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Review

A Review of the Role of Hydrogen in the Heat Decarbonization of Future Energy Systems: Insights and Perspectives

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Abstract: Hydrogen is an emerging technology changing the context of heating with cleaner combustion than traditional fossil fuels. Studies indicate the potential to repurpose the existing natural gas infrastructure, offering consumers a sustainable, economically viable option in the future. The integration of hydrogen in combined heat and power systems could provide residential energy demand and reduce environmental emissions. However, the widespread adoption of hydrogen will face several challenges, such as carbon dioxide emissions from the current production methods and the need for infrastructure modification for transport and safety. Researchers indicated the viability of hydrogen in decarbonizing heat, while some studies also challenged its long-term role in the future of heating. In this paper, a comprehensive literature review is carried out by identifying the following key aspects, which could impact the conclusion on the overall role of hydrogen in heat decarbonization: (i) a holistic view of the energy system, considering factors such as renewable integration and system balancing; (ii) consumer-oriented approaches often overlook the broader benefits of hydrogen in emission reduction and grid stability; (iii) carbon capture and storage scalability is a key factor for large-scale production of low-emission blue hydrogen; (iv) technological improvements could increase the cost-effectiveness of hydrogen; (v) the role of hydrogen in enhancing resilience, especially during extreme weather conditions, raises the potential of hydrogen as a flexible asset in the energy infrastructure for future energy supply; and finally, when considering the UK as a basis case, (vi) incorporating factors such as the extensive gas network and unique climate conditions, necessitates specific strategies.

Keywords: hydrogen; heat decarbonization; hydrogen boilers; heat pumps; whole-energy system; resilience

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1. Introduction

1.1. Background and Motivation

In the context of a decarbonized future, hydrogen stands out as a pivotal element in transforming energy systems. Its versatility allows it to bridge gaps in renewable energy supply, acting as both a high-density energy carrier and a storage medium [1–3]. References [4,5] address the broader implications of energy substitution in achieving carbon neutrality. They underscore the significance of renewable energy sources, including hydrogen, in reducing carbon emissions and outline the role of solar, wind, hydropower, nuclear, and hydrogen energy in this context. The articles present an analysis of carbon dioxide (CO_2) trends and the impact of renewable energy on reducing these emissions, underscoring the essential role of transitioning to a new energy structure to achieve carbon neutrality. The utilization of hydrogen energy within the energy systems in various countries has received significant attention because of its potential to contribute to net-zero energy systems. Studies such as [6], conducted for Germany in 2045, have explored the role of liquid hydrogen (LH_2) in achieving greenhouse gas neutrality within the national energy supply system. These investigations emphasize the impact of hydrogen demand, whether liquid or gaseous, on the design and optimization of future energy systems, highlighting the importance of considering factors such as import, transportation, and production of LH_2. Furthermore, global reviews on hydrogen energy needs, policies, and practices underscore its potential as a key component in accelerating the transition towards clean, zero-carbon, renewable energy systems [7]. The integration of hydrogen technologies with existing renewable energy resources, such as solar and wind, demonstrates its potential to emerge as a vital energy ecosystem, offering solutions for energy production, storage distribution, and utilization. Additionally, literature reviews on hydrogen energy systems provide insights into the challenges, prospects, and convergence with renewable energy sources (RESs), shedding light on the critical role of hydrogen in the transition to sustainable energy economies [8]. Different aspects of available technologies for utilizing hydrogen as an energy carrier in various countries such as the United Kingdom (UK), Germany, the United States, Norway, and Australia are demonstrated in [9]. Furthermore, the need for further research, innovation, and collaboration to maximize its potential in facilitating the decarbonization of global energy production and utilization is highlighted.

1.2. Hydrogen Production and Alternative Energy Carriers

The transition towards fossil-free energy systems necessitates the development of renewable power-to-fuel (PtF) technologies, as outlined in [10]. These technologies utilize renewable electricity and capture CO_2 to produce carbon-neutral synthetic fuels, including power-to-methane, power-to-methanol, and power-to-ammonia, which can serve as effective energy carriers. Moreover, the PtF concept offers grid-balancing capabilities and long-term energy storage solutions, contributing to the decarbonization of the energy sector by reducing greenhouse gas emissions. Clean methanol, produced from renewable hydrogen and captured CO_2, emerges as a promising alternative to fossil-based methanol production, as discussed in [11]. Utilizing renewable energy sources for hydrogen production and employing membrane technology for water removal during methanol synthesis enhances production efficiency while minimizing energy consumption. Additionally, hydrogen carriers play two pivotal roles in enabling the widespread utilization of hydrogen as an energy vector, as highlighted in [12]. Another compelling aspect that could make hydrogen a promising energy carrier is the potential to import alternatives (e.g., ammonia). Ammonia, when decomposed, can release hydrogen, allowing regions with limited renewable energy resources to import and store energy in a more condensed form. This diversifies the energy supply chain and provides a pathway for integrating global renewable energy markets, ensuring a more resilient and interconnected energy future. Various hydrogen carriers, including methanol and liquid organic hydrogen carters, offer alternatives to conventional storage and transportation methods, presenting promising pathways for sustainable hydrogen utilization.

In categorizing the literature on hydrogen production methods, two primary themes can be demonstrated as follows: technological approaches and challenges in scaling up the hydrogen economy. References [13–15] primarily focus on technological aspects, detailing various methods for hydrogen production and their associated benefits and drawbacks. These articles explore diverse approaches, including electrolysis, natural gas, biomass mechanisms, and renewable energy-based processes, highlighting the potential of renewable sources in advancing hydrogen production. In [13], different colors of hydrogen production are presented and the environmental and economic performance of different hydrogen production methods such as green hydrogen (i.e., via electrolysis) and blue hydrogen (i.e., via steam methane reformers (SMRs) or auto thermal reformers (ATRs) coupled with carbon capture and storage (CCS)) is evaluated. Additionally, they delve into the technical challenges faced in implementing these methods, such as feedstock type, conversion efficiency, and integration with purification and storage technologies. A comparative study of different types of electrolyzers offering an economic assessment of green hydrogen production, shedding light on the cost implications and efficiency of various production methods is presented in [14]. References [15,16] demonstrate the advancements in hydrogen production technologies, including photo fermentation, dark fermentation, and microbial electrolysis cells. They emphasize the potential of utilizing waste materials as feedstocks and the pivotal role of nanotechnology in boosting the efficiency of biohydrogen production. These references highlight the importance of sustainable practices and technological innovation in enhancing the viability of hydrogen as an energy source. The obstacles that delay the widespread adoption of hydrogen energy are presented in [17,18]. These works discuss the absence of a cohesive hydrogen value chain, as well as the challenges associated with the storage and transportation of hydrogen. They underline the necessity for international standards, effective policy frameworks, and strategic investments to address these issues, which are crucial for scaling up the hydrogen economy. By categorizing these articles based on technological approaches and scalability challenges, a comprehensive understanding of the current landscape of hydrogen production and the necessary steps for its integration into sustainable energy systems could be realized. The literature also explores the critical importance of materials science in the development of hydrogen technologies, as discussed in [19,20]. These studies shed light on the need for innovative materials that can enhance production efficiency, ensure storage safety, and maintain cost competitiveness, highlighting the interdisciplinary nature of the current challenges.

1.3. Hydrogen Transport and Utilization

Hydrogen can be integrated into existing gas networks [21–23], providing a cleaner alternative to fossil fuels for heating and industrial processes [24–26]. Additionally, its role in sector coupling—linking electricity, heat, and transport sectors—enhances overall system efficiency and resilience [27,28]. The utilization of green hydrogen further reduces carbon emissions, aligning with global climate goals [29,30]. Moreover, hydrogen's potential in fuel cells for transportation [31,32] and in flexible power generation [33–35] positions it as a key enabler of a sustainable, low-carbon energy ecosystem. Its adaptability to various applications and its capacity to store and release energy as needed make hydrogen a critical component in the transition to a decarbonized future, facilitating more balanced, reliable, and sustainable energy grids [36–38]. In this context, clean hydrogen could provide added value by decreasing greenhouse gas (GHG) emissions from the heating sector. In [39], the options for a greener gas grid are explored, and the feasibility of converting existing natural gas infrastructure to hydrogen is examined. The study notes that approximately 85% of the households in the UK use natural gas for heating. The study suggests that hydrogen could be a viable alternative to natural gas for heating and could be less disruptive to consumers than other low-carbon heating technologies. The evaluation presented in two UK white papers [40,41] indicates that transitioning the gas grid to hydrogen for heating might be more cost-effective than existing alternatives. This aligns with the results of other studies on this topic [42,43]. Consumers not connected to the gas network will turn to electrification through heat pumps as a primary solution for their heating requirements [44].

The utilization of hydrogen for fuel cells offers a promising pathway for electricity production, accompanied by generating heat as a by-product suitable for heating purposes. Research in this domain has explored various strategies to enhance the efficiency and sustainability of hydrogen utilization within fuel cell systems. In [45], the authors propose a novel approach to improve the utilization of RES and reduce carbon emissions by using hydrogen as an energy carrier for heating. Specifically, they analyze a two-stage power-to-gas (P2G) technology called power-to-heat-synthetic natural gas, which involves converting excess renewable electricity into hydrogen gas through electrolysis and then using the hydrogen gas to produce heat and electricity through a hydrogen fuel cell and a combined heat and power (CHP) system. The authors also propose an electrothermal hybrid energy storage model with power-to-heat (PtH) equipment and an electric boiler to store excess heat energy generated by the system. By optimizing the dispatch of electricity, hydrogen, gas, and heat in this integrated energy system, the authors aim to improve the efficiency and economics of renewable energy utilization for heating. In [46], a grid-connected hybrid wind/hydrogen CHP system for residential energy systems that incorporates hydrogen in a fuel cell to generate electricity and heat is proposed. The hydrogen is produced from renewable sources and is used in the fuel cell along with wind energy to meet the electrical and thermal demands of the residential load. The thermal recovery from the fuel cell is also considered in the economic model. The paper highlights the importance of using hydrogen for residential applications to address concerns such as increasing energy demands, reductions in fossil fuel sources and reservoirs, global warming, and environmental degradation. In the context of hydrogen-to-power for providing the demand (e.g., heat demand), in [47], the use of hydrogen in a reconfigurable residential smart hybrid microgrid for producing/storing hydrogen for later usage and increasing fuel cell efficiency is discussed. It is mentioned that hydrogen is injected during high thermal demand hours in a hydrogen tank for later use in generating electricity during low thermal load hours. The simulation results show the significance of considering thermal power recovery and hydrogen generation in the fuel cell model for supporting part of the heat demand. In [48], integrating small-scale biohydrogen production systems with renewable energy sources like solar and wind to facilitate a sustainable hydrogen economy is investigated. These integrated systems employ advanced technologies such as anaerobic fermentation microbial electrolysis cells and microbial fuel cells, coupled with electrolysis of water and hydrogen fuel cells, to efficiently produce hydrogen. In [49], it is demonstrated that the waste heat of a fuel cell can be absorbed and utilized to preheat the process of methanol reforming. This could decrease the required extra heat for the reactants' consumption and, consequently, enhance the energy efficiency of the system. In [50], it is indicated that while generating electricity through the use of solid oxide fuel cells (SOFC), the produced heat (i.e., as a by-product) can be used for domestic hot water production and space heating. Additionally, efforts have been made to optimize the energy conversion process, as highlighted in [51], which evaluates the potential of solar and wind energy-driven electrolysis technologies for green hydrogen production, specifically for fuel cell applications. Such initiatives aim to address global energy challenges while minimizing environmental impacts by reducing greenhouse gas emissions associated with conventional energy production methods. Moreover, the application of fuel cells in various sectors, as discussed in [52], underscores their versatility and potential contribution to mitigating climate change. Fuel cells offer environmentally friendly energy conversion solutions fueled by green hydrogen or biofuel derived from biomass and waste streams, with water as the only by-product. These findings underscore the significance of hydrogen fuel cells as a key component of sustainable energy systems, with implications for diverse applications including residential, transportation, and power generation. In Figure 1, a value chain approach for hydrogen including production, conversion, transport, storage, and end-use is presented (based on [53]).

1.4. Hydrogen System Integration

Regarding the techno-economic analysis of the role of hydrogen from a whole energy system perspective, strategic insights into the economic performance of alternative heat decarbonization scenarios are provided in [54]. It assessed the role and value of emerging low-carbon and flexibility technologies, considering their future cost and availability uncertainties. The research also conducted an impact assessment of different heat decarbonization scenarios. It analyzed the system capacity and operational characteristics of electricity, natural gas, and hydrogen technologies. Using a holistic approach, the study also considered their associated infrastructure requirements and optimal energy vector interactions. The findings indicated that all heat decarbonization scenarios could achieve 2050 net-zero emissions ranging between 98 and 103 £bn/yr (total annual costs of the energy system), where the hydrogen heating strategy costs 2 £bn/yr less than full electrification. However, the hybrid heating pathway emerged as the most cost-effective solution. The study also emphasized the importance of enhancing system flexibility in all pathways, especially in full electrification. Strong interactions were observed across system components, notably power, heat, and natural gas/hydrogen. The research also found that integrating multiple forms of energy storage (e.g., linepack in the gas pipelines) and focusing on multi-energy vector optimization using the integrated hydrogen and electricity system (IHES) model resulted in significant cost savings. The research presented in reference [44] strongly suggests that investing in energy flexibility can provide up to GBP 16.7 billion in annual savings in 2050 across all net-zero scenarios using the integrated whole energy system (IWES) model. These significant net savings are supported by a diverse array of flexibility technologies, including energy storage systems (i.e., battery and thermal), demand-side response mechanisms (domestic and non-domestic), interconnectors, and electric vehicle (EV) sectors. Moreover, such flexible systems prove invaluable in managing the energy challenges of extreme weather events. During these periods of high demand and stress on the energy system, low-cost fossil fuel plants, particularly gas plants, have historically provided reliable, dispatchable power to ensure stability. However, the research underscores the necessity of either integrating negative emissions technology or, alternatively, deploying fossil fuel plants without carbon abatement measures. In the case that these technologies are not available, reliable power sources like hydrogen-fueled generation are required to maintain the security of supply. The study found integrating hydrogen and electricity system management is essential, as a siloed approach in planning those energy systems will result in a higher system cost.

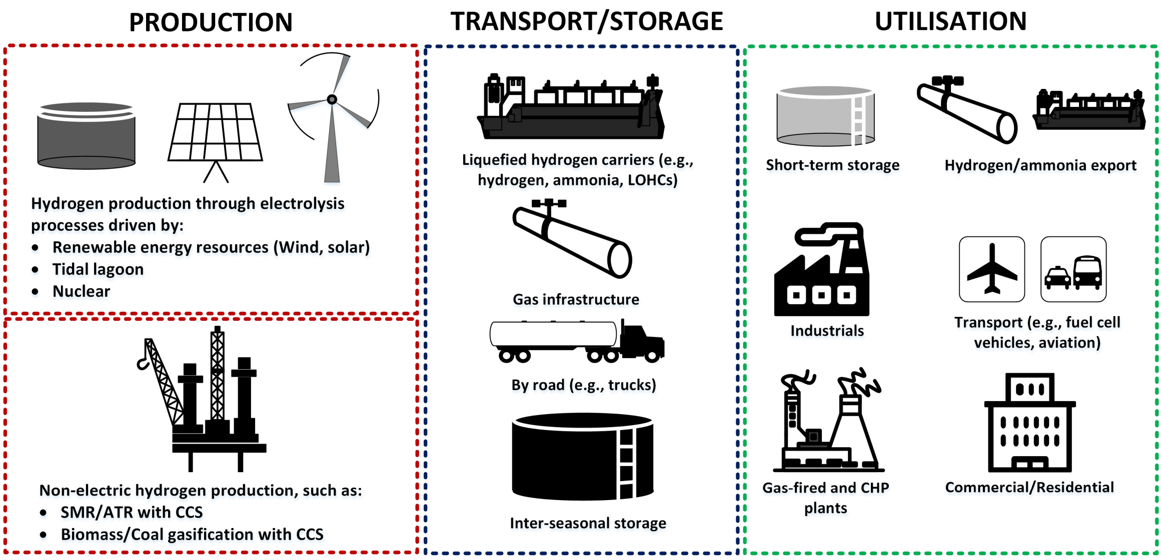

Figure 1. Hydrogen value chain.

1.5. Contribution

Despite the above-mentioned role of hydrogen as one of the key reflections it could play in decarbonizing heat, numerous studies have pointed out the complications associated with using hydrogen for heating, mainly due to the broad adoption it demands [55]. Conventional hydrogen production methods, such as steam methane reforming, are cost-effective yet result in significant CO_2 emissions if not coupled with carbon capture and storage technologies, as noted in references [56–58]. While producing green hydrogen through electrolysis powered by renewable energy is an attractive alternative, its efficiency, particularly for heating purposes, falls short when compared with the direct electrification methods discussed in [59–64]. Hydrogen storage and transport also pose notable challenges, necessitating either high-pressure or cryogenic storage solutions, which subsequently increase infrastructure costs. It is also demonstrated that retrofitting or replacing the existing infrastructure for hydrogen transport can lead to leakages [64–66].

In this paper, to establish a robust foundation for our investigation, as the contribution of this work, numerous studies are reviewed, some of which indicate that hydrogen might not be a leading fuel in future heating decarbonization, which underlines the essence and context of this detailed review. The review of these references points out a rather varied landscape where some studies might have either ignored, oversimplified, or not considered integral elements related to hydrogen's viability, especially for the UK, which is the basis case for this review. These gaps in approach or emphasis could influence the overall outlook on hydrogen's role in decarbonizing the heating sector. In order to better understand the conclusions derived from the references, it becomes essential to go in-depth into the specific dimensions and constraints of each study to identify the potential factors that could lead to underestimating the economic role of hydrogen in a net-zero energy system.

The remainder of this paper is structured as follows: Section 2 presents a detailed review of all the studies on the role of hydrogen for heat decarbonization, which from now on are called "heat decarbonization" studies. Each study is initially summarized, followed by a critical evaluation focusing on its treatment of hydrogen's role in heating decarbonization. Section 3 presents a synthesized table that categorizes certain criteria that potentially influence hydrogen's contribution to the decarbonization of heating, and the key elements are further discussed. Finally, this paper wraps up with Section 4, providing a summary of our findings.

2. Review of "Heat Decarbonization" Studies

2.1. Introduction

In this section, a comprehensive overview of each of the reviewed references, which did not consider a major role for hydrogen in heat decarbonization, is provided, followed by an in-depth exploration of the factors that, in our assessment, these studies might not have fully taken into account or assumed. These oversights could have contributed to the conclusion that hydrogen's role in heating may not be significant. This assessment aims to shed light on the aspects of hydrogen's potential in heat decarbonization that might have been missed.

In this review, it is noted that many studies have focused on the UK and Germany. In this context, and in order to provide a better understanding and to avoid repetition later on, two key observations regarding the cases of the UK and Germany from an energy system perspective are outlined as follows:

The capabilities and utilization of CCS in the UK and Germany demonstrate different trajectories and priorities in their efforts to reduce carbon emissions. In the UK, CCS has been a focal point in decarbonizing its energy-intensive industries, particularly in the power generation sector. The UK has advanced several CCS projects, including the Peterhead [67] and White Rose [68] projects, which aim to capture and store carbon emissions from power plants. Moreover, the UK government has shown commitment to funding CCS development as part of its broader climate strategy. However, the pace of progress has been subject to policy changes and funding challenges, which have caused some delays. Conversely, Germany has approached CCS from a more cautious perspective. While it recognizes the importance of CCS in achieving emission reduction targets, the country has faced public opposition and regulatory hurdles, particularly regarding underground storage [69,70]. Instead, Germany has concentrated on expanding renewable energy, energy efficiency measures, and enhancing industrial processes to reduce emissions. As a result, CCS projects are currently limited in Germany, reflecting a deliberate choice to prioritize other decarbonization strategies.

The provision of heat in the UK and Germany exhibits commonalities and distinctions. Both nations rely significantly on natural gas boilers for heating, a dominant approach in residential and commercial sectors. Additionally, they share the objective of transitioning towards renewable heat sources, integrating technologies like heat pumps and solar thermal systems to mitigate carbon emissions in heating. One key difference lies in the extent of their district heating infrastructure [71]. Germany has a well-established network, particularly in urban areas, fostering efficient centralized heating systems. In contrast, district heating in the UK is less utilized compared with Germany. Germany also excels in adopting diverse renewable heat technologies, such as solar thermal, geothermal, and biomass heating, especially in its district heating systems. This progressive approach is complemented by strict energy efficiency regulations. Conversely, the UK is working to enhance its adoption of renewable heating technologies and enforce building regulations more strictly. These variations reflect the unique energy landscapes and policy priorities of each country as they navigate the transition to more sustainable and efficient heating solutions.

2.2. Summary and Evaluation

In this section, individual insights on the overview and our evaluation of each of the reviewed "heat decarbonization" studies are provided. If necessary, a comparison with the UK energy system aspects (basis region for this study) is provided.

The Agora Energiewende report [72] critically examines hydrogen's role in the energy sector, debating the required early-stage public financial support and highlighting hydrogen's inefficiencies compared with electrification, particularly in heating and transport. It discusses the challenges of sourcing and storing hydrogen and its less efficient production process. However, the study's evaluation suggests a potential bias in underestimating hydrogen's efficiency and cost-effectiveness, particularly in heating applications, by not fully considering factors like peak demand management and future technological advancements.

In [57], a multi-model assessment of the UK's heat decarbonization options using electricity and hydrogen, employing the resource-technology network (RTN) and whole-electricity System Investment Model (WeSIM) models for an integrated analysis are presented (Figure 2). The study concludes that a balanced mix of electricity and hydrogen, including blue hydrogen for medium-term use in dealing with the peak demand, and electric heat pumps as the primary heating technology, can efficiently deliver zero-carbon heat in the UK. However, the study primarily focuses on hydrogen as a supplemental heat source in hybrid air source heat pumps used only during extreme weather events. This perspective potentially underestimates hydrogen's broader potential, especially considering the advancements in green hydrogen production, in which a large-scale hydrogen infrastructure could enhance its economic viability in heating, allowing for more optimized usage.

The reports by Baldino et al. in 2020 and 2021 analyze the costs of low-carbon heating technologies in different regions, including the Netherlands [73], the UK [74], Germany [75], and all of Europe [76] identifying air source heat pumps (ASHPs) using renewable electricity and hybrid heat pumps with auxiliary hydrogen boilers as the most cost-effective options for 2050. However, their consumer-oriented focus primarily on consumer bills misses broader considerations such as heat storage, the role of district heating systems in the UK, and the variability in the heat pump coefficient of performance (COP) in different temperatures. The studies also potentially rely on outdated electricity demand data and do not address the impact of these technologies on the grid, which are critical for a comprehensive understanding of their role in a resilient and evolving energy ecosystem.

In [77], a scenario-based analysis is conducted on transitioning to RES for heating in Europe (EU) to achieve climate neutrality by 2050 [78–81], highlighting the significant need to increase electricity generation from wind and solar. The study finds that direct electrification is the most cost-efficient pathway, with scenarios identifying heat pumps to be more cost-effective than hydrogen or electro-fuels (E-fuels). However, the study focuses on electrification, potentially overlooking the advantages and challenges of other energy vectors like hybrid systems, green gases like hydrogen, and the role of storage in grid stability. A broader approach considering various energy sources and technologies would likely offer a more diversified and resilient energy system.

In [82], various low-carbon heating options, including heat pumps, district heating, hydrogen, and biomass boilers, are investigated, emphasizing the need for a diverse portfolio to achieve net-zero targets. The study assesses how residential heating scenarios might impact sectoral and system-wide changes towards net-zero goals. It identifies barriers such as the need for infrastructure upgrades, immature low-carbon technologies, and societal factors. However, it may not fully recognize hydrogen's role, especially in resilience and beyond residential heating. It overlooks hydrogen's potential in commercial, industrial, or district heating and assumes high costs for green hydrogen production, potentially underestimating its technological development and future economic feasibility. In addition, the study's economic analysis and assumed biomass supply limit may constrain the viability of hydrogen, as it does not consider the potential reduction in hydrogen production costs and the evolving technology landscape. This perspective could underplay hydrogen's broader role in the UK's heating sector.

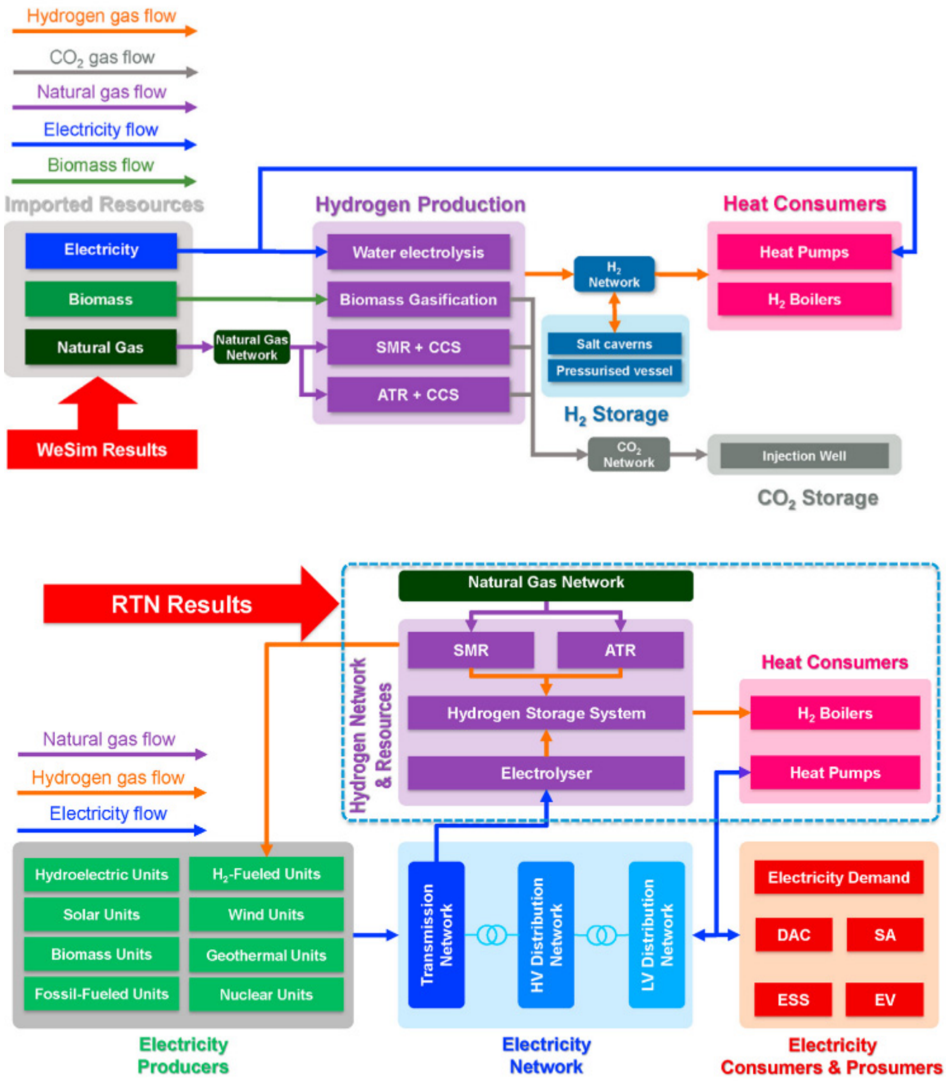

Figure 2. High-level diagram of the interaction between RTN and WeSIM [57].

The authors of [78] utilize an energy model to explore various scenarios and policy targets, highlighting "no-regret" options like investment in insulation, efficient equipment, and electrification of transport and heat. The study emphasizes the need for an integrated approach to energy and climate policies involving regulatory, market-based, and financial instruments. Furthermore, it highlights the importance of public engagement and international cooperation. The study compares hydrogen's efficiency and emission reduction potential with heat pumps and electric boilers, pointing out the high costs, low energy efficiency, and safety concerns of hydrogen for heating. The analysis, however, excludes crucial aspects, particularly in the context of hydrogen's broader role in the energy system. It adopts an 80% GHG emission reduction target, which might undervalue the necessity of deploying hydrogen as an alternative to fossil fuels. Moreover, it overlooks the critical role of resilience in energy systems, especially for hydrogen, which can provide a buffer during supply disruptions and extreme weather events, ensuring the security of supply.

In [59] it is discussed how the UK can meet its heat demands in zero-emission renewable energy systems using storage and interconnectors, employing a whole-system modeling approach that combines hourly simulations of demand and supply with storage and European interconnections. The study finds that heat pumps are four times more electricity-efficient than the green hydrogen route, and the cost of heating with green hydrogen is double that of heat pumps. It also explores the trade-offs in investing in different infrastructures for the UK heat supply, noting that increasing renewable capacity or interconnections can significantly reduce storage needs. However, the evaluation raises several critical points, which the study may overlook or under-emphasize regarding hydrogen's role in heating. Notably, the article does not consider blue hydrogen, potentially missing a key aspect of the current hydrogen market important for the energy sector's transition. It also highlights the high peak electricity demand in the hydrogen scenario, which could be mitigated by including blue hydrogen, potentially enhancing grid stability. The study's high heat pump to hydrogen boiler (HP/H2B) efficiency ratio suggests a priority for heat pumps, overlooking the benefits of diversified solutions like hydrogen boilers for system resilience. This ratio, especially given the UK's expected weather forecasts, leads to further justification considering regional climate variations in evaluating energy solutions.

The cost of low-carbon heating options in four European countries—Spain, Italy, Czechia, and Poland, representing archetypal warm and cold climates (Figure 3)—highlighting the cost-effectiveness of heat pumps and the high expense of hydrogen boilers is analyzed in [61]. The report finds that in warmer countries like Spain and Italy, heat pumps are particularly cost-efficient, while the cost gap between heat pumps and hydrogen boilers varies depending on fuel costs, sometimes making hybrid heat pumps competitive. It also notes the potential of low-carbon district heat networks for domestic heating, offering demand flexibility and easier decarbonization than individual home systems. The report anticipates that by 2040, carbon prices will influence electricity costs in regions still using fossil fuels. As the electricity system fully decarbonizes, flexible heating could offer significant cost savings. However, the report's consumer-centric approach, focusing on individual heating choices, may overlook broader supply chain implications. It reveals regional differences in infrastructure, such as the lower gas grid connection in Spain, Czechia, Poland, and Italy compared with the UK, affecting the viability of hydrogen heating. The reported HP/H2B efficiency ratio of 4.5 suggests a preference for heat pumps, but a more holistic analysis considering system upgrades for peak demand is necessary for a complete evaluation. Additionally, the report does not consider blue hydrogen, which could be influenced by the specific policies of these countries, omitting a potentially sustainable pathway in the energy sector's decarbonization.

The Energy Transition Commission (ETC) report [63] provides insights on accelerating clean hydrogen within an electrified economy, emphasizing its crucial role in decarbonizing sectors like heavy industry, shipping, and aviation. It highlights green hydrogen, produced from renewables, as the most sustainable form and anticipates a significant cost reduction in the future, enhancing its competitiveness with fossil fuels. The study's analysis of hydrogen's role in the energy sector has certain limitations. It primarily focuses on the complexities of hydrogen production and transportation, potentially giving an imbalanced view of hydrogen's role in the entire energy ecosystem. The study's HP/H2B efficiency ratio of 5–6 may imply a preference for heat pumps over hydrogen boilers, which could reduce hydrogen's potential in specific scenarios. Furthermore, the lack of comprehensive energy system optimization in the study limits the applicability of its findings in broader energy strategy discussions. This absence of a holistic approach could restrict the understanding of hydrogen's full potential in an integrated energy landscape.

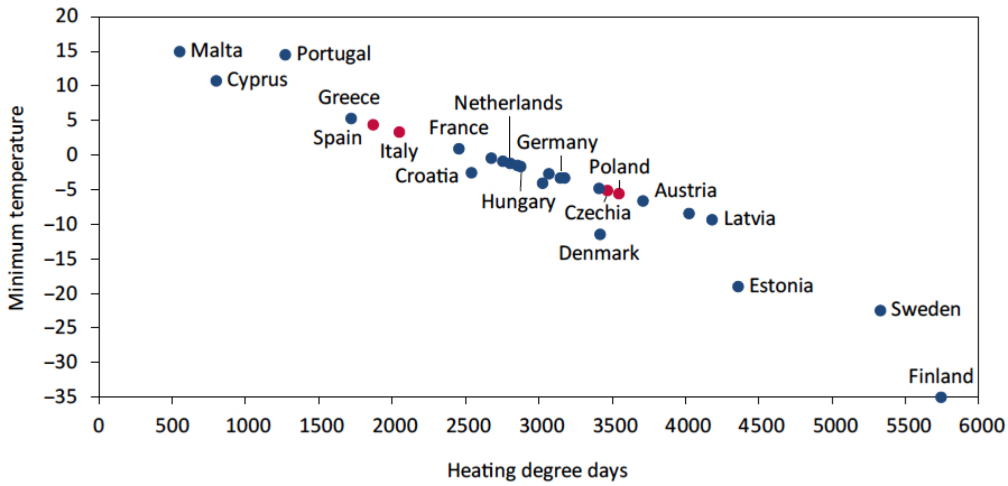

Figure 3. Representation of EU countries' climate by minimum temperature and heating degree days [83], showing the four selected countries as archetypal warm and cold climates [61].

In [65], the use of hydrogen in German gas distribution grids, comparing the continuation of natural gas, transitioning to synthetic natural gas, and shifting to hydrogen, is evaluated. The study highlights the necessity of region-specific modeling for distribution network transitions, indicating that the current value of existing gas infrastructure might be overestimated. However, the study's focus is limited to the conversion of gas grids and does not fully encompass broader aspects of energy transition, such as the efficiency of consumption technologies, energy supply costs, electricity grid expenses, and building-related measures. This might miss out on capturing the full scope and complexity of a comprehensive energy transition, underlining the need for an integrated approach that includes all these critical elements for a complete analysis.

The International Energy Agency (IEA) report, "A Roadmap for the Global Energy Sector" [84], offers a comprehensive analysis of actions needed to achieve global net-zero emissions by 2050 and limit the global temperature rise to 1.5 °C above pre-industrial levels. It proposes a detailed pathway involving the rapid deployment of clean energy technologies, enhancing energy efficiency, and accelerating innovation in hydrogen and carbon capture, utilization, and storage (CCUS). The report discusses hydrogen blending into the gas network, projecting a 15% hydrogen blend by 2030 for a 6% emissions reduction. It suggests that electrification will generally be the most energy-efficient and cost-effective option for heating. It is mentioned that heat pumps will account for about 30% of total heat demand by 2050; however, hydrogen and bioenergy will play more minor roles in high-temperature heat. However, the report's evaluation may not fully capture the broader role of hydrogen in the energy system. It views hydrogen production as energy-intensive and mentions limited infrastructure as a barrier, but this perspective overlooks hydrogen's potential to enhance energy resilience and stabilize the grid, especially with fluctuating renewable energy outputs. The study does not sufficiently consider the benefits of adapting existing natural gas infrastructure for hydrogen. This could reduce infrastructure challenges and costs, facilitating a smoother transition to hydrogen use for storage, transportation, and other purposes. This adaptation could make hydrogen a more cost-effective and practical option within the broader energy system.

The Intergovernmental Panel on Climate Change (IPCC) work [85] focuses on mitigating climate change through sustainable building practices, highlighting challenges such as the long lifespan of buildings, slow turnover of building stock, and barriers to adopting energy-efficient technologies. The report suggests that building design and construction incorporating energy-efficient technologies, materials, and passive design strategies can significantly contribute to climate change mitigation. However, while the study emphasizes sustainable building practices, it does not deeply explore other crucial aspects of the energy landscape. Its limited scope on sustainability in building practices misses a broader analysis of how these practices integrate with wider energy strategies and technological advancements, particularly in the context of hydrogen's role in heating.

The report published by the International Renewable Energy Agency (IRENA) [86] provides a comprehensive analysis of hydrogen's role in the energy transition to a low-carbon future, covering its production, transportation, storage, and usage across various sectors. It highlights hydrogen's potential to decarbonize challenging sectors and add flexibility to the energy system through storage. However, the report demonstrates significant challenges for hydrogen deployment, such as high costs, infrastructure gaps, and safety concerns [87]. The report particularly recognizes hydrogen's importance in enhancing resilience, especially for remote communities reliant on smaller grids and diesel generators, suggesting hydrogen as a sustainable alternative. The study's notable limitation is its lack of optimization scenarios, meaning while hydrogen's potential is acknowledged, the report does not extensively explore strategic implementations, quantify benefits, or compare hydrogen-based solutions with other energy alternatives.

The authors of [56] introduce an urban energy systems model, applying it to Sao Paulo in Brazil to explore decarbonization pathways. The model assesses energy service demands for heating, cooling, electricity, and transport, using a bottom-up approach to disaggregate demand into various zones and sectors, identifying cost-effective, low-carbon supply pathways. The key findings for Sao Paulo include significant carbon reductions in decarbonization scenarios, substantial renewable energy and low-carbon transport investments leading to long-term cost savings, and necessary infrastructure changes like expanding district heating/cooling networks and hydrogen facilities. The study does not thoroughly examine energy system resilience, which is crucial for long-term strategy viability. Its analysis of hydrogen boilers as transitional technologies might not fully align with UK-specific research and policy trends, necessitating a comparative evaluation. Additionally, Sao Paulo's specific climate, infrastructure, and socio-economic context differ significantly from the UK, limiting the direct applicability of its findings to the UK energy landscape. Applying these findings to the UK without appropriate adjustments could lead to misguided or suboptimal conclusions for the UK energy system.

The feasibility of using hydrogen directly in a fossil-free Europe by 2050, focusing on different energy sectors, is assessed in [88]. It concludes that integrating direct hydrogen technologies raises the cost of the energy system, with its primary use in heavy-duty transport and as a range extender for vehicles, while its application for heating, especially in urban areas, significantly increases costs. The study suggests hydrogen is less advantageous in heating compared with its use in industry or power production. However, the research has limitations, including a strict focus on a 100% renewable energy system, excluding nuclear energy and CCS, which raises questions about the system's adaptability and comprehensiveness. In addition, the study's potential lack of consideration of resilience, particularly in an all-renewable scenario, could pose risks to the reliability of the energy system, highlighting the need for a more holistic approach that includes diverse energy sources such as hydrogen for a balanced and resilient energy strategy.

The authors of [89] investigate the use of renewable energy for space heating within the EU's decarbonization strategy, highlighting technologies like district heating, heat pumps, and solar thermal systems. The study points to the Renewable Energy Directive II (RED II) as a foundational policy framework but suggests that more measures might be necessary. Case studies in the report demonstrate the successful implementation of renewable heating solutions, highlighting their benefits in reducing GHG emissions. However, the study overlooks the importance of resilience in energy systems, particularly concerning hydrogen's role. It misses the potential benefits of hydrogen in enhancing energy resilience during peak demands or variable renewable energy output and its capability for storing surplus renewable energy.

The report [90] highlights the crucial role of energy-efficient buildings in sustainable development, emphasizing that buildings are major energy consumers and significant contributors to GHG emissions. It argues that enhancing building energy efficiency can have multiple benefits, such as climate protection, improved health and comfort, and increased supply security. The report supports a mix of policy measures, financial incentives, and stakeholder engagement to foster energy-efficient practices and suggests practical steps for individuals to improve energy efficiency, like installing efficient appliances and using renewables. It is worth mentioning that it points to synthetic methane as a viable alternative to natural gas for reducing building sector emissions. However, the report's analysis of synthetic methane lacks a comprehensive perspective on the broader role of hydrogen, particularly in the P2G process, and its implications for synthetic methane production. This oversight limits the understanding of the entire value chain and the potential benefits of synthetic methane, such as grid balancing, storage, and possible cost savings from local hydrogen production, leading to a potentially narrow view of synthetic methane's feasibility and benefits in the energy sector.

Reference [91] explores the complexities of decarbonizing non-electric fuels in transportation, industry, and buildings compared to electric energy. The study acknowledges the challenges posed by the current reliance on fossil fuels for non-electric energy and discusses strategies to reduce emissions, such as energy demand reduction, decreasing carbon intensity via biomass or CCS, and using carbon dioxide removal (CDR) technologies. It emphasizes the importance of electrification in end-use sectors, noting its efficiency and sustainability advantages, especially for integrating RES like wind and solar. However, the study's consideration of hydrogen, particularly as a heating source, seems limited. It largely excludes hydrogen's potential in heating, particularly in countries with established gas infrastructures like the UK. The research's focus is on heat pumps, which may not fully capture the range of heating solutions, including hydrogen as an alternative or complementary method. Moreover, the study's characterization of green hydrogen as "indirect electrification" is unconventional and might lead to misunderstandings about its production and utility, as well as underrepresenting the role of blue hydrogen.

In [62], Germany's hydrogen strategy is evaluated, offering measures and recommendations for its implementation, including sector allocation, financing, infrastructure development, and supply. The report analyzes hydrogen's competitiveness in various applications, including transport and building heating, based on detailed cost analyses. It concludes that hydrogen is not cost-competitive with heat pumps at a price of EUR 4.5/kgH_2, even in inefficient scenarios like unrenovated buildings. Despite this, heat pumps maintain a cost advantage over hydrogen for heating unless hydrogen prices fall below EUR 2.2/kgH_2. The study also notes that in unrenovated buildings, hydrogen boilers require significantly more electricity to generate hydrogen compared with air heat pumps, a gap that enlarges in renovated buildings. The study, however, seems to overlook several critical aspects in its evaluation of hydrogen's role in the energy sector. It primarily focuses on household or consumer perspectives in cost evaluation, neglecting the broader economic and system-wide implications. This limited view can result in an incomplete analysis, not fully capturing the technology's or policy's comprehensive impact. Additionally, while the report presents a high HP/H2B efficiency ratio for Germany, it does not align with the HP/H2B efficiency ratio, particularly in the UK context. This gap in analysis could mean missing out on understanding the full potential and limitations of hydrogen and heat pumps in different national contexts and energy systems.

The report of [92] delves into the transition to a net-zero economy, highlighting its impacts across various sectors, including energy, transportation, and agriculture, and emphasizing the need for collaboration between businesses and governments. It identifies challenges such as high costs, consumer behavior changes, and potential job losses, proposing solutions through policy measures, technological innovation, and behavioral shifts. However, the report notably omits the potential of hydrogen as a sustainable heating solution despite its growing global importance as a versatile energy carrier. The report's lack of focus on hydrogen in heating solutions indicates a missed opportunity to explore this sustainable pathway, underscoring the importance of keeping research up to date with the evolving dynamics and innovations in the energy sector.

The study by [93] explores hydrogen's potential in de-fossilizing the building sector, distinguishing between its centralized and decentralized applications. Centralized hydrogen use in heating networks is seen as less controversial and potentially supportive in the energy system due to its flexibility. However, the economic viability of decentralized hydrogen, such as hydrogen boilers in buildings, raises concerns about the feasibility of repurposing natural gas infrastructure. The study suggests hydrogen's role in achieving climate neutrality in buildings may be minor and advises against diverting resources from key technologies like green district heating and heat pumps. It also considers blue hydrogen a transitional step towards a green hydrogen infrastructure. The focus is on household financial implications, highlighting the cost challenges in transitioning to sustainable energy. The study overlooks wider aspects of green hydrogen production, such as its production costs and the varied renewable resource availability in different countries, which could affect green hydrogen's economic viability and applicability in the global energy landscape.

In [94], a techno-economic and whole-system analysis of electricity- and hydrogen-driven technologies for domestic heating in the UK, comparing electric heat pumps and hydrogen boilers, is presented (Figure 4). It finds hydrogen-driven absorption heat pumps more sustainable than electric vapor-compression heat pumps powered by renewable hydrogen with a lower carbon footprint. However, the study demonstrates the substantial investment required for hydrogen heating pathways, including generation, electrolysis or reformation, and storage, potentially making them more expensive than electrification. The cost-effectiveness of both pathways relies on hydrogen and electricity prices and varying weather conditions. The study suggests hydrogen technologies are economically favorable if hydrogen is priced below half of the electricity price. It emphasizes the need for significant infrastructure investments and policy support for low-carbon heating technologies. However, the study's focus on household costs, while neglecting broader economic, environmental, and infrastructural factors, limits its scope. Furthermore, it lacks spatial resolution, which is crucial given the diverse energy dynamics across different regions. The study did not consider hydrogen's potential to enhance energy system resilience. This omission overlooks the broader role hydrogen could play in a resilient energy infrastructure, especially if a large-scale hydrogen infrastructure is developed, potentially making hydrogen more economically viable for heating by enabling efficient infrastructure use.

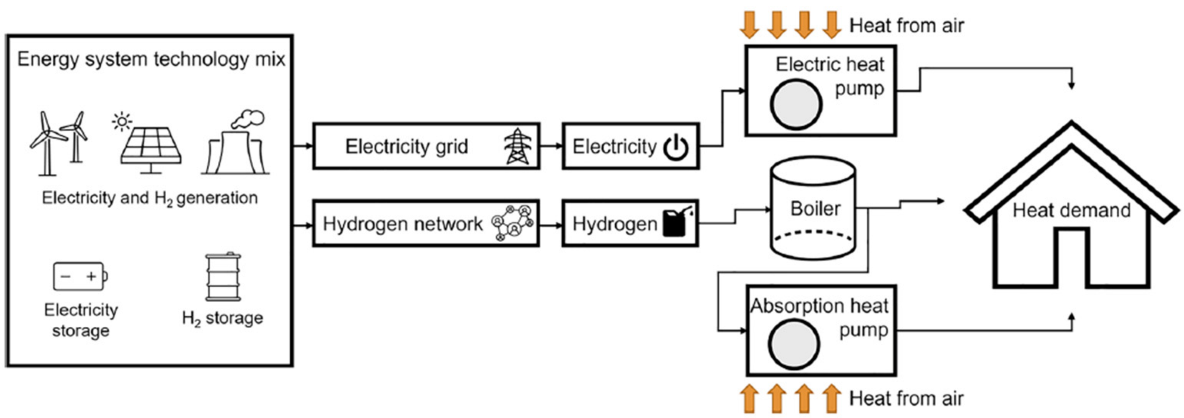

Figure 4. Schematic diagram of investigated electricity- and hydrogen-driven domestic heating options [94].

Oshiro and Fujimori's study assesses the role of hydrogen-based energy carriers, including hydrogen, ammonia, and synthetic hydrocarbons, in reducing emissions and contributing to decarbonization goals by mid-century [66]. The research suggests their limited role in the global energy system, with less than 5% contribution to the global final energy demand by 2050 in 2 °C scenarios, although this share increases in more strict scenarios or scenarios without CCS. The study demonstrates the importance of a holistic policy approach, integrating strategies like electrification and biofuels alongside hydrogen-based solutions, and stresses the importance of policy support for developing low-carbon hydrogen production and infrastructure. However, the study overlooks significant aspects, such as utilizing existing energy infrastructure for hydrogen deployment, which could facilitate cost savings and accelerate the transition to hydrogen-based systems. Moreover, it fails to adequately address the resilience provided by hydrogen, particularly its storage and transportation capabilities, which are essential for energy security and reliability during supply disruptions.

Quarton and Samsatli's study explores the practicalities and whole-system optimization of injecting hydrogen into gas grids, assessing the opportunities and challenges involved [95]. The study suggests that hydrogen injection can significantly reduce or eliminate GHG emissions from building heating and cooking, utilizing the existing gas infrastructure. It outlines that partial hydrogen injection offers modest emission reductions, while complete grid conversion to hydrogen could eliminate end-use GHG emissions. The study points out technical and economic challenges, such as gas properties, low-cost hydrogen supply chain development, and appliance modifications, which are being addressed by projects like NaturalHy [96] and Hy4Heat [97]. The study concludes that the long-term preference for complete hydrogen conversion versus electrification depends on the value of gas grid linepack flexibility and electricity infrastructure expansion costs. However, the study seems to overlook the role of hydrogen in supporting resilience, particularly in ensuring supply consistency during disruptions. While power-to-heat-to-power (PtHtP) may appear less efficient than PtH conversion, its benefits in energy storage and grid stabilization are significant. The study's approach to green hydrogen production is limited, focusing on excess night-time RES. Also, categorizing green hydrogen as an expensive option without considering its long-term potential and economies of scale may not fully represent its future viability. Anticipated technological advancements could lower hydrogen production costs, making it crucial to consider these future developments alongside current cost evaluations.

The study In [98] presents a cost–benefit analysis comparing heat pumps and condensing boilers using natural gas and green hydrogen for individual heat supply. The analysis finds that heat pumps are generally more efficient and cost-effective than green hydrogen, suggesting green hydrogen be reserved for applications where other decarbonization alternatives are not available. The study highlights the crucial role of power and gas grids in providing affordable heat supply, noting that heat pump usage may increase power grid load, potentially causing overload. Conversely, using green hydrogen for heating would necessitate expensive and complex gas grid refurbishments. For Hamburg to meet its 43% CO_2 reduction target by 2030, as per the Climate Protection Act [99], a comprehensive building renovation and rapid reassessment of heating technologies are required. However, the study overlooks several critical aspects in evaluating hydrogen's role in the energy sector. Notably, it does not consider blue hydrogen, possibly due to restricted policies on CCS projects in Germany, despite its potential importance in a sustainable energy landscape. The analysis emphasizes the higher cumulative cost of boilers compared with heat pumps but fails to assess these costs comprehensively, including factors like infrastructure adaptation and total ownership cost over time. Moreover, the study does not account for the resilience aspect of hydrogen. By skipping this resilience factor, the study might not fully capture the complete range of hydrogen's benefits, potentially underestimating its value in the energy sector.

The authors of [100] comprehensively analyze various low-carbon heating systems, assessing their economic and environmental viability across different dwelling types and climates. The study finds that electrified heating emerges as the most economically favorable option among the low-carbon technologies considered, taking into account lifetime costs and emissions. The study underscores the significance of the consumer perspective in decarbonizing heat, noting that the optimal heating technology varies based on the dwelling's properties and location. It also indicates that improvements in thermal efficiency through retrofitting and new housing standards, coupled with global warming, reduce heating demands and enhance the competitiveness of district energy heating against heat pumps. However, the study's primary focus on the consumer perspective may overlook broader systemic challenges, infrastructure needs, and larger economic or policy implications. This includes the need for a whole-system approach that considers interactions among all energy system components and diverse stakeholder perspectives for comprehensive energy sector decision-making and policy development.

The study by [58] analyzes a range of technologies for achieving a climate-neutral energy system in the Netherlands, including renewables like solar, wind, and geothermal, along with energy storage, demand-side management, and CCS. It explores the following two scenarios: one assumes a gradual transition focusing on electrification and energy efficiency, while the other envisages a rapid shift with a strong reliance on renewables and hydrogen as an energy carrier. The scenarios reveal that the optimal energy system by 2050 will depend highly on technological cost assumptions, societal preferences, and policy decisions. Common elements in both scenarios include energy efficiency measures, renewable energy deployment, and CCS for industrial emissions reduction. The study emphasizes the need for cross-sectoral integration and policy measures like carbon pricing and renewable energy subsidies to support the transition. However, the study has gaps in its approach to future heating solutions, notably the omission of hydrogen for heating. This absence is significant given hydrogen's potential in decarbonizing heating, particularly in areas where electrification is challenging. The study also overlooks the resilience aspect of energy systems, an essential factor in ensuring adaptability and recovery from disturbances. While the Netherlands and the UK have similar extensive gas grids, the Netherlands' newer infrastructure and green hydrogen initiatives provide valuable insights for the UK's hydrogen transition. Lessons from Dutch regulatory frameworks, pilot projects, and public acceptance strategies can inform both countries' approaches despite differences in infrastructure, policy, and socio-economic conditions.

Sheikh and Callaway's study demonstrates electrification as the most effective strategy for reducing carbon emissions in the heating sector, comparing it with alternatives like solar thermal, biogas, and synthetic natural gas [60]. They conclude that electrification could serve all heating loads and reduce emissions more cost-effectively than other options. While solar thermal offers immediate decarbonization, it falls short in cost-effectiveness compared with electrification, even when renewable costs are considered. Biogas and synthetic methane are limited by their low potential and high costs. However, the study's applicability is limited by its specific context to California, with its unique climate and energy infrastructure, which differs notably from the UK. Using an HP/H2B efficiency ratio of six significantly influences the outcomes, particularly regarding energy efficiency and system costs. Without adjustments for the UK's specific conditions, including its colder winters, maritime climate, and energy policy framework, the study's conclusions might not be directly relevant or applicable to the UK context, highlighting the need for region-specific energy research.

In [101], a potential energy transition pathway for Germany to achieve a sustainable, low-carbon system is outlined, focusing on increasing renewable energy use, electrifying transport and heating sectors, and utilizing hydrogen and synthetic fuels within a 7 Gt CO_2 budget. The pathway emphasizes energy efficiency and a flexible, interconnected energy system but faces challenges such as substantial investments in renewables, energy storage, and grid infrastructure and necessitates supportive policy measures. The transition offers opportunities for economic growth in the renewable sector, potentially positioning Germany as a leader in low-carbon energy. However, the study's omission of carbon removal technologies like biomass energy with carbon capture and storage (BECCS) and direct air capture (DACS) limits its scope, as these are increasingly important in global climate strategies for reducing atmospheric carbon and balancing hard-to-abate sector emissions. This gap suggests a need for their integration into broader climate models for a more holistic approach to achieving carbon neutrality or negativity.

The study by Slorach et al. assesses the environmental sustainability of various heating technologies in the context of the UK's 2050 net-zero emission target [102]. It identifies ASHPs and boilers burning blue hydrogen as the most sustainable heating options currently available; nevertheless, modern gas boilers still rank lowest in terms of environmental impact across several categories. The study considers future electricity and natural gas mix scenarios, including the potential increase in domestic shale gas, but does not specifically analyze its impact on achieving net-zero targets. Additionally, the study suggests that emerging and decentralized heating technologies such as solar thermal, geothermal, alternative hydrogen production methods, and thermal storage should be similarly evaluated for their potential to contribute to net-zero goals. Despite its detailed analysis of environmental impacts, the study lacks emphasis on the broader energy system optimization, missing potential synergies and efficiencies that are crucial for sustainable resource deployment. This oversight suggests the need for a more holistic approach that combines environmental impact assessments with energy system optimization to fully understand and develop sustainable heating solutions.

The Wuppertal Institute's "Zukunftsimpuls 21" report outlines a policy strategy for achieving CO_2-neutral buildings in Germany by 2045, addressing the challenges and opportunities [103]. It proposes measures like expanding efficient, climate-friendly heating technologies and enhancing the visibility of building renovations. The report underscores the need for data provision to municipalities and service providers for effective implementation. A key finding is that using a condensing boiler with synthetic renewable hydrogen requires significantly more electricity than a heat pump, necessitating a substantial expansion of upstream power generation capacities. The report presents a comprehensive view of achieving CO_2-neutral buildings, focusing on policy strategies. However, the study has some limitations in its exploration of hydrogen's role in the energy sector. It places considerable emphasis on heat pumps over boilers, as indicated by an HP/H2B ratio of 4–5, potentially influenced by current technological, economic, or policy factors. The study also sets a relatively low electrolyzer efficiency at 70%, raising questions about the sustainability of using hydrogen for heating, especially considering future advancements in electrolyzer technology. Focused primarily on buildings from a consumer perspective, it may overlook wider systemic benefits of hydrogen in the energy system. Additionally, the absence of CCS infrastructure in the analysis limits the study's scope, particularly concerning blue hydrogen production, which is integral to reducing CO_2 emissions in a low-carbon energy transition.

The study in [64] delves into E-fuels, synthesized from hydrogen and CO_2, and their potential for reducing carbon emissions in various sectors, including transportation and heating. E-fuels, produced using renewable electricity, offer a way to mitigate carbon emissions, but their effectiveness relies on the carbon intensity of the input electricity and the CO_2 source. The study points out significant challenges in E-fuel production, such as high costs, low energy efficiency, and the need for substantial technological progress to make them competitive with traditional fossil fuels. Furthermore, the study indicates that producing E-fuels requires considerably more electricity than direct electrification methods, raising concerns about their overall efficiency and sustainability. Despite providing insights into the environmental implications of E-fuels, the study lacks an in-depth analysis of energy system optimization, which is crucial for a comprehensive understanding of their potential and limitations within broader energy strategies, especially under the constraints of climate change.

A sector-coupled energy system model is used in [104] to analyze the technological transformations needed in the EU to meet climate goals, with a focus on temperature increases between 1.5 and 2 °C. The study examines various sectors like electricity, heating, transport, and industry, and evaluates the scale-up and costs of solar and wind technologies for different scenarios. It also explores the impact of excluding a hydrogen network and considers investment in building retrofitting. The study concludes that while achieving ambitious climate targets requires significant technological changes and rapid expansion of solar and wind technologies, these goals are feasible and cost-effective in the long run. However, the study's approach to hydrogen's role in the energy transition has notable gaps. It bypasses the intermediate step of blue hydrogen production, which combines SMR with CCS, and it does not thoroughly analyze the implications of choosing SMR over the more efficient method of ATR for hydrogen production. This assumption could overlook blue hydrogen's potential as a sustainable solution, using existing infrastructures and transitioning away from carbon-intensive production, thus potentially limiting the study's scope in capturing the full spectrum of hydrogen's potential in the energy sector.

In [105], decarbonization alternatives to traditional heating systems in the EU, identifying heat pumps, hydrogen boilers, and alternative district heating systems as key options, are evaluated. The study finds that while blue hydrogen is a slight improvement over current systems, green hydrogen is economically challenging due to the need for extensive renewable energy infrastructure. The analysis, developed through a bottom-up optimization model incorporating life cycle assessment constraints, concludes that large-scale electrification via heat pumps is a feasible and sustainable solution for building heating. However, the study emphasizes the high costs associated with building storage tanks for hydrogen, particularly for homes not connected to the gas grid, suggesting that excluding these homes from hydrogen conversion could provide a more accurate cost representation. Additionally, the study's lack of focus on resilience and the omission of discussions on hydrogen-based power generation limit the comprehensiveness of its findings, potentially not taking into account the crucial aspects of the broader energy system's transition to sustainability.

The HYPAT Working Paper 01/2023 investigates the price-elastic demand for hydrogen in Germany, particularly in the conversion and transportation sectors [106]. The study finds that hydrogen demand in these sectors is influenced by the cost of hydrogen production, renewable energy availability, hydrogen prices, and the presence of refueling infrastructure. It suggests that combining renewable electricity, hydrogen production technologies, and refueling infrastructure could meet this demand cost-effectively. However, the study anticipates that building heating will primarily rely on heat pumps and district heating, except in special cases where hydrogen could be used if it is economically viable. Furthermore, the study does not consider blue hydrogen, which could be a sustainable solution for low-carbon hydrogen supply, especially in contexts with established CCS infrastructures. Furthermore, the study's conclusion that hydrogen is only feasible for heating at low costs overlooks its broader potential, such as its role in grid resilience, storage, and integration with renewables. This perspective is particularly relevant for the UK, suggesting the need for a more comprehensive economic model that includes these considerations to assess hydrogen's role in heating systems and overall decarbonization strategies.

3. Discussions on the Role of Hydrogen in Heat Decarbonization

3.1. Critical Assessment Table

A synthesizing table is provided, spotlighting critical factors that potentially influence the reviewed studies' conclusions regarding the role of hydrogen in heating systems. The factors (as indicated in Row 1) within Table 1 are organized into the following categories: (i) studied region and emission strategy, (ii) whole energy system-related aspects, (iii) hydrogen production technologies and CCS infrastructure, (iv) modeling granularities, (v) heat appliance characteristics, and (vi) resilience. By examining these factors, the aim is to understand the perspectives summarized in the reviewed references regarding hydrogen's role in heat decarbonization.

Table 1. Summarized factors impacting the role of hydrogen in the reviewed "heat decarbonization" studies.

	Studied Region and Emission Strategy				Whole Energy System-Related Aspects		H_2 Production Technologies and CCS Infrastructure			Modeling Granularities		Heat Appliance Characteristics		Resilience	
References	Country	Year	Emission Target	Impact of Electrification on Peak Demand	Opt. of Heat Decarb.	H_2 Assets opt.	NET Based on CCS	Mix of H_2 Production	Sufficient Spatial Granularity	Sufficient Temporal Granularity	HP's COP Vary	Cost of Heating Appliances	Extreme Events	H_2-Based Power Generation
[72]	EU (DE)	2050	Net-zero											
[57]	UK	2050	Net-zero											
[74]	UK	2050	Net-zero											
[76]	EU	2050	Net-zero											
[73]	NL	2050	Net-zero											
[75]	DE	2050	Net-zero											
[77]	EU	2050	Net-zero											
[82]	UK	2050	Net-zero											
[78]	EU	2050	GHG 95% lower (to 1990)											
[59]	UK	2050	Net-zero											
[61]	EU (SP, IT, CZ and PL)	2040	Electricity grid significantly decarb. by 2040 in line with 2050 Net-zero											
[63]	GL	2050	Net-zero											
[65]	DE	2050	Below 1.5 °C											
[84]	GL	2050	Net-zero											
[85]	GL	2050	Low- and net-zero-energy buildings											
[86]	GL	2050	UN 1.5 °C target											
[56]	Sao Paolo (Brazil)	2050	43% below 2005 levels by 2030; decarb. 2050											
[88]	EU	2050	100% RES system											
[89]	EU	2050	GHG below 2% compared with 1990											

Table 1. *Cont.*

	Studied Region and Emission Strategy			Whole Energy System-Related Aspects		H_2 Production Technologies and CCS Infrastructure			Modeling Granularities		Heat Appliance Characteristics		Resilience	
References	Country	Year	Emission Target	Impact of Electrification on Peak Demand	Opt. of Heat Decarb.	H_2 Assets opt.	NET Based on CCS	Mix of H_2 Production	Sufficient Spatial Granularity	Sufficient Temporal Granularity	HP's COP Vary	Cost of Heating Appliances	Extreme Events	H_2-Based Power Generation
[90]	DE	2050	GHG 80–95% reduction (level to 1990)											
[91]	GL	2050	UN 1.5 °C target											
[62]	DE	2050	Net-zero											
[92]	GL	2050	Net-zero											
[93]	DE	2050	GHG 95% lower (to 1990)											
[94]	UK	2035	Net-zero carbon heating											
[66]	GL	2050	UN 1.5 °C target											
[95]	UK	2050	Net-zero											
[98]	Hamburg (DE)	2050	Net-zero carbon heating											
[100]	UK	2035	UN 1.5 °C target											
[107]	NL	2050	GHG 95% lower (to 1990)											
[58]	NL	2050	Net-zero											
[60]	California (USA)	2050	GHG 80% reduction (level to 1990)											
[101]	DE	2050	Net-zero											
[102]	UK	2050	Net-zero											
[103]	DE	2045	Net-zero in buildings											
[64]	GL	2050	Seems to be UN 1.5 °C target											
[104]	EU	2050	Net-zero											
[105]	EU27 + UK	2040	Decarb. of heating sector											

: considered; : not mentioned/not found in the study; : not considered; CCS: carbon capture and storage; COP: coefficient of performance; CZ: Czechia; DE: Germany; Decarb.: decarbonization; EU: Europe; EU27: 27 EU countries; GHG: greenhouse gas emissions; GL: global; H_2: hydrogen; HP: heat pump; IT: Italy; NET: negative emission technologies; NL: the Netherlands; Opt.: optimization; PL: Poland; RES: renewable energy sources; SP: Spain; UK: the United Kingdom; UN: United Nations; USA: the United States of America.

3.2. Key Aspects

In this section, based on the reviewed studies in Section 2, the critical factors that could potentially impact the role of hydrogen in heat decarbonization are presented.

- Studied region and emission strategy

Many research investigations might not have the same emission reduction strategies with the distinct objectives and policy frameworks set by the UK government (as the basis region of this study). The UK has made a commitment to reach net-zero emissions by the year 2050. This ambitious goal dictates the formulation of strategies that may diverge considerably from other international or regional benchmarks, for example, in likely future electricity generation mix. The UK heat demand can also be distinguished from other countries in terms of the demand profile and the nature of building fabric. For instance, in Germany, the utilization of blue hydrogen is not on the net-zero agenda, while in the UK, it can play an important role. In contexts where these unique challenges and targets of the UK are not given due consideration, there is a likelihood that hydrogen's important role in heating will become inadequately represented [56,60,61,63,64,66,84–86,90–92,98].

An important topic in this context is to consider the history and conditions in different regions. The UK stands unique in Europe with its extensive gas network, which began in 1813 with the Gas Light and Coke Company (London, UK) [108]. Meanwhile, many European regions solely depend on electricity, making their transition from oil or resistive heaters to heat pumps relatively straightforward. Geographical constraints, like Scandinavia's vast archipelagos, have limited the expansion of gas grids [109]. Such challenges led them to innovate with oil pressure jet burners and log burners [110], paving the way for earlier adoption of heat pumps. Unlike the UK, where heating systems are designed to meet the entirety of a location's outside temperature, Scandinavian countries can supplement heat pumps with log burners and resistive heaters. Another point of deviation is in counting air-to-air vapor technologies [111]. In summary, the varied historical, geographical, and regulatory contexts have shaped different heating choices for the UK and other European countries.

Demonstrating the adaptability of existing natural gas infrastructure for hydrogen injection [54] could mitigate infrastructure challenges and reduce associated costs. This strategic repurposing enables a smoother transition to hydrogen utilization and makes it a more economically viable option for various applications, including energy storage and transportation. The UK stands out among many other countries due to its robust and extensive gas distribution network. Firstly, the UK's gas distribution network covers the entire nation, threading through urban centers and reaching even the most remote areas. With connections extending to approximately 23 million households [112], it plays a pivotal role in ensuring that a significant portion of the population has access to this essential energy source. In Figure 5, the households connected to gas grids in different countries are presented [95]. Secondly, the UK's gas infrastructure is not just a static system; it is subject to continuous investment and improvement, particularly with a focus on safety [113]. One notable initiative in this regard is the Iron Mains Replacement Programme [114]. This ongoing effort not only ensures the safety and reliability of the network but also makes substantial sections of the infrastructure "hydrogen-ready". This unique combination of factors positions the UK as a noteworthy player in the global energy landscape, with the potential for seamless integration of hydrogen technologies into its existing infrastructure.

An essential factor to consider is the COP of the heat pump [115]. The COP is fundamentally linked to temperature, which varies from region to region, making it a geographically specific parameter. For the UK, with an assumed average COP of 3.4 for the heat pump and a 90% efficiency for the hydrogen boiler in 2050, the anticipated efficiency ratio of HP/H2B is projected to be less than four. This highlights the importance of considering regional climate conditions and their implications when assessing the efficiency and effectiveness of energy solutions.

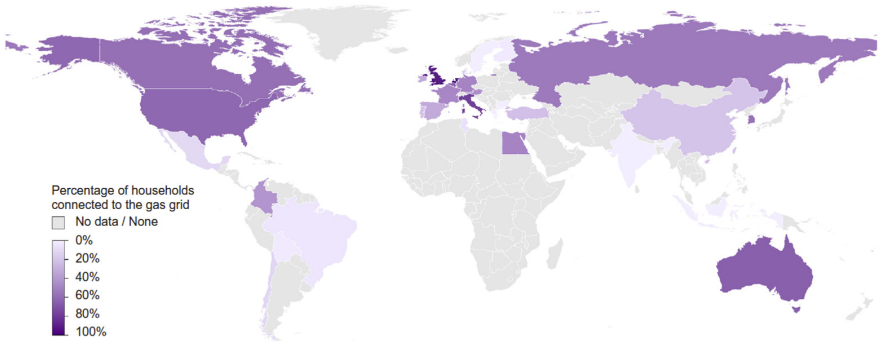

Figure 5. Percentage of households connected to the gas grid in selected countries [95] (data from [40]).

- Whole energy system-related aspects

To assess the potential role of hydrogen in the energy matrix, it is essential to employ a holistic system perspective that integrates elements of modeling, optimization, and inherent constraints. For instance, while hydrogen produced through the reformers with CCS may be more cost-effective, green hydrogen (i.e., produced from RES like wind) offers superior benefits in terms of managing renewables and providing balancing services [44]. This underscores the importance of a holistic system approach to evaluate the merits and trade-offs between different hydrogen production technologies. Another potential consideration is the integration of hydrogen-based CHP systems within district heating networks [71]. These systems not only provide heat under normal conditions but, in times of contingencies, can be utilized to produce electricity, thereby enhancing the security of supply. Certain studies, possibly due to oversight or methodology limitations, do not fully examine the complexities of the energy system (e.g., the impact of increased electrification on peak demand). An omission or oversimplification of the interaction between the electricity and gas/hydrogen sectors could consequently yield an incomplete or biased viewpoint [63–65,73–76,85,86,100,103]. In Figure 6, an example of the interaction between different energy vectors is presented based on the work in [116].

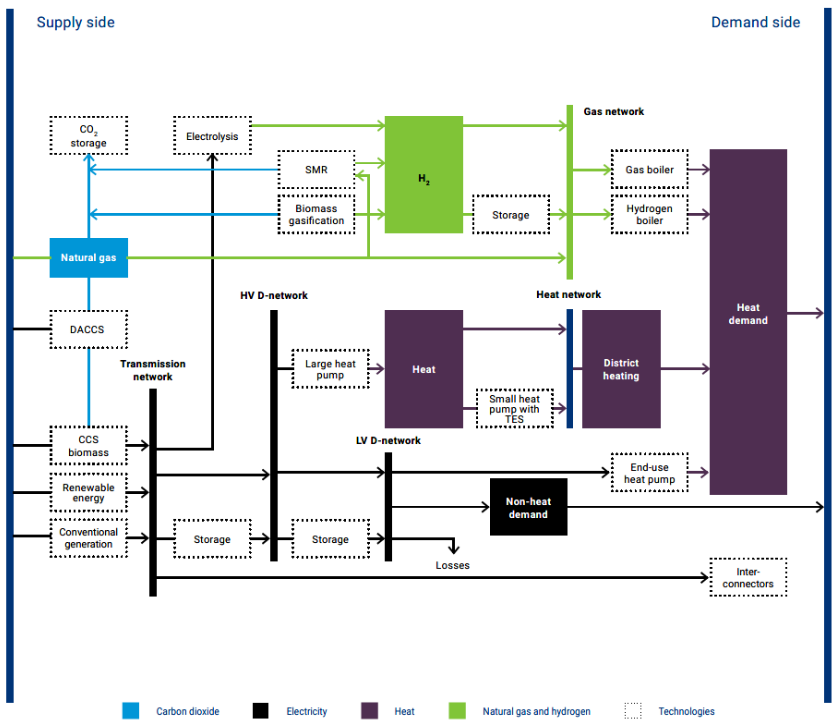

Figure 6. Interaction between gas, heat, and electricity systems [44] (based on [116]).

- Focus on the consumer perspective

A significant number of studies tend to view the potential of hydrogen solely through the consumer and end-user perspective, and so primarily focus on household costs [61,73–76,98,100,103]. While this perspective is undeniably important, it can sometimes overlook the broader system benefits and infrastructural considerations. Concentrating on consumer costs might underestimate the long-term value and systemic advantages of hydrogen integration. Additionally, a consumer-centric view might not fully account for the potential cost savings from reduced emissions, improved grid stability, and enhanced energy security. Thus, a comprehensive assessment should balance both individual household implications and broader energy system aspects and hence, the overall system costs.

- Hydrogen production technologies and CCS infrastructure

The efficiency and feasibility of hydrogen utilization in heating rely heavily on the methodology used to produce hydrogen. Some studies did not factor in hydrogen production through ATR/SMR plants, especially when produced with CCS, i.e., blue hydrogen, since the policies in the studied region did not permit it (e.g., Germany). However, some of the reviewed references did not give adequate attention to the technological advancements or the expected scalability of blue hydrogen production [59–61,85,86,88,90,93,98,100,101,103,106]. Not considering the role of CCS in hydrogen production raises the risk of neglecting the practicality of hydrogen due to concerns with emissions or financial barriers.

In the discussion of the cost of hydrogen production, it should be pointed out that an immediate transition to hydrogen-based solutions is not being proposed. A transition of this scope is aimed to be a gradual evolution necessary for detailed planning, infrastructure development, and societal adjustment. Furthermore, at the same time, as technological advancements are expected over time, the potential reduction in hydrogen production costs should be anticipated. Hence, while this current evaluation of costs is vital, the projections of how these might change with the broader incorporation of hydrogen into energy systems are crucial.

- Negative emission technologies

Factoring in the incorporation of negative emission technologies, such as BECCS and DACS, could increase the significance of hydrogen within the future energy decarbonization. Disregarding these technologies can specifically reduce the role of blue hydrogen and hence, limit the hydrogen supply for a range of applications [59–61,85,86,88,90,93,98,100,101,103,106].

- Temporal and spatial granularities

The viability of integrating hydrogen into our energy solutions can exhibit considerable variability when observed through high temporal and spatial granularities. Operating on high-level granularity might overlook the localized benefits or the time-specific advantages of hydrogen-based heating solutions [58,72–76,85,86,89,91,92,103,104]. For instance, hydrogen could emerge as an invaluable asset during times of peak energy demand in geographically remote locations where the efficacy of other heating solutions (e.g., electrification) may be compromised, or in geographic areas where the cost and ability to build sufficient electricity system infrastructure in the time required is restrictive.

- Characteristics of heating appliances

Technological characteristics significantly impact the assessment of potential solutions in the provision of heat. Within this scope, factors like economic considerations, efficiency levels, and other integral parameters such as capital and operational expenditures, as well as a heat pump's COP and a hydrogen boiler's efficiency, become central to discussions. A notably high HP/H2B efficiency ratio, for instance, can act as an influential determinant, leading some studies to not favor hydrogen as an important choice for heating [59–64,72]. While a high-efficiency ratio between heat pumps and hydrogen boilers might seem to favor heat pumps, it is crucial to consider the broader implications for the energy system. For instance, while individual technology efficiency is important, other systemic costs, such as the necessary upgrades to the network to accommodate peak demand, play a significant role in determining the overall feasibility and cost-effectiveness of a solution. Thus, a holistic approach that includes both efficiencies and system-wide implications is essential for an accurate assessment.

Furthermore, some references do not consider that the COP of a heat pump is variable based on the ambient temperature [56,57,60,61,63,72,85,86,90,103]. Such studies might demonstrate lower economic and efficiency trade-offs for hydrogen when compared with other emerging or established technologies. In-depth evaluations that thoroughly examine these technological characteristics are thus pivotal in making informed decisions about the role of hydrogen in the decarbonization of heating.

- Resilience

Another important factor is to ensure the resilience of the energy infrastructure and supply, especially when confronted with extreme weather events, which will be of increasing importance in an energy system with high penetration of intermittent renewables. Hydrogen can provide long-duration energy storage and, therefore, act as an important asset positioned to ensure the security of energy supply during unforeseen challenges. In this context, if hydrogen infrastructure is required at scale to enhance resilience, its cost-effective role in heating becomes more attainable, as heating can then facilitate the efficient utilization of this infrastructure. Research that does not include resilience as a core parameter might fall short of capturing the comprehensive array of benefits that hydrogen can offer, specifically for extreme events or emergencies [58,63–66,78,82,85,92,94,95,100,102,105,107].

4. Conclusions

Hydrogen is emerging as a clean alternative for heating, with the potential to repurpose gas infrastructure, offering cost benefits over other low-carbon methods. For areas without gas network access, electrification via heat pumps is preferred. Hybrid systems integrating hydrogen are promising for enhancing energy efficiency, with economic analyses suggesting comparable costs for diverse net-zero emission strategies. However, the transition to hydrogen heating faces challenges, with production methods like steam SMR emitting CO_2 (unless coupled with CCS) and green hydrogen production facing efficiency challenges. Additionally, hydrogen storage and transport present challenges, alongside the need for retrofitting to prevent leakages due to hydrogen's small molecular size.

The research on hydrogen's viability for heat decarbonization is extensive, yielding a spectrum of conclusions. Many studies suggest hydrogen may not become an important fuel for future heating solutions. These studies vary in their approaches and may not fully consider all aspects of hydrogen's use, particularly in the UK context, potentially leading to a misunderstanding of hydrogen's economic impact in achieving a net-zero energy system. A detailed examination of each study's limitations and assumptions is crucial to accurately assess hydrogen's role in the transition to greener heating. For instance, the UK's commitment to achieving net-zero emissions by 2050 necessitates unique strategies tailored to its specific policy frameworks, distinct historical use of an extensive gas network, and its particular climatic conditions. This differs from some other European countries, with the UK potentially utilizing its existing gas infrastructure, which could be "hydrogen-ready" due to continuous investments (e.g., Iron Mains Replacement Programme), to transition smoothly to hydrogen use for heating and other applications.

Furthermore, a whole energy system perspective is crucial for evaluating hydrogen's role, looking beyond cost-effectiveness and considering elements like the integration with renewable sources and the ability to provide balancing services. Moreover, while consumer perspectives focusing on household costs are essential, they often overlook the broader system benefits, such as reduced emissions, improved grid stability, and energy security, underlining the need for a balanced assessment that considers individual and systemic implications. Another aspect is that hydrogen's role in heating relies on its production methods, particularly the scalability and integration of CCS, which is necessary for producing low-emission blue hydrogen. While initial costs are high, anticipated technological advancements could make hydrogen more cost-effective. The interplay of negative emission technologies could further increase hydrogen's position in the energy mix. Spatial and temporal analyses reveal that hydrogen's benefits are context-dependent, offering unique advantages in specific areas and times. Heat appliance efficiency (e.g., heat pumps and hydrogen boilers) must be assessed in light of overall system implications rather than individual performance metrics. Finally, the resilience provided by hydrogen, essential for maintaining energy supply during extreme weather, underscores its potential in future energy infrastructures, with the ability to adapt to the requirements for energy decarbonization.

Following the review and evaluation of hydrogen's role in decarbonizing heat, policymakers and other key stakeholders could have a working framework to design the proper strategies for energy system planning. To analyze hydrogen's role in heat decarbonization, integrating multiple perspectives could help inform investment decisions and incentive structures to drive the transition to hydrogen. In this context, a whole system perspective enables more effective policies for a cost-effective transition to net-zero emissions, realizing the long-term systemic benefits critical for energy system decarbonization. This includes recognizing the sustainability and energy resilience benefits of hydrogen integration that will align with national/international commitments to lowering emissions and the world's ability to meet ambitious sustainability targets.

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Nomenclature

ASHP	air source heat pumps
ATR	auto thermal reformers
BECCS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
CCUS	carbon capture utilization and storage
CDR	carbon dioxide removal
CHP	combined heat and power
CO_2	carbon dioxide
COP	coefficient of performance
DACS	direct-air capture and storage
E-fuels	electro-fuels
ETC	Energy Transition Commission
EU	Europe
EV	electric vehicles
GHG	greenhouse gas
HP/H2B	heat pump to hydrogen boiler

IEA	International Energy Agency
IHES	integrated hydrogen and electricity system
IWES	integrated whole energy system
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LH_2	liquid hydrogen
P2G	power-to-gas
PtF	power-to-fuel
PtH	power-to-heat
PtHtP	power-to-heat-to-power
RED II	Renewable Energy Directive II
RESs	renewable energy sources
RTN	resource-technology network
SOFC	solid oxide fuel cell
WeSIM	whole-electricity System Investment Model

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