suggests a significant role for hydrogen in space or hot water heating, points to a pathway dominated by hydrogen as the least-cost pathway, or suggests lower consumer costs for hydrogen compared with the alternatives such as electrification and district heating. The fundamental reason for this finding goes back to the introduction of this paper and the underlying thermodynamics: Heating with hydrogen is significantly less efficient compared to heat pumps and district heating combined with heat pumps requiring around 4-6 times more energy input depending on the input parameters.

This is not to say that there is no role for hydrogen in heating at all. Some of the studies carried out suggest a limited role for hybrid heating solutions, for example in areas with industrial clusters with high hydrogen use and production. A recent review of the performance of heat pumps in cold climates also considers hybrid heating systems may be required for very cold temperatures given that heat pump performance drops with decreasing outside temperatures [65] and heat demand is highly seasonal. Many of the whole energy system studies also explicitly considered the potential for using hydrogen as a storage medium and in hybrid systems and hydrogen is also included in the electricity system for long-durational storage by many of the whole energy system models. However, the share of hydrogen of final energy used for heating according to the studies reviewed would be very low in a cost-optimal pathway (median = 1%).

Of course, hydrogen technologies will become more efficient over time and costs will most likely decline. But such cost-reductions are built into the modelling studies assessed in this paper already and given the underlying physics and conversion efficiencies the relative economics of hydrogen compared with alternative technologies are unlikely to change fundamentally.

Another consideration is scalability and the practicability to produce vast quantities of clean hydrogen within the timescales required to decarbonise heating. At the moment, green and blue hydrogen provide less than 1% of total hydrogen production with the majority of hydrogen coming from unabated fossil fuels [66,67]. Even if green hydrogen grew as fast as wind and solar have grown it would only contribute 0.7%–3.3% to global energy demand in 2040 [68]. When assuming similar growth rates for green hydrogen as for technologies with unconventionally high growth rates that have been achieved under very specific circumstances (emergency deployment e.g. during a war) the result of scaling electrolysis is that green hydrogen would provide 6.6%–7.8% of global final energy demand by 2040.

Even just achieving the scale up of green hydrogen we need to satisfy demand in industry, hydrogen derivates for shipping and long-durational storage in the power sector to meet net zero is extremely challenging and will require strong policy support. This suggests that assuming hydrogen could play a major role for heating buildings is at best a risky strategy and at worst a dead end locking in new fossil fuel infrastructure. A poor outcome for carbon emission reductions of an approach relying on hydrogen being widely available for heating in the future would be to delay policy implementation focusing on the rollout of tried and tested technologies today.

In conclusion, Despite the considerable focus on hydrogen for heating, a thorough examination of independent evidence fails to substantiate the widespread adoption of hydrogen for space and hot water heating. A comprehensive review, encompassing 54 independent studies, reveals that none of them presents compelling evidence in favour of extensively utilizing hydrogen for heating purposes. However, some studies acknowledge complementary roles for hydrogen, particularly in district heating and hybrid heating systems. Only one study found that the energy system costs of hydrogen were comparable to electrification, but the rest found that the costs were considerably higher.

In light of these findings, policymakers are strongly encouraged to scrutinise existing research diligently before allocating substantial public funds for hydrogen heating initiatives or drafting decarbonisation strategies centred around hydrogen for heating as a bulk solution.

4. Experimental Procedures

This meta-review follows the same methodology as the original study carried out in 2022 [9].

A Rapid Evidence Assessment (REA) was conducted and subsequently updated following a comprehensive meta-review in 2022 to identify existing studies related to hydrogen-based heating. The REA methodology is a well-established approach for systematically locating and evaluating extant research within a specific domain, aiming to establish the current state of knowledge on a subject and provide valuable insights for informing policy decisions.[69] This paper aligns with the REA guidelines developed by the UK Energy Research Centre (UKERC), a framework frequently applied in energy research.[70]

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).

To gather pertinent literature, online databases such as Web of Science and Academic Search Complete were used. Furthermore, Google Scholar was employed to uncover grey literature, with a restriction imposed on the analysis of only the first 200 results for each set of search terms. The research strategy involved the utilization of Boolean combinations of relevant terms, as detailed in 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 apply:

- Only evidence published since 01 January 2019 was taken into account.
- Only publications in English and German were reviewed due to language proficiency limitations.
- Publications conducted by or on behalf of a specific industry were excluded. Information on funding used for the undertaking of the studies was obtained from the acknowledgements in the different studies. Where funding was provided by industry or industry association the study was excluded from the meta-review.

The identified studies indicate a significant concentration of national-level analysis in a few countries, primarily Germany and the UK. This concentration is likely due to the REA's focus on English and German languages and because these countries have been prolific in producing research on hydrogen-based heating.

To ascertain relevance, the returned results were initially filtered based on the title and abstract. When this initial filter was insufficient, the main text was examined. The criteria for establishing relevance included:

- research related to the use of hydrogen for space and/or hot water heating in buildings;
- modelling of system and/or consumer costs associated with using hydrogen for space and/or hot water heating in buildings in comparison to alternative technologies; and
- evidence reviews pertaining to the use of hydrogen for space and/or hot water heating in buildings.

After the filtering process, key descriptive information was collected for each retained result, including:

- geographic focus
- type of analysis (energy systems modeling, consumer cost modeling, and evidence reviews).
- year to which the findings are applicable (if specified)
- findings regarding the relative costs of heating with hydrogen compared to alternative technologies

- findings regarding the efficiency of heating with hydrogen compared to alternative technologies
- findings concerning the environmental impacts of heating with hydrogen compared to alternative technologies

5. References

1. IEA (2023). Buildings. https://www.iea.org/energy-system/buildings.
2. Rosenow, J., and Hamels, S. (2023). Where to meet on heat? A conceptual framework for optimising demand reduction and decarbonised heat supply. Energy Res Soc Sci *104*, 103223. https://doi.org/10.1016/j.erss.2023.103223.
3. Lowes, R., Rosenow, J., Qadrdan, M., and Wu, J. (2020). Hot stuff: Research and policy principles for heat decarbonisation through smart electrification. Energy Res Soc Sci *70*, 101735. https://doi.org/10.1016/j.erss.2020.101735.
4. Palmer, J., and Terry, N. (2021). Cost Optimal Domestic Electrification (CODE). BEIS Research Paper 2021/051 .
5. Lowes, R., Woodman, B., and Speirs, J. (2020). Heating in Great Britain: An incumbent discourse coalition resists an electrifying future. Environ Innov Soc Transit *37*, 1–17. https://doi.org/10.1016/j.eist.2020.07.007.
6. Szabo, J. (2022). Energy transition or transformation? Power and politics in the European natural gas industry's trasformismo. Energy Res Soc Sci *84*, 102391. https://doi.org/10.1016/j.erss.2021.102391.
7. ENA (2023). Tomorrow's Heat, Today's Opportunity. https://www.energynetworks.org/campaigns/tomorrows-heat-todays-opportunity.
8. EHI (2021). EHI position paper on the use of green gases for heating .
9. Rosenow, J. (2022). Is heating homes with hydrogen all but a pipe dream? An evidence review. Joule *6*, 2225–2228. 10.1016/j.joule.2022.08.015.
10. Sun, Y., Ogden, J., and Delucchi, M. (2010). Societal lifetime cost of hydrogen fuel cell vehicles. Int J Hydrogen Energy *35*, 11932–11946. https://doi.org/10.1016/j.ijhydene.2010.08.044.
11. Pye, S., and Bataille, C. (2016). Improving deep decarbonization modelling capacity for developed and developing country contexts. Climate Policy *16*, S27–S46. 10.1080/14693062.2016.1173004.
12. Lopion, P., Markewitz, P., Robinius, M., and Stolten, D. (2018). A review of current challenges and trends in energy systems modeling. Renewable and Sustainable Energy Reviews *96*, 156–166. https://doi.org/10.1016/j.rser.2018.07.045.
13. Nakata, T. (2004). Energy-economic models and the environment. Prog Energy Combust Sci *30*, 417–475. https://doi.org/10.1016/j.pecs.2004.03.001.
14. Gudmundsson, O., and Thorsen, J.E. (2022). Source-to-sink efficiency of blue and green district heating and hydrogen-based heat supply systems. Smart Energy *6*, 100071. https://doi.org/10.1016/j.segy.2022.100071.
15. Hoseinpoori, P., Hanna, R., Woods, J., Markides, C.N., and Shah, N. (2023). Comparing alternative pathways for the future role of the gas grid in a low-carbon heating system. Energy Strategy Reviews *49*, 101142. https://doi.org/10.1016/j.esr.2023.101142.
16. Aurora (2023). Decarbonising heating systems: evidence and options (B). Energy sector modelling to support the second National Infrastructure Assessment. Prepared for the National Infrastructure Commission.
17. LCP Delta (2023). Heating homes in different regions of Great Britain. A study on locational costs of electricity and gas network infrastructure.

18. Weidner, T., and Guillén-Gosálbez, G. (2023). Planetary boundaries assessment of deep decarbonisation options for building heating in the European Union. Energy Convers Manag *278*, 116602. https://doi.org/10.1016/j.enconman.2022.116602.
19. Cassarino, T.G., and Barrett, M. (2022). Meeting UK heat demands in zero emission renewable energy systems using storage and interconnectors. Appl Energy *306*, 118051.
20. Billerbeck, A., Kiefer, C.P., Winkler, J., Bernath, C., Sensfuß, F., Kranzl, L., Müller, A., and Ragwitz, M. (2024). The race between hydrogen and heat pumps for space and water heating: A model-based scenario analysis. Energy Convers Manag *299*, 117850. https://doi.org/10.1016/j.enconman.2023.117850.
21. Korberg, A.D., Thellufsen, J.Z., Skov, I.R., Chang, M., Paardekooper, S., Lund, H., and Mathiesen, B.V. (2023). On the feasibility of direct hydrogen utilisation in a fossil-free Europe. Int J Hydrogen Energy *48*, 2877–2891. https://doi.org/10.1016/j.ijhydene.2022.10.170.
22. Giehl, J., Hollnagel, J., and Müller-Kirchenbauer, J. (2023). Assessment of using hydrogen in gas distribution grids. Int J Hydrogen Energy *48*, 16037–16047. https://doi.org/10.1016/j.ijhydene.2023.01.060.
23. Baldino, C., O'Malley, J., Searle, S., and Christensen, A. (2020). Hydrogen for heating? Decarbonization options for households in the United Kingdom in 2050. Preprint.
24. Baldino, C., O'Malley, J., Searle, S., and Christensen, A. (2021). Hydrogen for heating? Decarbonization options for households in the European Union in 2050. Preprint.
25. Baldino, C., O'Malley, J., Searle, S., and Christensen, A. (2021). Hydrogen for Heating? Decarbonization Options for Households in the Netherlands in 2050. Preprint.
26. Baldino, C., O'Malley, J., Searle, S., and Christensen, A. (2021). Hydrogen for heating? Decarbonization options for households in Germany in 2050.
27. Element Energy (2022). The Consumer Costs of Decarbonised Heat.
28. 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.
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. 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.
31. Ryland, M., and He, W. (2022). Heating economics evaluated against emissions: An analysis of low-carbon heating systems with spatiotemporal and dwelling variations. Energy Build *277*, 112561. https://doi.org/10.1016/j.enbuild.2022.112561.
32. 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.
33. Sheikh, I., and Callaway, D. (2019). Decarbonizing Space and Water Heating in Temperate Climates: The Case for Electrification. Atmosphere (Basel) *10*. 10.3390/atmos10080435.

34. Aunedi, M., Olympios, A. V, Pantaleo, A.M., Markides, C.N., and Strbac, G. (2023). System-driven design and integration of low-carbon domestic heating technologies. Renewable and Sustainable Energy Reviews *187*, 113695. https://doi.org/10.1016/j.rser.2023.113695.
35. 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.
36. Beckford, T., Jackson-Johns, G., Daoud, A., Finn, G., and Dowden, T. (2023). The Role of Hydrogen and Batteries in Delivering Net Zero in the UK by 2050.
37. 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.
38. BNEF (2023). New Energy Outlook 2022.
39. Committee on Climate Change (2021). Sixth Carbon Budget report. .
40. European Commission (2021). Energy scenarios - Explore the future of European energy. https://visitors-centre.jrc.ec.europa.eu/en/media/tools/energy-scenarios-explorefuture-european-energy.
41. IEA (2023). A renewed pathway to net zero emissions.
42. IEA (2021). Net Zero by 2050. A Roadmap for the Global Energy Sector.
43. 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.
44. IRENA (2023). World Energy Transitions Outlook 2023: 1.5oC Pathway.
45. 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.
46. Keramidas, K., Fosse, F., Diaz Rincon, A., Dowling, P., Garaffa, R., Ordonez, J., Russ, P., Schade, B., Schmitz, A., Soria Ramirez, A., et al. (2022). Global Energy and Climate Outlook 2022: Energy trade in a decarbonised world (Publications Office of the European Union) 10.2760/863694 (online).
47. 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.
48. 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.
49. McKinsey & Company (2022). The net zero transition. What if would cost, what it could bring.
50. 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.
51. 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.

52. Panos, E., Kannan, R., Hirschberg, S., and Kober, T. (2023). An assessment of energy system transformation pathways to achieve net-zero carbon dioxide emissions in Switzerland. Commun Earth Environ *4*, 157. 10.1038/s43247-023-00813-6.
53. 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.
54. 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.
55. 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.
56. Wietschel, M., Weißenburger, B., Rehfeldt, M., Lux, B., Zheng, L., and Meier, J. (2023). Preiselastische Wasserstoffnachfrage in Deutschland - Methodik und Ergebnisse 10.24406/publica-856.
57. Deloitte (2023). Green hydrogen: Energizing the path to net zero- Deloitte's 2023 global green hydrogen outlook.
58. EASAC (2023). The Future of Gas.
59. Agora Energiewende, and Agora Industry (2021). 12 Insights on Hydrogen.
60. IRENA (2022). Geopolitics of the Energy Transformation: The Hydrogen Factor.
61. 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.
62. Wietschel, M., Zheng, L., Arens, M., Hebling, C., Ranzmeyer, O., Schaadt, A., Hank, C., Sternberg, A., Herkel, S., Kost, C., et al. (2021). Metastudie Wasserstoff – Auswertung von Energiesystemstudien - Studie im Auftrag des Nationalen Wasserstoffrats.
63. Riemer, M., Zheng, L., Eckstein, J., Wietschel, M., Pieton, N., and Kunze, R. (2022). Future hydrogen demand: A cross-sectoral, global meta-analysis 10.24406/publica-339.
64. 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.
65. Gibb, D., Rosenow, J., Lowes, R., and Hewitt, N.J. (2023). Coming in from the cold: Heat pump efficiency at low temperatures. Joule *7*, 1939–1942. 10.1016/j.joule.2023.08.005.
66. Rosenow, J., and Lowes, R. (2021). Will blue hydrogen lock us into fossil fuels forever? One Earth *4*, 1527–1529.
67. IEA (2023). Global Hydrogen Review 2023.
68. Odenweller, A., Ueckerdt, F., Nemet, G.F., Jensterle, M., and Luderer, G. (2022). Probabilistic feasibility space of scaling up green hydrogen supply. Nat Energy *7*, 854–865. 10.1038/s41560-022-01097-4.
69. Fell, M.J. (2019). The Economic Impacts of Open Science: A Rapid Evidence Assessment. Publications *7*. 10.3390/publications7030046.
70. Speirs, J., Gross, R., and Heptonstall, P. (2015). Developing a Rapid Evidence Assessment (REA) Methodology A UKERC TPA Technical Document.