hydrogen

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Review

Meta-Analysis of Hydrogen's Role in Residential Heat Decarbonization

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Abstract

Hydrogen is a potential energy carrier for the decarbonization of the heating sector; however, its long-term role remains highly debated. This meta-analysis (2024–early 2025) assesses hydrogen's potential for domestic heating regarding consumption, costs, and environmental impacts. Current scientific evidence distinguishes between hydrogen use for direct residential heating and its role in integrated energy systems. For residential decarbonization, the literature does not support hydrogen as a primary solution: electrification, especially through heat pumps, remains the most efficient and cost-effective long-term pathway. Direct hydrogen heating faces major thermodynamic and economic barriers, including low conversion efficiency, high Levelized Costs of Energy (LCOE), infrastructure limitations, and challenges in achieving broad social acceptance. Hydrogen's more strategic value emerges at the system level. Hybrid configurations that combine heat pumps with hydrogen storage show strong potential by using heat pumps to efficiently meet thermal demand while reserving hydrogen for flexible backup and storage. In particular, hydrogen is well suited for long-term seasonal energy storage and grid balancing, enhancing system flexibility and reliability. Its main contribution therefore lies not in direct end-use heating, but in strengthening grid resilience and supporting energy autarky in net-zero scenarios. Hydrogen blending into existing gas networks is widely viewed as a transitional measure to stimulate the hydrogen economy and deliver limited short-term emission reductions, rather than a definitive net-zero solution. Overall, hydrogen's residential role remains niche, requiring targeted research, development, and large-scale pilot projects to validate competitive applications.

Keywords: hydrogen; residential heating; decarbonization; electrification; energy costs; environmental impacts; social acceptance; techno-economic feasibility; grid resilience; seasonal energy storage; heat pump

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1. Introduction

The escalating urgency of mitigating climate change is creating a global imperative to decarbonize energy systems, prompting significant research and investment in alternative energy carriers [1]. The European Union's goal of achieving climate neutrality by 2050, as set out in the European Climate Law, highlights the urgent need for a significant and rapid transformation of the energy landscape [2]. This transition is further complicated by persistent global energy demand, which continues to rise despite decarbonization efforts [1]. The building sector plays a central role in this context, accounting for a significant share of global greenhouse gas (GHG) emissions [1,3,4]. Decarbonizing residential heating has therefore become a key component of climate policy and a major challenge on the path toward net-zero emissions. Shifting households away from fossil fuel-based heating is not only desirable but essential to achieving climate neutrality. In specific national contexts, such as Italy, the residential sector is the second-largest energy consumer, accounting for 30% of total consumption and 26% of emissions. Meeting the 2050 net-zero target thus requires a deep transformation of residential heating systems. Hydrogen holds significant potential for heat decarbonization, providing a cleaner combustion alternative to traditional fossil fuels [5].

In the search for viable decarbonization pathways, hydrogen has emerged as a leading candidate. As a versatile energy carrier, it can be produced through various methods, commonly distinguished by a color-based nomenclature. These range from "gray" hydrogen produced from fossil fuels with high associated emissions, to "blue" hydrogen where these emissions are captured, and "green" hydrogen, which is produced via electrolysis powered by renewable electricity, resulting in near-zero emissions [6–8]. As an energy carrier, hydrogen can convey and store energy, which is crucial for solving the problems of intermittency and storage associated with renewable sources, such as solar and wind power [9]. In the residential sector, the proposed applications of hydrogen are diverse and include its use in pure hydrogen boilers, its blending with the existing natural gas supply and its use in powering high-efficiency micro-combined heat and power (m-CHP) fuel cell systems [3,10]. Despite its potential, hydrogen remains a highly controversial solution. On the one hand, its proponents highlight its potential for energy security and system flexibility. On the other hand, its critics point to significant efficiency losses and high costs [3,11]. Specifically, the high capital expenditure of technologies like Proton Exchange Membrane Fuel Cells (PEMFCs) is largely driven by the use of expensive noble-metal catalysts, such as platinum, and specialized perfluorosulfonic acid (PFSA) membrane materials, alongside the complexity of the required Balance of Plant (BOP) components. Furthermore, the technical challenge of managing non-uniform temperature distribution is critical to prevent catalyst sintering and membrane dehydration [6,12]. Beyond initial capital costs, the long-term economic and technical viability is challenged by efficiency losses primarily linked to degradation and durability issues; fuel cells undergo gradual performance degradation during long-term operation [10,13]. This decline is triggered by complex mechanisms including electrode material degradation, catalyst loss, and mechanical damage to the membrane electrode assembly (MEA), all of which are often exacerbated by fluctuations in operating conditions and frequent start-stop cycles [6,14]. This degradation not only reduces efficiency and power output but also shortens service life, leading to higher maintenance and replacement expenditures è [3,12,13]. Therefore, the widespread adoption of hydrogen is constrained by significant challenges that require a comprehensive understanding of technological advancements, infrastructure implications, economic viability, and societal acceptance [3]. Key issues include the following:

- Environmental Footprint: the necessity of minimizing CO_2 emissions resulting from current production methods (e.g., gray/blue hydrogen).
- Infrastructure and Safety: the urgent need for substantial infrastructural modifications for safe and efficient transport and distribution.
- Competitiveness and Acceptance: The requirement to establish long-term economic competitiveness and gain widespread societal acceptance.

Scientific research on the application of hydrogen in the building sector is a rapidly evolving and debated field. While some studies indicate its feasibility for heat decarbonization, others question its long-term, primary role, often favoring direct electrification pathways. The debate on using hydrogen for residential heating has stimulated a significant amount of research. This has generated a complex and often contradictory body of scientific and technical evidence. Without a consolidated framework of scientific evidence, policy-makers, investors and the public are left to navigate a fragmented landscape, hindering the development of coherent and effective decarbonization strategies.

While several review and meta-review studies have explored the role of hydrogen in building heating, most have focused on isolated technical or economic aspects. In contrast, this study examines the most recent peer-reviewed literature (2024–early 2025), incorporating newly available empirical evidence and emerging research directions that earlier reviews did not capture. By highlighting these recent contributions, it offers an up-to-date and comprehensive perspective on the evolving landscape of hydrogen in residential heating.

This paper aims to advance the discussion on hydrogen by providing a comprehensive and up-to-date overview of its multifaceted role in future energy systems, with a particular focus on residential heating. To this end, we conduct a systematic meta-analysis of recent studies (2024–early 2025), offering an updated framework of scientific and technological evidence that identifies opportunities, limitations, and future directions for hydrogen implementation in residential heating. The framework evaluates four key dimensions:

1. Techno-economic feasibility, including comparative costs and overall energy efficiency.
2. System-level opportunities, particularly regarding grid integration, flexibility, and energy storage.
3. Critical limitations and barriers, spanning infrastructure, cost, and safety concerns.
4. Social acceptance, including public perceptions, consumer preferences, and trust.

By synthesizing the latest empirical data and modeling results, this analysis seeks to provide a clear, evidence-based assessment to inform future policy, research, and investment decisions in residential hydrogen applications.

2. Materials and Methods

The study followed a structured approach to provide a comprehensive, transparent, and replicable synthesis of recent literature. A robust search strategy was developed to identify relevant academic studies.

The systematic literature search was conducted using the Scopus database. The search strategy applied the following query: TITLE-ABS-KEY (search strings reported in Table 1), with results filtered to include publications from January 2024 to early 2025. The review was restricted to peer-reviewed journal articles published in English. The gray literature was consulted exclusively to provide contextual information on policy and regulatory frameworks but was deliberately excluded from the formal synthesis to ensure consistency, reproducibility, and a high level of peer-reviewed rigor in the analyzed dataset.

Table 1. Search strategy and initial results for the systematic review.

Boolean Operator	# Initial Rec.	# Rec. Screened	# Rec. Included
hydrogen AND "space heating"	19	8	3
hydrogen AND "home heating"	21	14	12
hydrogen AND heating AND buildings	126	46	26
hydrogen AND heating AND homes	21	17	13
hydrogen AND "heat pumps"	115	35	21
hydrogen AND electrification AND heating	43	8	5
Total	345	124	50

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To minimize selection bias, two authors independently performed the title and abstract screening. Full-text eligibility was then assessed against the inclusion criteria. Any discrepancies were resolved through discussion and consensus. Studies were included if they quantitatively or qualitatively assessed hydrogen applications in residential heating, whereas studies focusing exclusively on industrial use, transportation, or purely theoretical concepts were excluded.

The systematic review was conducted following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement. The initial literature search was performed in the Scopus database, utilizing various combinations of Boolean operators to ensure comprehensive coverage of the topic (Table 1).

The selection process is fully detailed in the PRISMA flow diagram (Figure 1). This diagram visually summarizes the four stages of the process (Identification, Screening, Eligibility, and Inclusion) and was generated using the PRISMA Flow Diagram web tool [15]. All 345 records were screened based on title and abstract. At this stage, no records were removed as duplicates were addressed later in the process. Following this screening, 221 irrelevant articles were excluded, as they were deemed non-pertinent to the scope of hydrogen application in domestic or space heating. The full texts of the remaining 124 articles were retrieved and assessed for eligibility against the predefined inclusion and exclusion criteria. During this eligibility phase, 74 articles were excluded based on the following pre-defined criteria:

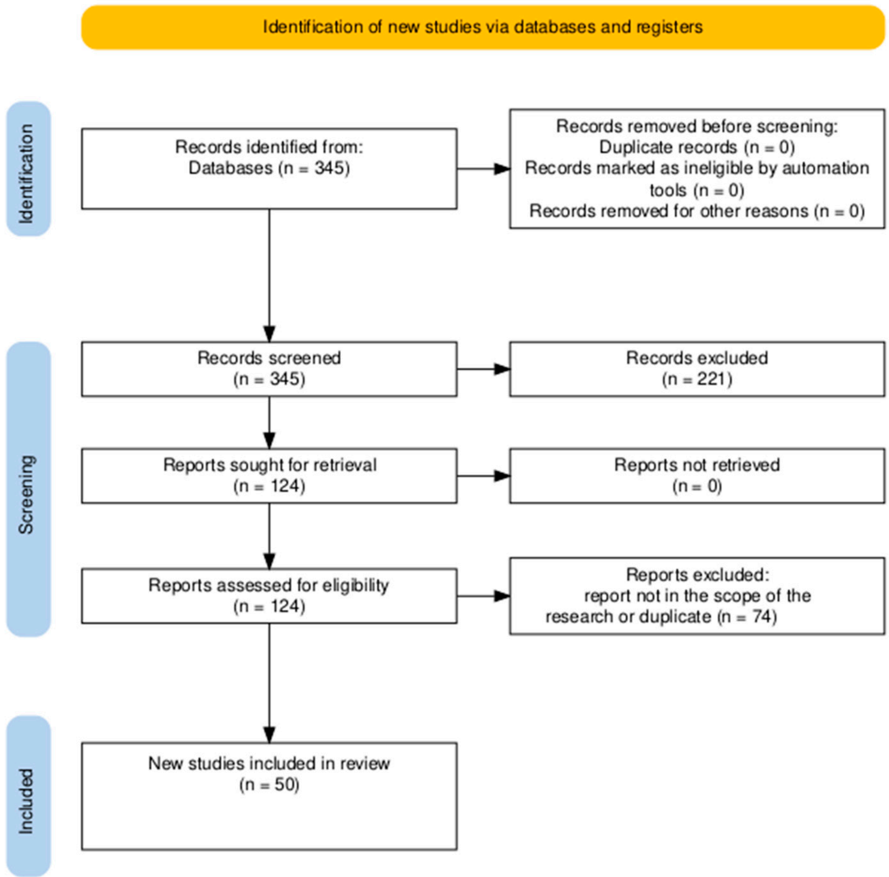

Figure 1. Refinement of studies based on the PRISMA workflow.

- Sectoral misalignment: studies focused exclusively on hydrogen applications in the industrial sector (e.g., steel or chemical production), heavy transport, or maritime applications, without direct implications for residential heat demand.

- Upstream focus: documents focused solely on the chemical optimization of electrolyzers or carbon capture membranes without investigating the integration of these technologies into domestic heating systems.
- Redundancy and Duplication: identification of duplicate records not captured during initial screening or earlier conference versions of subsequent peer-reviewed journal papers.

This screening resulted in a final selection of 50 studies included in the qualitative and quantitative synthesis.

To ensure a rigorous evaluation, this work is structured as a semi-quantitative meta-analysis. While it does not employ statistical pooling (e.g., forest plots or effect-size weighting) common in clinical research, it applies meta-analytic synthesis by harmonizing heterogeneous data from the 2024–2025 literature into comparable indicators to identify overarching technological and economic trends.

Data Synthesis and Terminology Quality Assessment and Methodological Robustness

To ensure the reliability of the synthesis, the included studies were evaluated based on their methodological transparency and the clarity of their underlying assumptions. Given the multidisciplinary nature of the research, spanning techno-economic modeling, environmental impact, and social acceptance surveys, a differentiated qualitative assessment was applied. Modeling-based studies were scrutinized for their sensitivity to key variables, such as electricity prices and hydrogen production learning curves, while empirical and survey-based papers were evaluated based on sample size and geographical context. To mitigate potential risk of bias, conclusions were drawn from the convergence of findings across different study types rather than from isolated results. It is noted that while modeling outcomes provide essential long-term projections, they are inherently sensitive to input assumptions; conversely, social acceptance data are highly context-dependent. This cross-methodological triangulation enhances the overall robustness of the review's conclusions regarding the secondary role of hydrogen in residential heating compared to electrification.

3. Synthetic Analysis of Identified Papers

This section presents a synthesis of the findings extracted from the 50 included studies (2024–early 2025), followed by a critical discussion of the evidence regarding the use of hydrogen in residential heating. The publications were systematically organized and grouped by specific themes into dedicated tables (Tables 2–8), facilitating a structured synthesis of findings across the different areas of discussion: Social Acceptance, Environmental-Economic Analysis, Technical-Economic Analysis and Efficiency, Energy System Modeling, Consumer Cost Modeling, and Environmental Impact. The data extraction focused on the following core elements essential for the subsequent thematic analysis:

Author(s) and Year: The lead author and publication year.

Geographical Focus: The region or country of application for the study's findings, when available.

Applicable Year of Results: The temporal horizon considered for the results (if specified by the authors).

Publication Outcomes: A synthesis of the main results and key conclusions.

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Table 2. Social study on public acceptance of hydrogen.

Bibliographic Reference	Geographical Focus	Reference Year	Main Results
Gordon [11]	U.K.	n.a.	Used the Domestic Hydrogen Acceptance Model (DHAM) to study public perception in the UK. Found that Public Trust, Production Perceptions, Perceived Community Benefits, and Positive Emotions were key predictors of Domestic Hydrogen Acceptance (DHA).
Gordon [16]	U.K.	n.a.	Applied Multigroup Necessary Condition Analysis (MG-NCA) to consumer segments. Concluded that Safety, Technology, and Production Perceptions are both 'should-have' (sufficiency) and 'must-have' (necessity) factors for enabling perceived adoption potential of hydrogen homes.
Gordon [17]	U.K.	n.a.	Integrated Domestic Hydrogen Acceptance (DHA) and Willingness to Adopt (WTA) models. Found that Perceived Socio-economic Costs (PSC) negatively impact DHA and WTA, while positive emotions are strong predictors of WTA.
Gordon [18]	U.K.	n.a.	Identified eight major consumer perspectives towards domestic hydrogen, with the "hydrogen hopeful yet cautious" group being a major category, demonstrating varied attitudes toward adoption.
Gordon [19]	U.K.	2026	Applied PLS-SEM and NCA using the STEEEP Framework. Concluded that perceived relative advantage associated with hydrogen boiler performance is a necessary ("must-have") factor for adoption potential, whereas perceived hob performance is a beneficial ("should-have") but non-essential factor.
Rekker [20]	Netherlands	n.a.	Used a latent-class model to determine Dutch households' Willingness-to-Pay (WTP) for heating systems (district heating, electric, hydrogen). Found WTP for emission reduction ranged from 51 to 114 €/t CO_2.

Table 3. Efficiency.

Bibliographic Reference	Geographical Focus	Reference Year	Main Results
Doucet [21]	Germany	2045	Green hydrogen in the residential sector does not constitute a viable alternative compared with other fields (such as industry and transport), as it is economically disadvantageous and exhibits lower efficiency when compared to heat pumps.
Mellot [22]	Switzerland	n.a.	Focused on methodological aspects, software visualization, and system modeling related to hydrogen demand and energy systems planning. Hydrogen proves to be a technology whose costs remain prohibitively high.

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Table 4. Environmental Impact.

Bibliographic Reference	Geographical Focus	Reference Year	Main Results
Akbar [23]	Netherlands	n.a.	It presents a "solar/green hydrogen house" concept with advanced, pumpless PVT panels, integrated thermal storage, and on-site hydrogen production as an alternative to traditional district systems.
Dominic [24]	Germany	2045	Proposed sizing an electrolyzer (155 GW) and fuel cell (123 GW) system to compensate for Germany's increased electricity demand by 2045. Calculated the hydrogen system Payback Period (PP) to be 11 years, noting that fuel cell operation is profitable only if electricity is sold above 0.3 AC/kWh.
Roy [25]	UK	n.a	Assessed the techno-economic performance of Solid Oxide Fuel Cell (SOFC)-CHP systems integrated with Heat Pumps (HP) compared to conventional natural gas (NG) systems for a UK cluster. SOFC-HP systems fueled by NG showed lower emissions (0.213 kg/kWh) than SOFC-CHP systems.

Table 5. Economic and Environmental Analysis.

Bibliographic Reference	Geographical Focus	Reference Year	Main Results
Eldakadosi [26]	Germany	n.a.	Used multi-objective optimization (cost vs. emissions) for district energy systems. Found that costs derived from present input data for H_2-based configurations are significantly higher than alternative energy systems. The hydrogen-based solution incurs a cost 83% higher than the gas system and 33% higher than the heat pump system. CO_2 emissions are 11% lower for the hydrogen configuration compared to the gas system, but 47% higher than the heat pump system.
Malcher [27]	Sweden, France, Germany, and Poland	n.a.	Assessed the effectiveness of decarbonization strategies for District Heating (DH) across four European countries. Found that increasing renewable heat sources is the most effective measure, followed by increasing heat pumps, even in countries with carbon-intensive electricity grids. The use of 1% green hydrogen would contribute to a reduction of only 0.3–0.5 kg of CO_2e per GJ of heat, thus highlighting its lower effectiveness compared to strategies such as heat pumps and electric boilers.

Table 6. Consumer cost modeling.

Bibliographic Reference	Geographical Focus	Reference Year	Main Results
Billerbeck [28]	EU-27	2030–2050	Compared heating electrification pathways for EU-27 by 2050. Concluded that direct electrification scenarios (heat pumps) lead to the lowest total system costs (around 11%) in almost all member states. Robust developments include strong uptake of renewable electricity and significant building renovation.
Billerbeck [29]	EU-25	2050	Modeled district heating (DH) technology mixes in Europe for 2050 show that heat pumps consistently reach high shares in the DH generation mix, driven by their cost efficiency and their ability to enhance flexibility in the electricity system. Overall, heat pumps emerge as the most cost-effective domestic heating solution for achieving decarbonization by 2050, outperforming alternatives such as biomass or hydrogen boilers and cogeneration systems.

Table 6. *Cont.*

Bibliographic Reference	Geographical Focus	Reference Year	Main Results
Dill [30]	USA	2022–2042	Three scenarios are evaluated for Midwestern U.S. cities not connected to the natural gas network: renewable natural gas, an H_2–natural gas blend, and heat pumps. A comparative net present value (NPV) analysis for 2022–2042 is conducted, based on a techno-economic framework in which greenhouse-gas reduction is monetized using the social cost of GHGs. The study also accounts for the different investment timelines required for each pathway. Considering both costs and GHG emissions, renewable natural gas emerges as the preferred option
Ryland [8]	UK	2035–2050	Analyzed low-carbon solutions for UK homes. Found that systems incorporating heat pumps and hydrogen subsystems (Cases 5 and 6) had the highest Capital Expenditure (CAPEX) but achieved the lowest Levelized Cost of Energy (LCOE) (down to £0.76/kWh) due to high heat pump efficiency.
Vecchi [31]	Australia	n.a.	Analyzed the least-cost supply mix from a building owner's perspective. Concluded that full building electrification is the cheapest net-zero solution across temperate and subtropical climates. Choosing a dual-fuel system could result in cost penalties up to 94% if suboptimal. The alternative use of biomethane or synthetic methane may be more promising, as it reduces or even eliminates the need to upgrade upstream infrastructure and end-use equipment.
Viesi [32]	Italy	2024–2050	Energy consumption scenarios for six buildings in the province of Trento are assessed for 2024 and 2050 in the context of decarbonization, considering both costs and CO_2 emission reductions. When comparing hydrogen with fossil fuels at equal CO_2 emissions, total annual costs for H_2 are higher. An energy transition relying exclusively on hydrogen-based technologies proves more expensive, less efficient, and less capable of achieving high decarbonization levels, mainly due to the limited availability of local renewable energy in the district.

Table 7. Energy system modeling.

Bibliographic Reference	Geographical Focus	Reference Year	Main Results
Andrade [33]	Spain, France, Sweden, Finland	n.a.	Investigated a residential Fuel Cell (FC) Combined Heat and Power (CHP) system integrated with a heat pump (HP). Found that energy savings (at least 40%) compensate for the higher initial investment cost in less than 5 years for colder locations (Paris, Gothenburg, Oulu).
Badakhsh [34]	UK	n.a.	Using H_2 within existing natural gas distribution networks requires significant adjustments and is not free of challenges in the production, transmission, and distribution stages. Therefore, H_2 does not constitute the solution for reducing household GHG emissions, but rather an option to be combined with other heating technologies, e.g., heat pumps.
Bendaikha [35]	Algeria	n.a.	Analyzed a simulated Central Energy System (CES) based on PEM Fuel Cells (PEMFCs) for an 80 m^2 residential dwelling in Algeria, focusing on simulations for electrical and thermal energy production supplied by hydrogen. The CES for a residence in an arid region requires a peak power of about 1 kW and a hydrogen consumption of 5 kg.

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Table 7. *Cont.*

Bibliographic Reference	Geographical Focus	Reference Year	Main Results
Blumberga [36]	Latvia	2022	The article aims to identify the economically optimal solutions to decarbonize the Riga Technical University (RTU) campus, consisting of 15 buildings in Latvia, using multiple renewable sources combined with various storage technologies. The optimal solution includes rooftop, façade, and parking solar panels (total capacity 3.4 MW) and a 3 MW external wind turbine. Electrical storage is provided by batteries, while building heating is supplied by heat pumps.
Cornette [37]	Belgium	n.a.	Developed a statistical approach to incorporate mutual price correlations between conventional and hydrogen energy carriers to assess the economic feasibility of energy systems under price uncertainty, with relevance to European and global contexts.
Maleki Dastjerdi [4]	USA	n.a.	Standalone 100 m^2 residential building in Phoenix, AZ (4 occupants): PV system with excess electricity stored in hydrogen tank (primary storage) and battery (backup); fuel cell boiler and electrolyzer heat used for heating, cooling, and domestic hot water; hydrogen stove proposed for zero-emission cooking, with safety measures required (leak detectors, ventilation, flame sensors).
De Masi [38]	Italy	n.a.	Focused on integrating a micro-CCHP unit based on SOFC technology fueled by green hydrogen into a Nearly Zero Energy Building (nZEB). Preliminary results showed that the combination of PV and fuel cell systems could yield a positive energy surplus (approx. 23.8 kWh in autumn).
Dezhdar [39]	Italy and France	n.a.	Optimized an innovative combined cooling, heating, and power (CCHP) cycle using geothermal, solar, wind, fuel cells, and hydrogen storage for 100 residential units in Marseille, Monaco, Montpellier, Naples, Perpignan, and Rome. The results showed that the use of the innovative cycle allows a reduction in annual electricity and natural gas costs and an increase in system efficiency when integrated with hydrogen and battery storage.
Elkhatib [10]	France	n.a.	Annual micro-cogeneration with fuel cells and green hydrogen from solar and wind for a single-family home in Normandy: minimum 57% self-sufficiency; renewables cover up to 65% of total hydrogen demand
Elkhatib [13]	France	n.a.	Presented an innovative Micro-CHP (MCHP) unit using Low-Temperature PEMFC, a hydrogen condensing boiler, and solid hydrogen storage via a metal hydride tank, analyzing its performance and sizing for homes with low thermal demands
Elmamoun [1]	Morocco	n.a.	Study on a PEM-fuel-cell-based CCHP system for a typical residential building in Morocco. Results show strong influence of climate zone and operating strategy on system performance; energy storage integration could further enhance CCHP efficiency and grid interaction
Mobayen [40]	Sweden	n.a.	Hybrid wind–gas–PEM electrolyzer system for a 16-unit residential building in Sweden; produces 10 kg H_2/h, reduces CO_2 by 10,416 t/year, supporting ZEB targets
Moradpoor [41]	Finland	2040	Investigated the integration of waste heat recovered from H_2 electrolysis plants into District Heating Networks (DHNs) in Finland. The feasibility and economic justification of this recovery depend on the substantial costs related to hydrogen transfer over long distances.

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Table 7. *Cont.*

Bibliographic Reference	Geographical Focus	Reference Year	Main Results
Pinter [42]	Hungary	n.a.	Green hydrogen production from solar panels by employing power-to-gas (P2G) technology to manage surplus generation; estimated annual yield from Hungary's full PV output: 5.48 Mt (losses not included).
Rolo [6]	n.a.	n.a.	The study reviews hydrogen as an energy carrier, covering green hydrogen production and storage methods (underground, physical, material-based). Hydrogen shows potential for transport and building heating, but high-pressure storage technologies need further R&D. Blending H_2 with natural gas in existing pipelines is feasible up to 20%, reducing CO_2 by ~7%, but higher blends require more research and investment. Challenges include infrastructure limits, higher costs, and hydrogen purity loss.
Tosatto [14]	Austria	n.a.	Compared seasonal thermal energy storage (TES) with long-term H_2/RE-fuel storage for achieving building stock self-sufficiency. Found that H_2/RE-fuel storage might not be crucial for high penetration of variable PV resources.
Vespasiano [43]	Italy	n.a.	H_2–natural gas blends (0–30%) in a residential building in Rome reduce energy consumption by 12% and significantly decrease GHG emissions; identified as a short-term decarbonization pathway for Italy's gas-dependent heating sector.

Table 8. Techno-economic assessment.

Bibliographic Reference	Geographical Focus	Reference Year	Main Results
Ameli [3]	UK and Germany	2050	Critically reviewed studies on heat decarbonization, noting a tendency in some literature to ignore or under-simplify factors like peak demand management and future technological advancements, potentially leading to an underestimation of hydrogen's economic role in a net-zero system
Cornette [44]	Belgium	2050	Conducted a literature analysis to quantify the operational Greenhouse Gas (GHG) emissions of various energy carriers, including LCA for electrolyzer, compression, and hydrogen storage, providing average estimates relevant to the European context.
Esposito [12]	Italy	n.a.	Performed a techno-economic assessment of three H_2 storage solutions (Compressed, Liquid, Metal Hydride) for heating a 10-apartment residential building in Milan. The analysis shows that compressed hydrogen is the most favorable option, but its cost remains too high for small-scale residential use while being economically feasible for large-scale systems.
Gabbar [45]	Canada	n.a.	Assessed Integrated Renewable Energy Systems (HRES) for buildings, concluding that integrating green hydrogen amplifies environmental impact, offering a clear pathway to replace fossil fuels, reduce GHG emissions, and lower operational costs. The scenario using a hydrogen–LPG blend as fuel reduces greenhouse gas emissions from 540 to 324 tCO_2/year.
Iunco [46]	Italy	n.a.	Presented a case study of a residential building in Rome (part of a renewable energy community), focusing on the legislative context for renewable energy solutions and energy performance indicators in Italy.

Table 8. *Cont.*

Bibliographic Reference	Geographical Focus	Reference Year	Main Results
Jafarian [47]	USA, Canada	n.a.	Hybrid residential system with renewable energy and storage: PCM storage outperforms hydrogen and batteries; annual electricity savings 1088 kWh (hot)/731 kWh (cold); low ozone impact
Kaabinejadian [5]	n.a.	n.a.	A comprehensive review discussing the benefits and challenges of hydrogen heating systems (boilers, fuel cells) in residential applications across centralized, semi-decentralized, and decentralized scales. Highlighted the potential role of smart techniques (ML, optimization) in reducing energy costs.
Klemm [48]	Germany	n.a.	Optimized technology capacities in urban heating systems (including ASHP, PV, H_2 CHPP) based on minimizing GHG emissions, illustrating the balance required between different zero-carbon technologies
Marrasso [49]	Italy	n.a.	Defined the optimal energy configuration for a mixed-use district in Southern Italy aiming for Positive Energy District (PED) status. The optimal system, incorporating PV, wind, and an 80 kW electrolyzer (20% H_2 blending), achieved a positive energy balance and carbon neutrality
Olympios [9]	Cyprus	n.a.	Developed an optimization framework for multi-energy vector technology sizing in buildings to achieve net-zero. Concluded that efficient sizing and integration lead to the lowest-cost transition. H_2 storage is best suited for storing excess generated energy.
Roy [7]	UK	n.a.	Assessed the techno-economic performance of Solid Oxide Fuel Cell (SOFC)-CHP systems integrated with Heat Pumps (HP) compared to conventional natural gas (NG) systems for a UK cluster. SOFC-HP systems fueled by NG showed lower emissions (0.213 kg/kWh) than SOFC-CHP systems.
Samantha [50]	UK	2020–2050	Performed detailed thermodynamic and economic performance analysis of an SOFC-based cogeneration system for households. Studied the impact of blending green hydrogen with natural gas (H_2NG), confirming the system's high potential efficiency.
Vespasiano [51]	Italy	n.a.	Assessed the impact of H_2 blending (30% vol.) on condensing boilers. Found that H_2NG blending resulted in a substantial reduction of 12.05% in primary energy consumption for the boiler.
Williams [52]	Scotland	n.a.	Sought a sustainable net-zero energy solution for the Isle of Rum (heating and electricity) using renewables and hydrogen. Confirmed that systems using heat pumps (along with H_2 subsystems) achieved the lowest LCOE despite high CAPEX

Analysis of the geographic distribution reveals a significant concentration of studies in a few countries, primarily the United Kingdom and Germany (Figure 2). This outcome reflects the high level of interest and intense research activity in these nations concerning hydrogen heating. Both countries possess extensive and established natural gas networks, a critical factor that directs decarbonization strategies toward integrating hydrogen into existing infrastructure. This approach is widely considered advantageous, as it enables a significant reduction in emissions without requiring the complete replacement of infrastructure, potentially representing a more immediate and cost-effective solution compared to alternative technologies.

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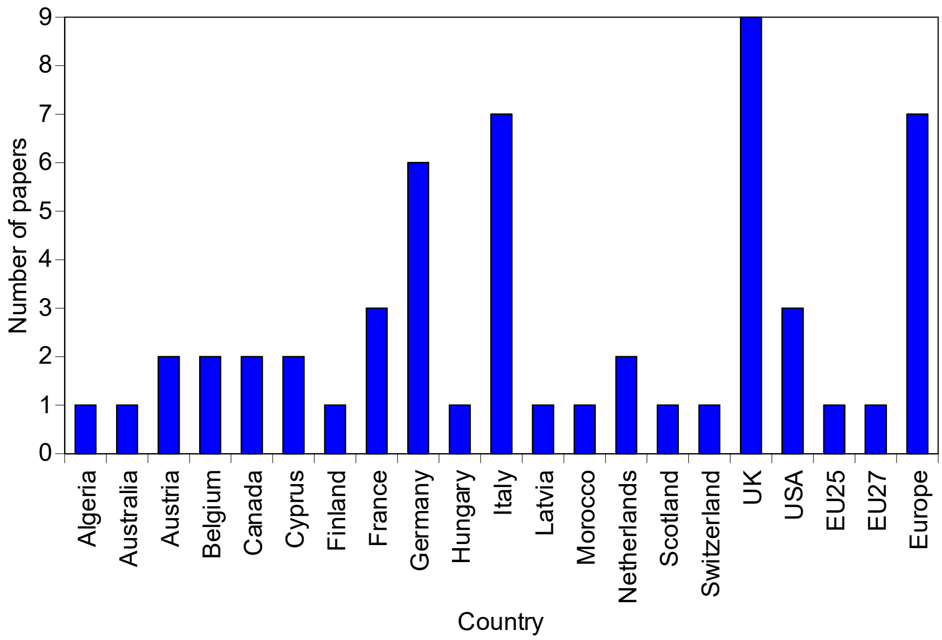

Figure 2. Number of papers investigated divided by country.

Furthermore, a prevalent trend is the inclination toward evaluating consumer costs through modeling that accounts for final user expenditure, typically measured in €/£/$ per kilowatt-hour of heat delivered. Many analyses have also focused on energy system modeling, an innovative approach that transcends traditional sectoral boundaries by considering the interaction and interdependence of various energy domains. Finally, a significant number of publications concentrated on the degree of Social Acceptance of hydrogen by the public (Figure 3 summarizes the distribution of the selected articles in the different discussion areas).

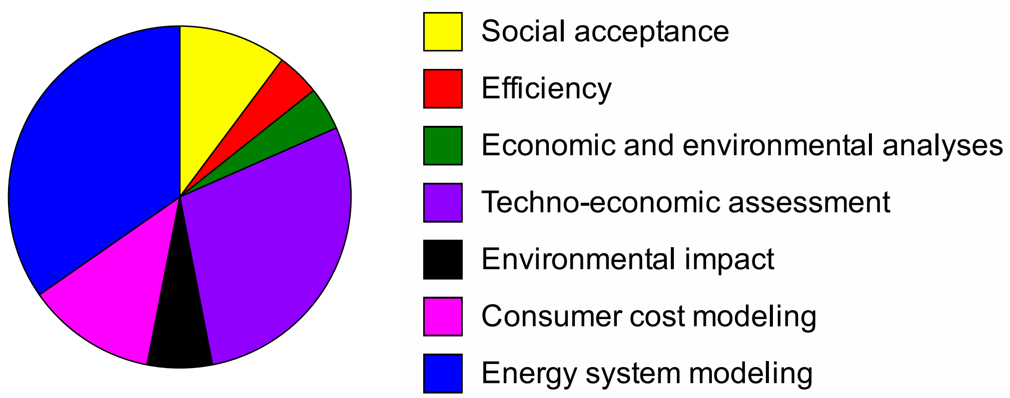

Figure 3. Distribution of the selected articles in the different discussion areas.

Table 9 serves as a critical analytical tool, offering a structured and comparative overview of the technological options for heat decarbonization, with a particular focus on the role of hydrogen.

Unlike studies that examine isolated aspects, the table emphasizes how costs, CO_2 emissions, and efficiency are interdependent factors shaping the choice among technological solutions such as pure hydrogen boilers, H_2 + CH_4 blends, and hybrid systems. The comparative analysis reveals substantial consistency in the trends identified across the literature, while also exposing notable data gaps in certain studies, as indicated by the empty cells. Overlooking the full spectrum of economic, environmental, and systemic parameters may lead to incomplete or even misleading conclusions, especially when the dynamic nature of the broader energy system is not fully considered.

Table 9. Synthesis of analyzed literature. Legend: Purple (Cost analysis), Blue (CO_2 emissions), and Green (Energy efficiency) indicate the primary focus of each study. Empty cells indicate that the cited manuscript did not address that specific aspect as a primary focus of its analysis. Due to the high heterogeneity of metrics across studies, specific units are detailed in the text to ensure accuracy.

Ref.	**Cost**			**CO_2 Emissions**			**Efficiency**		
	H_2	**$H_2 + CH_4$**	**Hybrid**	**H_2**	**$H_2 + CH_4$**	**Hybrid**	**H_2**	**$H_2 + CH_4$**	**Hybrid**
Akbar [23]									
Ameli [3]									
Andrade [33]									
Badakhsh [34]									
Bendaikha [35]									
Billerbeck [29]									
Billerbeck [28]									
Blumberga [36]									
Cornette [37]									
Cornette [44]									
Maleki Dastjerdi [4]									
De Masi [38]									
Dezhdar [39]									
Dill [30]									
Dominic [24]									
Doucet [21]									
Eldakadosi [26]									
Elkhatib [10]									
Elkhatib [13]									
Elmamoun [1]									
Esposito [12]									
Gabbar [45]									
Iunco [46]									
Jafarian [47]									
Kaabinejadian [5]									
Klemm [48]									
Malcher [27]									
Marrasso [49]									
Mellot [22]									
Mobayen [40]									
Moradpoor [41]									
Olympios [9]									
Pintér [42]									
Rekker [20]									

Table 9. *Cont.*

Ref.	Cost			CO_2 Emissions			Efficiency		
	H_2	$H_2 + CH_4$	Hybrid	H_2	$H_2 + CH_4$	Hybrid	H_2	$H_2 + CH_4$	Hybrid
Rolo [6]									
Roy [7]									
Roy [25]									
Ryland [8]									
Samantha [50]									
Tosatto [14]									
Vecchi [31]									
Vespasiano [43]									
Vespasiano [51]									
Viesi [32]									
Williams [52]									

A key insight emerging from the table is the broad recognition of hybrid systems (H_2/HP hybrids) as a promising pathway. These configurations combine the efficiency of heat pumps with the flexibility of hydrogen boilers, providing a solution that can balance efficiency, costs, and environmental impact, particularly in contexts where full electrification is not immediately feasible. In summary, Table 9 is not simply a data summary but a valuable analytical framework that captures the complexity of the heat decarbonization debate. Although the results vary in detail, they collectively reinforce the need for a holistic assessment that accounts for the multiple interacting factors involved, as emphasized in the most recent literature.

3.1. Techno-Economic Performance and Comparison

A primary focus of recent research has been the direct techno-economic comparison between hydrogen-based heating pathways and both incumbent fossil fuels and alternative low-carbon technologies. This body of evidence consistently evaluates hydrogen's viability based on cost, energy efficiency, and its potential to reduce greenhouse gas emissions.

3.1.1. Comparative System Costs and Economic Viability

The economic case for using hydrogen for widespread residential heating appears challenging based on the current evidence. The overwhelming consensus across a majority of studies is that direct electrification with heat pumps represents the most cost-efficient decarbonization pathway for residential buildings [3,28]. While some whole-system models indicate that a hydrogen-heavy decarbonization strategy could be marginally less costly than a full electrification scenario, these studies often identify hybrid heating pathways as the most cost-effective solution overall [3]. The primary driver of this economic disparity is the inherently lower overall system efficiency of hydrogen and the high cost of producing green hydrogen. The "power-to-hydrogen-to-heat" pathway is subject to substantial energy losses at each conversion step: electrolysis, storage, and final conversion to heat. The cost of heating a home with green hydrogen can be double that of using a heat pump powered by the same renewable electricity [3]. The overall efficiency of this process can be as low as 25% [6]. In sharp contrast, heat pumps exhibit a high Coefficient of Performance (COP), meaning they transfer multiple units of heat for every unit of electricity consumed. This fundamental efficiency advantage confers superior environmental and energy performance upon direct electrification pathways [14,26]. This fundamental thermodynamic disadvantage translates directly into higher energy costs for the consumer and places a significantly greater demand on renewable electricity generation capacity compared to direct electrification. The cost-effectiveness of alternatives such as district heating is crucially dependent on the national context and existing infrastructure, a dependence highlighted by its extensive use in Germany versus the UK [3]. The fundamental driver of this economic disparity is the high cost associated with green hydrogen production. Current and projected costs subsequently render green hydrogen uncompetitive with heat pumps and, where pertinent, district heating for decentralized applications [21]. Systematic comparative analyses of hydrogen-based solutions versus direct electrification via heat pumps [26,28,43] consistently demonstrate that hydrogen entails significantly higher end costs for both the energy system and the consumer. Specifically, the cost gap ranges from 5% to over 30%, depending on the degree of hydrogen integration (Figure 4).

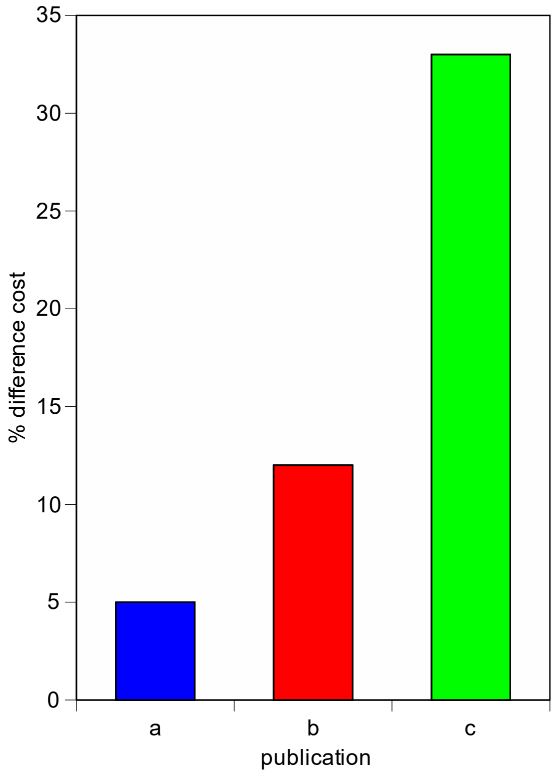

Figure 4. Cost difference (%) between hydrogen and electrification for residential heating (a, blue [43]; b, red [28]; c, green [26]).

This poor economic performance is fundamentally attributed to the high Capital Expenditures (CAPEX) required for essential system components, including electrolyzers, fuel cells, and specialized storage, which renders hydrogen pathways economically unfeasible for residential application without substantial and sustained government subsidies [7,12,26]. Conversely, research into highly integrated systems, such as the DO-IT (Design and Operation of Integrated Technologies) framework proposed by [9], suggests that hydrogen integration can reduce overall costs by up to 26% when compared against a high-carbon baseline (total grid electricity withdrawal and oil-fired boiler heating). However, this benefit stems from exploiting synergies and operational flexibility in advanced system configurations and does not establish hydrogen's competitiveness as a primary solution for decentralized domestic heating.

It should be noted that the values presented in Figure 4 represent mean estimates across the analyzed literature; however, significant uncertainties persist due to regional variations in fuel taxes and subsidies. Sensitivities observed in recent studies suggest a potential

LCOE fluctuation of ±10–15% depending on the volatility of natural gas and renewable electricity prices [37]. From a policy perspective, the absolute cost of hydrogen heating must be weighed against its affordability index. When compared to average European disposable income levels, the current LCOE of hydrogen-based systems poses a significant barrier to adoption, potentially requiring substantial public subsidies to prevent an increase in energy poverty. Unlike heat pumps, which benefit from higher operational efficiency (COP), the high sensitivity of hydrogen costs to upstream prices makes it a higher-risk solution for low-to-middle-income households, reinforcing the need for targeted policy interventions rather than a pure market-led transition.

A crucial distinction emerges from the analysis regarding the technological configuration of hydrogen use. Studies focusing on direct heating via pure hydrogen boilers consistently report higher costs and lower efficiency [3]. However, research into integrated hybrid systems provides a different perspective. For instance, Ryland [8] found that systems integrating renewables, heat pumps, and hydrogen subsystems for storage achieved the lowest LCOE (£0.76/kWh) compared to diesel-based or electricity-only systems, despite having the highest initial CAPEX. This is further supported by Dominic [24], whose modeling of a self-sustaining electrolyzer-fuel cell system in Germany resulted in a payback period of only 11 years. These findings suggest that hydrogen's economic role is not monolithic: its primary value in the residential sector lies not as a combustion fuel, but as a high-capacity storage medium that enhances the viability of highly efficient electrification technologies like heat pumps, particularly in remote or islanded energy systems.

The economic viability of hydrogen is critically sensitive to both the evolving regulatory landscape and rapid technological learning. Recent estimates indicate that a carbon tax ranging from 67.5 to 123 €/tonCO_2 is required to achieve cost parity between blue and gray hydrogen, depending primarily on the carbon capture efficiency assumed [37]. A sensitivity analysis incorporating a ±50 €/tCO_2 deviation from the 2024 baseline demonstrates a pronounced effect on the LCOE. Specifically, a 50 €/tCO_2 increase substantially penalizes gray hydrogen production, which exhibits an emissions intensity of approximately 77.3 kgCO_2/GJ [37,43]. This additional cost burden materially alters operational expenditures, thereby incentivizing a transition toward low-carbon hydrogen pathways. In parallel, capital expenditures (CAPEX) for green hydrogen technologies are declining. Electrolysers and fuel cells currently account for roughly 55% of the total investment cost in compressed hydrogen systems [12]. However, as global manufacturing capacity expands, learning-by-doing effects are driving cost reductions, with empirically observed learning rates ranging from 10% to 30% [37]. When a 30% reduction in electrolyser CAPEX is incorporated into the model, the resulting impact exerts significant downward pressure on the Levelized Cost of Hydrogen (LCOH) for green hydrogen. Despite these improvements, heat pumps continue to retain a cost advantage unless hydrogen prices fall below approximately 2.2 €/kgH_2 (equivalent to roughly 0.06 €/kWh) [3]. Nevertheless, the combined effect of higher carbon prices on fossil-based hydrogen and accelerated CAPEX reductions for electrolysis technologies may advance the breakeven point and reinforce hydrogen's role as a strategic, system-level energy carrier [3,33,43]. However, even under these optimistic scenarios of high carbon taxation and significantly reduced capital costs, the power-to-hydrogen-to-heat pathway remains structurally disadvantaged in terms of overall system efficiency when compared to direct electrification via heat pumps. Consequently, while green hydrogen is therefore expected to become increasingly competitive relative to fossil-based alternatives, its most economically rational deployment is more likely to occur in hard-to-abate industrial sectors, high-temperature process applications, and long-duration or seasonal energy storage, rather than as a primary solution for residential base-load heating.

In summary, the economic viability presented across the analyzed literature highlights a high sensitivity to regional assumptions, such as electricity pricing and hydrogen production pathways. Rather than attempting an ex-post harmonization of these variables, this study deliberately preserves the diversity of national contexts to test the consistency of the overarching trends. The analysis reveals that these economic conclusions remain robust even under optimistic scenarios: studies assuming rapid learning curves for green hydrogen and significant reductions in electrolyzer costs still consistently identify heat pumps as the more cost-effective solution for widespread residential heating. Consequently, the variability in study assumptions does not weaken the findings but rather reinforces the conclusion that hydrogen's economic competitiveness is limited to specific niche applications, regardless of localized advantages.

3.1.2. Operational Stability and Adaptive Control Strategies in Residential PEMFCs

Empirical evidence from recent residential applications underscores that operating conditions, most notably ambient temperature and load fluctuations, are primary determinants of system performance and service life. Experimental studies conducted in real home environments demonstrate that PEMFC cogeneration efficiency is inversely proportional to ambient temperature [33,35]. In warmer climates or during summer seasons, the inability to dissipate generated heat often leads to overheating of the Heat Storage Tank (HST), which forces the system into frequent and discontinuous start-stop cycles [3,33]. This operational instability significantly impacts the fuel cell's durability; as observed in both stationary and mobile applications, large load-changing cycles are a primary driver of performance degradation [35]. To mitigate these effects, empirical models have established operation factor benchmarks (e.g., 2.4%) to quantify and limit degradation. Research indicates that implementing adaptive control strategies, such as establishing specific thermal (1000 W) and electrical (700 W) thresholds for system re-operation, is essential to reduce shutdown frequency and optimize the State-of-Health (SOH) [35]. Furthermore, the recent literature emphasizes that temperature management is core to stable operation, as the sensitivity of the membrane electrode assembly (MEA) to temperature fluctuations dictates the overall reliability and maintenance costs of residential fuel cell systems [3,35,53]. In this context, precise thermal management is essential to prevent catalyst sintering and membrane dehydration. To enhance operational stability under stochastic residential load profiles, advanced adaptive control strategies and scheduled regeneration cycles are required. These measures help manage thermal fluctuations, mitigate reversible voltage losses, reduce performance degradation, and ultimately extend the operational lifetime of the stack [53]. Future research should therefore prioritize adaptive state-of-health strategies [53] to harmonize energy delivery with the stochastic nature of residential thermal demands. Such optimization is essential not only to improve the round-trip efficiency of residential hydrogen systems but also to ensure the durability required for domestic applications, where maintenance-free operation is a key consumer expectation [3,35].

3.1.3. Emissions Reduction Potential

The potential for hydrogen to reduce GHG emissions is entirely dependent on its production method. "Gray" hydrogen, produced from natural gas without carbon capture, offers no climate benefit; indeed, using gray hydrogen in a boiler can result in significantly higher lifecycle emissions than burning natural gas directly due to the energy-intensive production process [8]. "Blue" hydrogen, which pairs fossil-fuel-based production with Carbon Capture and Storage (CCS), offers a low-carbon alternative, while "green" hydrogen produced from renewable electricity is a near-zero-emission energy carrier [6,8]. Modeling studies show that hydrogen-based systems can offer noteworthy emission reductions compared to conventional gas-based systems [26]. For example, specific analyses of Combined Cooling, Heating and Power (CCHP) systems have quantified significant potential CO_2 [1]. Figure 5 shows the potential reduction in CO_2 emissions achievable with hydrogen technologies in the residential sector.

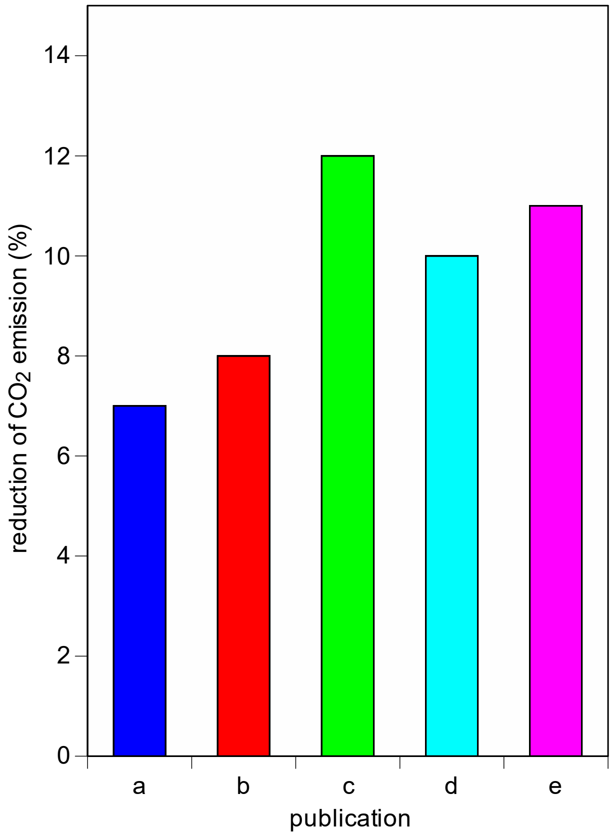

Figure 5. Reduction in CO_2 emissions for hydrogen use in residential heating (a, blue [6]; b, red [27]; c, green [51]; d, light blue [43]; e, purple [26]).

The use of blends with up to 30% H_2 allows for an average emissions reduction of approximately 10%. According to Vespasiano et al. [51], the progressive introduction of hydrogen into boilers reduces emissions from 27.08 to 23.82 annual tonnes (approximately 12%). Vespasiano et al. [43] confirm reductions exceeding 10% for 30% blends, with annual consumption drops of 141.2 MWh/year (−11.09%) for constant-efficiency boilers. Malcher et al. [27] highlight how a 1% share of green hydrogen and the use of CCS systems contribute to emission reduction, albeit marginally compared to heat pumps and electric boilers. Gabbar et al. [45] report a particularly high reduction (216 tCO_2/year), although this refers to scenarios involving hydrogen-propane blends and is therefore not directly comparable to the other results. However, hydrogen pathways are often outperformed in terms of emission reductions by heat-pump-based systems, particularly in regions where the electrical grid is already substantially decarbonized [26].

3.1.4. Life Cycle Emissions and Environmental Trade-Offs by Hydrogen Color

A critical assessment of hydrogen's environmental impact must move beyond stack emissions to a full Life Cycle Assessment (LCA). While green hydrogen is often presented as a zero-emission solution, its footprint is heavily influenced by the scarcity of renewable electricity and the high energy intensity required for electrolyzer manufacturing. Recent estimates suggest an upper limit for green hydrogen operational GHG emissions of approximately 4.9 $kgCO_2eq$/GJ when accounting for electrolyzer and storage subsystems [37].

This perspective clarifies findings where hydrogen scenarios emit 47% more than heat-pump-based systems; the latter leverage renewable electricity more efficiently through high COPs, whereas the hydrogen chain suffers from cumulative losses in electrolysis, compression, retrofitting-related energy penalties and storage [6,26]. The environmental gap is further compounded when the embodied carbon of infrastructure is considered. Retrofitting existing pipelines to mitigate hydrogen embrittlement, alongside the broader ecological impacts of green hydrogen production facilities, may contribute an additional 5–10% to the overall life-cycle impact. This environmental burden is further exacerbated by the implicit carbon costs associated with infrastructure modifications: repurposing existing natural gas networks requires significant energy and material-intensive interventions to mitigate hydrogen embrittlement in steel pipelines and to replace seals to prevent leakages.

Furthermore, the environmental performance of blue hydrogen is critically sensitive to the carbon capture rate and upstream methane leakages. Although theoretical capture rates can exceed 90%, empirical literature reviews indicate a wide performance range (47–93%) with an average efficiency of 74% [37]. Crucially, for blue hydrogen, indirect emissions, primarily from natural gas production, transport, and the energy required to drive the CCS process, constitute between 67% (GWP 100) and 81% (GWP 20) of total operational GHG [37]. Consequently, excluding these indirect flows results in a significant distortion of the relative sustainability ranking of heating technologies. Yellow hydrogen (grid-electrolysis) consistently exhibits the highest footprint, often exceeding the direct combustion of natural gas if the grid mix is not fully decarbonized, reinforcing the consensus that hydrogen's climate benefit is strictly contingent upon a low-carbon production chain and high-efficiency end-use [6,37]. Consequently, the environmental cost of hydrogen is highly sensitive to its color classification, and its adoption in the residential sector risks locking in a higher carbon footprint than heat pump alternatives unless 100% renewable supply and 100% electrolyzer recycling are achieved.

3.1.5. Social Acceptance

Data concerning the social acceptance of hydrogen in the residential sector are reported in Figure 6 [17–19]. An in-depth analysis of public perception in the United Kingdom, based on the three recent empirical surveys (N = 1845), reveals several determining factors for adoption acceptance, specifically: safety perceptions (concerns related to fire or explosion and trust in regulation), environmental considerations (the positive association with "green" energy solutions), emotional factors (positive emotions favoring adoption, negative ones reducing it), technological aspects (such as the perceived performance and reliability of hydrogen boilers), and economic factors (which were found to be less relevant in the initial phase of the transition).

Propensity for hydrogen adoption is higher among individuals with high involvement and good knowledge of renewable energy technologies, but remains low among those with limited knowledge, low involvement, or those experiencing energy poverty. Overall, the data indicate that hydrogen technology is currently far from uniformly accepted by British society, with over 60% of the population expressing doubts related to costs, safety, and environmental impacts. In contrast, a study by [20] found that Dutch households were willing to pay a 29.4% premium on their monthly energy bill to use hydrogen instead of natural gas. This suggests a relatively high initial level of acceptance, potentially favored by a positive public perception and less pronounced informational barriers.

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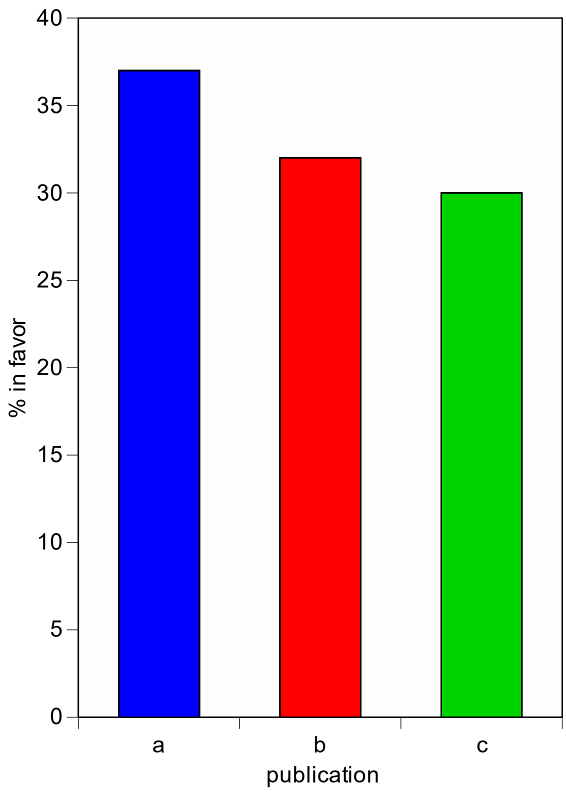

Figure 6. Percentage in favor of residential hydrogen (a, blue [19]; b, red [18]; c, green [17]).

The divergence between the findings of Rekker and Gordon highlights that hydrogen acceptance is highly sensitive to the national context and the prevailing political and media narrative. In contexts like the Netherlands where hydrogen is promoted as a natural evolution of the existing gas system, it tends to be more readily accepted. Conversely, in the United Kingdom, where the primary decarbonization strategy emphasizes electrification, the transition to hydrogen is a contested pathway that requires significant informational and communication efforts to overcome socio-technical barriers, particularly regarding domestic safety and system costs.

3.2. Technical and Safety Standards for Residential Hydrogen Applications

The deployment of hydrogen technologies in the residential sector is strictly governed by a complex framework of international and regional standards designed to mitigate risks associated with the fuel's unique physical properties. Key normative references include ISO 22734:2019, which specifies the design and safety requirements for hydrogen generators using water electrolysis, and EN 50465:2015, which defines standards for fuel cell-based micro-CHP appliances [6,38]. General safety guidelines, such as ISO/TR 15916:2015, provide a foundation for handling hydrogen by identifying hazards like its wide flammability range (4% to 76% in air) and low ignition energy (0.02 mJ) [6]. In domestic settings, these properties necessitate the integration of advanced safety systems, including leak detectors, flame sensors to identify otherwise nearly invisible flames, and mandatory ventilation protocols to prevent hydrogen buildup in enclosed spaces [4,6]. Furthermore, technical compliance with ISO 13686:2013 is essential when evaluating the interchangeability of hydrogen-enriched natural gas (H_2NG) blends in existing infrastructure, as the higher flame speed and potential for hydrogen embrittlement in metallic components require rigorous material assessment and burner head retrofitting [5,43,51]. For practical implementation, researchers emphasize the necessity of site-specific Quantitative Risk Assessments (QRA) to manage potential jet fires or flash fires, ensuring that risk contours are contained and that safety protocols align with established building codes [12,18]. While these standards ensure a high level of operational safety, the associated capital expenditure (CAPEX) for certified storage and monitoring systems remains a significant factor in the overall economic viability of hydrogen-based residential solutions [12,43].

3.3. The Role and Risks of Hydrogen Blending in the Energy Transition

Hydrogen blending into the existing natural gas grid should be viewed primarily as a strategic policy and market stimulus rather than a definitive long-term technical solution. By utilizing current infrastructure, blending offers a pragmatic “interim solution” to stimulate the development of an industrial hydrogen supply chain and mitigate financial risks for producers by providing a guaranteed immediate market [6,43,51].

However, from a thermodynamic perspective, blending is often characterized as a “last-choice option” because mixing gases of different qualities is an irreversible process, and their subsequent separation requires significant energy and cost. Furthermore, evidence suggests that even a 20% volumetric blend results in a limited CO_2 emission reduction of approximately 7%, which is insufficient for deep decarbonization [6,43]. There is a demonstrable risk that an over-reliance on blending may delay full decarbonization by extending the operational lifetime of fossil-based gas infrastructure and discouraging the deployment of more efficient alternatives like heat pumps or district heating [38,43]. Such a pathway risks the creation of “stranded assets” if investments continue to favor gas-based technologies over direct electrification, which remains the cost-optimal and most efficient strategy for the residential sector in the long term [43]. Consequently, while H_2NG can effectively reduce emissions from residual natural gas consumption during the transition, its implementation must be carefully managed to ensure it complements, rather than hinders, the broader shift toward end-use electrification [43].

3.4. Opportunities: Hydrogen’s Role in System Integration

Beyond its application as a direct fuel for heating individual homes, hydrogen’s primary value proposition, as consistently identified in the recent literature, lies in its potential to enhance the flexibility, resilience, and integration of the wider energy system. This is particularly relevant in future energy scenarios characterized by high penetrations of variable renewable energy sources like wind and solar.

The synergy within heat pump + hydrogen storage hybrid schemes is driven by the complementary roles of electrochemical and chemical storage. Quantitatively, the specific price of energy storage is the primary differentiator: while Lithium-ion batteries cost approximately 500 EUR/kWhe, pressurized hydrogen tanks are significantly more affordable for large volumes at 10 EUR/kWhH_2 [9]. Over a 20-year horizon, hydrogen-based storage can achieve a Total Life Cycle Cost (TLCC) up to 13% lower than battery-only systems, primarily because batteries require replacement every 10–12 years, whereas hydrogen infrastructure exhibits greater longevity [9,52].

However, technical compatibility remains a barrier due to the operational inertia of fuel cells. Solid Oxide Fuel Cells (SOFC), for instance, can require start-up times exceeding 12–24 h, making them unsuitable for rapid peak-shaving [38]. To overcome this, successful hybrid configurations utilize a hierarchical control strategy: a battery buffer handles the immediate, stochastic demand spikes from heat pump intelligent temperature control, while the fuel cell provides a steady-state base load [4]. This integration mitigates the start-stop cycles that accelerate fuel cell degradation and ensures system resilience during extreme weather events when heat pump COP seasonally declines [3,9]. Hydrogen is identified as a valuable asset for enhancing energy system resilience and security. By acting as an energy buffer, hydrogen storage can provide a crucial backup during supply disruptions, grid failures, or periods of extreme weather, thereby ensuring the security of supply for essential services [3]. This function positions hydrogen not just as a heating fuel but as a strategic component of a robust and reliable zero-carbon energy system. Perhaps the most significant opportunity for hydrogen is its unique capability for long-term, seasonal energy storage. There is a fundamental temporal mismatch between peak renewable energy generation (e.g., solar photovoltaic in the summer) and peak heat demand (in the winter). Hydrogen provides a technically viable mechanism to bridge this seasonal gap by converting surplus summer electricity into green hydrogen, storing it for months, and then converting it back to electricity or heat during the winter. Studies that explicitly model this function highlight seasonal hydrogen storage as a key enabler for achieving 100% energy autarky in districts, often outperforming alternatives like large-scale thermal energy storage in certain contexts [12,14,42].

Hydrogen production via electrolysis offers a powerful tool for sector coupling. It can absorb surplus electricity from wind and solar farms during periods of low demand, which would otherwise be curtailed. This process not only produces a valuable zero-carbon fuel but also improves the economic case for renewable energy projects by providing an additional revenue stream [42]. The literature provides numerous examples of integrated systems where local photovoltaic and wind installations power electrolyzers to produce green hydrogen. This hydrogen can then be used on-site in residential fuel cells for heat and power, or exported to serve other energy demands, effectively linking the power, heat, and transport sectors [32,39,40,52].

3.5. Limitations and Critical Barriers

This meta-analysis synthesizes findings from 50 studies published between 2024 and early 2025, spanning diverse European and non-European contexts, to provide a rigorous assessment of hydrogen's prospective role in residential heating. The aggregated evidence consistently demonstrates that a leading role for hydrogen in domestic space heating or domestic hot water production is currently unsupported. Critically, none of the analyzed studies suggest that a decarbonization pathway centered on hydrogen is economically more viable for the consumer compared to established, high-efficiency alternatives such as electrification via heat pumps or district heating.

The research does not entirely preclude a complementary role for hydrogen, particularly within advanced hybrid systems (e.g., cogeneration, integration with renewables and electrolyzers). These applications may be viable in specific contexts characterized by local H_2 availability or highly seasonal thermal demand. However, the wide-scale implementation of hydrogen for residential heating is consistently hampered by a formidable combination of technical, economic, production, and social barriers that are uniformly identified throughout the 2024–early 2025 literature.

The economic case for hydrogen heating is systematically undermined by high costs across the entire value chain. The primary impediment is the inherently lower overall system efficiency of H_2-based heating solutions, which translates directly into higher consumer and system-wide costs. For example, Billerbeck et al. [28] project an increase of at least 11% in energy system costs by 2050 under scenarios assuming widespread H_2 adoption, and [26] report cost savings of 33% for heat pump scenarios compared to hydrogen equivalents.

This poor economic performance is fundamentally driven by three key factors:

- High Component Costs (CAPEX): The high Capital Expenditure (CAPEX) for essential system components, including electrolyzers for production, fuel cells for conversion, and dedicated storage systems (compressed, liquid, or metal hydride), is a primary impediment to market competitiveness [12,26]. Studies dedicated to utilizing hydrogen for energy surplus storage indicate that the associated CAPEX and operational costs remain prohibitively high for residential applications, currently deemed sustainable only at an industrial or large-district scale [12].

- Cost of Green Hydrogen Production: The production cost of green hydrogen is fundamentally tied to the price of renewable electricity. For H_2 to become a competitive heating fuel, the cost of dedicated renewable generation must be dramatically reduced [21].
- Unfavorable Levelized Cost of Energy (LCOE): Consequently, the LCOE for hydrogen-fueled heating systems is currently estimated to be more than three times that of their established natural gas-based equivalents [7]. This significant cost disparity renders H_2 an economically unattractive option for consumers absent substantial financial intervention.

A further critical constraint is the challenge of producing clean hydrogen at the vast scale required and within the necessary timeframe to meet ambitious climate targets. Currently, the production of green and blue hydrogen accounts for less than 1% of global production, which is still overwhelmingly dominated by fossil fuel-based processes without effective carbon capture [54]. Even assuming aggressive growth rates comparable to those achieved in solar and wind deployment, H_2's contribution to global energy demand in 2040 is projected to fall between 0.7% and 3.3% [55], with extremely optimistic scenarios reaching a maximum of 6.6–7.8% [56]. These production data strongly suggest that reliance on hydrogen as the primary solution for residential heating represents a highly uncertain and high-risk hypothesis.

The infrastructure required to deliver pure hydrogen to homes at scale is another critical barrier. This would necessitate either the construction of entirely new pipeline networks or the costly and complex conversion of existing natural gas grids. Hydrogen is a smaller molecule than methane and can cause embrittlement in certain types of steel pipes. Furthermore, because of its lower volumetric energy density, hydrogen requires significantly more energy for compression compared to natural gas to transport the same amount of energy, adding to both the cost and inefficiency of the system [3,6]. These infrastructural hurdles represent not just a financial barrier but a multi-decade logistical challenge, significantly delaying hydrogen's potential contribution to near-term climate targets.

Beyond the techno-economic challenges, social and behavioral factors present a critical, and perhaps more complex, set of barriers. Social science studies robustly find that public factual knowledge about hydrogen is extremely low [18]. This knowledge gap means that public acceptance is heavily influenced by perceptions rather than established facts. Key determinants of acceptance include perceived safety, trust in the institutions managing the transition (e.g., government and energy companies), general environmental attitudes, and individual cost–benefit appraisals [11]. While research indicates a general public preference for green over blue hydrogen, more immediate concerns about energy insecurity and fuel poverty often outweigh considerations of purchase and running costs during the pre-deployment phase [17,18]. Addressing safety concerns and building public trust will be paramount for any future deployment.

3.6. Policy and Regulatory Implications

The synthesized evidence from the 2024–early 2025 literature provides clear, actionable insights for policymakers tasked with shaping the future of residential decarbonization. The findings strongly suggest that a nuanced and strategic policy approach is required, one that leverages hydrogen's unique strengths for system integration while candidly acknowledging its current limitations for mass-market residential heating. Based on the consistent evidence of superior cost-effectiveness and energy efficiency, policy should prioritize direct electrification with heat pumps as the primary strategy for mass-market residential decarbonization [3,21,29]. Hydrogen's role should be strategically targeted toward applications where it provides unique and irreplaceable value. This includes its use in hybrid heating systems designed for peak load management, in specific district heating applications where it can be produced and consumed locally, or as a key component of national energy security through seasonal energy balancing [3,27]. The evidence clearly demonstrates that a "one-size-fits-all" policy approach is destined to fail. Consumer acceptance of new heating technologies is not uniform; it is shaped by a complex interplay of factors including environmental engagement, income levels, housing tenure (owner vs. renter), and existing levels of fuel stress [16,18]. Effective policy must be designed with this heterogeneity in mind, offering a portfolio of solutions and tailored incentives that cater to the diverse needs and circumstances of different consumer segments. To unlock hydrogen's potential in targeted applications and manage the broader energy transition, a clear and supportive regulatory framework is essential. This framework must strategically address three key areas. Firstly, in terms of Technical Standards, it requires the development of clear guidelines for hydrogen blending in existing networks and for the safety and performance of new hydrogen-ready appliances [8]. Secondly, Market Signals must be established; specifically, new electricity tariff structures need to be designed to incentivize flexible energy use, rewarding consumers for using technologies like electrolyzers to absorb electricity during off-peak hours. Finally, proactive and transparent public engagement strategies are required to build social license, address safety concerns, and foster public trust in the transition [11,17]. These policy considerations provide a critical pathway for navigating the complexities of the energy transition, positioning hydrogen as a strategic asset rather than a universal solution.

3.7. Strategic Application Routes and Alignment with EU Policy

To move beyond generalized recommendations, the hydrogen strategy must be integrated into the EU's Fit for 55 policy framework through a layered and scenario-specific application route. Empirical evidence identifies off-grid islands and remote communities as primary priority scenarios; case studies like the Isle of Rum demonstrate that hydrogen storage, when coupled with heat pumps, achieves a superior economic balance (LCOE as low as £0.76/kWh) while ensuring 100% renewable energy autarky and grid resilience [3,52]. A second priority layer involves extremely cold climates where heat pump performance seasonally declines. In these regions, such as Finland, the integration of industrial hydrogen production with district heating networks offers a strategic advantage, recovering waste heat to reduce biomass dependency and manage extreme winter peak loads [3,5,41]. However, these strategic routes face potential policy conflicts, particularly regarding energy pricing. For instance, the phased introduction of the Carbon Border Adjustment Mechanism (CBAM) and the tightening of the EU Emissions Trading System (ETS) will inevitably increase the cost of fossil-based gray and blue hydrogen. While these tariffs accelerate the shift toward green hydrogen, they also risk widening the cost gap with direct electrification in the short term. Indeed, the competitiveness of low-carbon hydrogen is strictly contingent upon robust carbon pricing mechanisms; current regression models suggest that achieving cost parity between blue and gray hydrogen requires carbon taxes ranging from €67.5 to €123/tCO_2, depending on capture efficiency [3,44]. Without the full implementation of EU carbon tariffs, hydrogen-based heating risks being marginalized by cheaper fossil alternatives. Consequently, we propose a triple-layered deployment route: (i) immediate prioritization of "no-regret" industrial clusters and heavy transport, (ii) mid-term expansion into district-level seasonal storage and islanded micro-grids for resilience, and (iii) long-term deployment of hydrogen-ready hybrid systems for residential peak demand management in gas-reliant countries. This structured approach prevents the risk of extending fossil infrastructure indefinitely while ensuring that investments are channeled toward sectors where hydrogen provides irreplaceable systemic value.

4. Discussions

4.1. Reconciling Social Acceptance and Economic Disadvantage

The synthesis of recent literature (2024–2025) reveals a multifaceted landscape where technical efficiency, economic viability, and social perception often pull in different directions. A critical conflict emerges between studies focused on social acceptance [11,16–19] and those centered on techno-economic performance [3,16]. While models typically prioritize cost-optimality, consumer preferences are driven by non-technological factors such as "Public Trust," "Positive Emotions," and perceived "Community Benefits" [3]. For instance, while Gordon [11,17] identifies a significant "hydrogen hopeful" consumer segment in the UK driven by trust and perceived community benefits, Doucet [21] and Billerbeck [28] demonstrate a clear economic disadvantage and lower efficiency compared to heat pumps. This paradox can be explained through the lens of energy transition path dependence. In nations like the UK and Germany, the presence of extensive, high-value natural gas infrastructure creates a socio-technical momentum that favors "gaseous" solutions. In these contexts, public acceptance is often high because hydrogen is marketed as a "drop-in" replacement that requires minimal behavioral change or home renovation, even if the systemic LCOE is higher [3,11]. Conversely, in regions without such infrastructure, the debate is more strictly dictated by thermodynamic efficiency, where electrification is the undisputed leader [31]. Furthermore, studies on Willingness-to-Pay (WTP) show that households are often willing to pay a premium for hydrogen to achieve emission reductions, suggesting that the "economic disadvantage" cited in the literature may not be an absolute barrier if social capital and trust in the infrastructure remain high [3]. However, from a theoretical standpoint, this risks creating "stranded assets" by extending the life of fossil-fuel-based infrastructure at the expense of more efficient long-term alternatives [38]. The divergence in the literature conclusions is therefore not a sign of data inconsistency, but rather a reflection of different analytical scales: while hydrogen is often a "last-choice option" for individual home heating due to efficiency losses, it becomes a "must-have" at the system level for seasonal storage and grid resilience [14].

4.2. Path Dependence and Infrastructure Lock-In

The findings highlight a strategic tension in policy. The literature frequently describes hydrogen blending (H_2NG) as a pragmatic "interim solution" to stimulate the hydrogen market [3,6,43]. However, this finding must be critically examined through the theory of energy transition path dependence [11]. By utilizing existing gas grids, blending leverages legacy infrastructure to reduce immediate capital inertia, effectively extending the operational life of fossil gas assets [19]. While this facilitates a faster initial market stimulus for the hydrogen supply chain [19], it carries a significant risk of technological lock-in [11]. Continued investment in gas-based technologies, even those enriched with hydrogen, may delay the deployment of more efficient, purely renewable-based solutions like heat pumps, potentially creating "stranded assets" in the long term [11]. The "contested path" in countries like the UK reflects this tension between incumbent gas-regime actors and the growing electrification niche [3,11]. The divergence in the literature conclusions is therefore not a sign of data inconsistency, but rather a reflection of different analytical scales: while hydrogen is often a "last-choice option" for individual home heating due to efficiency losses, it becomes a "must-have" at the system level for seasonal storage and grid resilience [14].

4.3. Policy Implications: Beyond "One-Size-Fits-All"

The evidence gathered highlights that a "one-size-fits-all" policy is likely to fail due to significant consumer heterogeneity [3,19]. Factors such as "Fuel Stress" and geographical location (e.g., rural vs. urban) dramatically alter the hierarchy of adoption drivers [11,19]. For instance, while high-income "innovators" prioritize environmental benefits, the "Fuel Stressed Group" is primarily concerned with socio-economic costs and affordability [19]. Consequently, policy frameworks must transition toward spatially explicit and segment-specific strategies [19]. This includes prioritizing hydrogen for industrial clusters and peak heating demands while favoring full electrification for the majority of the residential stock where it remains the least-cost net-zero solution [29,37]. Finally, the high cost of components like PEMFCs and the inevitable performance degradation during long-term operation underscore the need for sustained RD&D and specialized technical support before hydrogen can move beyond its current "niche" status in the domestic context [3,6].

4.4. Structural Barriers, Regional Equity, and Political Economy

Beyond psychological variables, the transition to hydrogen homes is constrained by deep-seated structural barriers and political economy challenges. A critical obstacle is the eligibility-readiness gap: low-income and fuel-stressed households are significantly less able to afford the high upfront capital expenditure (CAPEX) required for hydrogen-ready equipment and building retrofits [16,18]. Empirical data suggests that while high-income 'innovators' display optimism, vulnerable groups view the transition through the lens of distributional injustice, fearing that decarbonization costs will fall disproportionately on their utility bills [16]. Regional equity also emerges as a decisive factor. In the Netherlands, higher willingness-to-pay in the Northern regions is linked to local industrial heritage and proximity to hydrogen demonstration projects [20]. Conversely, in the UK, local resistance in industrial clusters highlights a deficit in procedural justice, where communities feel like lab rats for unproven technologies [11,17]. In the Italian context, where residential buildings account for 26% of national emissions, social acceptance is further hindered by a lack of specialized technical support and concerns over system reliability [38]. Case studies in Rome and Southern Italy confirm that hydrogen-based solutions remain economically unfeasible compared to established heat pump and PV configurations unless government subsidies cover 58% to 89% of initial costs [38,46]. The regional applicability of social acceptance frameworks, such as the Domestic Hydrogen Acceptance Model (DHAM), must be critically assessed in light of differing national energy infrastructures. The UK often serves as a reference case due to its extensive gas network legacy, which simplifies the perception of hydrogen's benefits through the repurposing of existing heating systems. In contrast, regions with lower gas grid density, such as Italy and Spain, present divergent drivers of acceptance [3]. In Southern Europe, where residential heating and cooling can account for up to 30% of national energy consumption, the relative advantage of hydrogen is often secondary to the cost-efficiency and practicality of direct electrification via heat pumps [3,38]. Here, community willingness to adopt hydrogen may be influenced more by perceived local economic benefits, energy autonomy, or system resilience during extreme weather events rather than the preservation of gas-grid jobs [3,11]. While the DHAM identifies 'community-perceived benefit' as a primary driver of adoption in both the UK and Australia, its interpretation requires nuance when applied to Mediterranean contexts. Differences in trust, risk perception, and technological path dependency, shaped by the presence or absence of extensive gas infrastructure, mean that hydrogen's perceived benefit may manifest differently across socio-technical regimes. In areas with limited gas networks, the lack of technological inertia reduces path dependency, making the transition to alternatives like heat pumps more straightforward [3]. These variations underscore the

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urgent need for supplementary cross-cultural and comparative data to determine whether the DHAM's psychological constructs retain consistent predictive power in energy systems where gas is not the dominant heating vector.

From a political economy perspective, a 'one-size-fits-all' policy risks creating stranded assets and exacerbating regional inequalities [31,43]. To ensure a socially acceptable and equitable transition, policy frameworks must shift toward spatially explicit and segment-specific strategies, incorporating robust financial safety nets and price promises to protect energy-vulnerable citizens [31].

4.5. Life Prediction Complexity and Cost Uncertainties

A significant source of uncertainty in the technical economics of fuel cell systems, particularly in LCOE calculations, arises from the complexity of life prediction under variable load profiles. Residential heating demands are inherently stochastic, forcing fuel cells into intermittent operations that trigger complex degradation mechanisms. A core intrinsic factor often overlooked in simplified economic models is the distinction between irreversible degradation and reversible voltage loss. Recent literature emphasizes that the recovery characteristics of these reversible losses are critical to accurately assessing the actual system lifetime. Empirical strategies in residential setups already reflect this necessity; for instance, the implementation of specific 'regeneration phases'—such as a 3 h scheduled pause every 45.5 h of operation—is designed to mitigate performance decline and enhance durability [13]. Failing to incorporate these recovery dynamics into life-prediction models leads to substantial cost uncertainties, as it may result in overestimating the frequency of expensive stack replacements, which currently represent up to 26.7% of initial CAPEX [33,46]. Future research must therefore transition toward more granular, adaptive state-of-health (SOH) models that account for temperature sensitivity and voltage recovery. This approach is essential to provide building owners and investors with reliable data on long-term operating costs and to confirm the economic viability of fuel cells as a resilient alternative to direct electrification [9,38].

5. Conclusions

This systematic synthesis of the 2024–2025 evidence framework reveals that the scientific community considers a decarbonization strategy relying solely on hydrogen for residential heating neither economically competitive nor socially viable compared to established alternatives such as heat pumps or district heating. Nevertheless, hydrogen can play a complementary role in hybrid heating solutions, including cogeneration and micro-cogeneration. Its application may be particularly relevant in specific contexts, such as industrial clusters that already produce and consume hydrogen, or in cold climate regions where heat pump performance declines.

Hydrogen also offers strategic value for the energy system, enabling long-term (seasonal) storage and enhancing the flexibility of renewable-heavy electrical grids by balancing surplus energy from intermittent sources, such as solar and wind, during periods of high demand and cold weather. Public perception of hydrogen in the residential sector remains heterogeneous: most consumers express concerns regarding economic, environmental, and safety issues, with only a small proportion showing support. Trust in regulation and safety perceptions, such as fears of fires or explosions, along with the national political and media narrative, strongly influence acceptance.

In summary, while green hydrogen is the cleanest option in terms of direct emissions, its current economic and technical limitations, combined with social acceptance barriers, make direct use for widespread residential heating unfeasible. Electrification via heat pumps consistently emerges as a more efficient, cost-effective, and mature pathway for

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decarbonizing residential heating. Hydrogen's role is therefore expected to remain complementary, supporting system flexibility and long-term energy storage rather than serving as the primary heating solution.

Directions for Future Research

Based on the knowledge gaps identified in this analysis, a clear and targeted research agenda is needed to refine our understanding of hydrogen's potential role. The following areas are critical for future investigation:

- Large-Scale Pilot Studies and Demonstration: The majority of current evidence is based on modeling and laboratory-scale experiments. There is an urgent need for large-scale, real-world demonstration projects. These pilots are essential to move beyond theoretical assessments and validate the technical performance, real-world costs, and, most importantly, the social acceptance of hydrogen heating in diverse community settings.
- Socio-Economic and Behavioral Analysis: Further granular research into consumer behavior is required. Studies should focus on quantifying willingness-to-pay for hydrogen-based systems, understanding the impact of different policy incentives on adoption rates across varied socio-demographic groups, and identifying effective communication strategies to address public concerns and build trust.
- Whole-System Optimization Modeling: Future research must focus on identifying cost-optimal, whole-system decarbonization pathways. This requires integrated modeling that strategically combines hydrogen with other flexibility options, such as large-scale thermal storage, demand-side response programs, and smart hybrid heating systems, to find the most efficient and resilient energy system architecture.

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