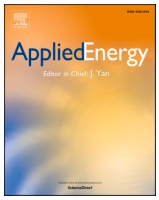
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Socio-technical barriers to domestic hydrogen futures: Repurposing pipelines, policies, and public perceptions☆

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HIGHLIGHTS

- Desirable hydrogen futures will rest on more than a repurposing of pipelines.
- Policymaking should couple techno-economic feasibility to social acceptability.
- Multi-regime interactions can enable synergies for blue and green hydrogen.
- Hydrogen backbones should be examined as a multi- and cross-scalar phenomenon.
- Socio-technical systems thinking supports an accelerated and just transition.

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ABSTRACT

The feasibility of the global energy transition may rest on the ability of nations to harness hydrogen's potential for cross-sectoral decarbonization. In countries historically reliant on natural gas for domestic heating and cooking such as the UK, hydrogen may prove critical to meeting net-zero targets and strengthening energy security. In response, the UK government is targeting industrial decarbonization via hydrogen, with parallel interest in deploying hydrogen-fueled appliances for businesses and homes. However, prospective hydrogen futures, and especially the domestic hydrogen transition, face multiple barriers which reflect the cross-sectoral dynamics of achieving economies of scale and social acceptance. Addressing these challenges calls for a deep

Abbreviations: ACO, Ant colony optimization; ADR, European Agreement Concerning the International Carriage of Dangerous Goods by Road; ASHPs, Air source heat pumps; ATEX, Equipment for explosive atmospheres; ATR, Auto-thermal reforming; ATR + CCS, Auto-thermal reformation with carbon, capture and storage; BEIS, Department for Business, Energy & Industrial Strategy; BEVs, Battery-electric vehicles; CV, Calorific value; CAPEX, Capital expenditure; CCC, Committee on Climate Change; CCS, Carbon, capture and storage; CCUS, Carbon capture utilization and storage; CGH_2, Compressed gaseous hydrogen; COMAH, Control of Major Accident Hazards; COP, Climate Change Conference of the Parties; CSP, Concentrated solar-thermal power; DECC, Department for Energy and Climate Change; DHT, Domestic Hydrogen Transition; DMS, Dimethyl sulphide; EC, European Commission; EHB, European Hydrogen Backbone; EU, European Union; ENA, Energy Networks Association; FBM, Future Billing Methodology; FID, Final Investment Decision; FIT, Feed-in-tariff; GAD, Gas Appliances Directive; GAR, Gas Appliances Regulation; GDNOs, Gas Distribution Network Operators; GDP, Gross domestic product; GHG, Greenhouse gas; GoO, Guarantee of Origin; GS(M)R, Gas Safety (Management) Regulations; GSHPs, Ground source heat pumps; HESs, Hydrogen Energy Systems; HETs, Hydrogen energy technologies; HFCVs, Hydrogen fuel cell vehicles; HyLAW, Hydrogen Law and removal of legal barriers to the deployment of fuel cells and hydrogen applications; H_2S, Hydrogen sulfide; IEA, International Energy Agency; IED, Industrial Emissions Directive; IES, Adoption of innovative energy services; IJHE, International Journal of Hydrogen Energy; IMRRP, Iron Mains Risk Reduction Programme; IPCC, International Panel on Climate Change; IRENA, International Renewable Energy Agency; LBD, Learning-by-doing; LCOH, Levelized cost of hydrogen; LCOT, Levelized cost of transmission; LHV, Lower heating value; LH_2, Liquid hydrogen; LOHCs, Liquid organic hydrogen carriers; LTS, Local Transmission System; MECs, Microbial electrolysis cells; MLP, Multi-Level Perspective; $MtCO_2$, Metric tons of carbon dioxide; NIST, National Institute of Standards and Technology; NO_x, Nitrogen oxides; NTS, National Transmission System; Ofgem, Office of gas & electricity markets; OPEX, Operating costs; PE, Polyethylene; PEM, Proton exchange membrane; PV, Photovoltaic; PPC, Pollution Prevention and Control Regulations; P2H, Power-to-hydrogen; RETs, Renewable energy technologies; RHS, Renewable hydrogen-based systems; ROW, Right-of-way; RSER, Renewable & Sustainable Energy Reviews (RSER); SLO, Social licence to operate; SOEC, Solid oxide electrolysis cells; SMR, Steam methane reformation; SMR + CCS, Steam methane reformation with carbon, capture and storage; STS, Socio-technical systems; TMB, tert-Butyl mercaptan; TRL, Technology readiness level; TNT, Trinitrotoluene; TSOs, Transmission System Operators; TWh, Terawatt hour; T&S, Transport and storage; UKCS, UK Continental Shelf; UK HFCA, UK Hydrogen and Fuel Cell Association; UNC, Uniform network codes; UHS, Underground hydrogen storage; WI, Wobbe Index.

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understanding of socio-technical factors across different scales of the hydrogen economy. In response, this paper develops a socio-technical systems framework for overcoming barriers to the domestic transition, which is applied to the UK context. The paper demonstrates that future strategies should account for interactions between political, techno-economic, technical, market, and social dimensions of the hydrogen transition. In parallel to techno-economic feasibility, the right policies will be needed to create an even playing field for green hydrogen technologies, while also supporting stakeholder symbiosis and consumer buy-in. Future studies should grapple with how an effective repurposing of pipelines, policies, and public perceptions can be aligned to accelerate the development of the hydrogen economy, with maximum net benefits for society and the environment.

1. Introduction

Despite sustained scientific[1] and commercial[2] interest over several decades, hydrogen's promise as a revolutionary clean energy carrier has been largely characterized by 'false starts' [1] and 'false dawns' [2]. Hydrogen's shortcomings [3] are partly explained by high infrastructure costs for production, storage, and distribution; owing to its low energy density per volume, explosive characteristics, and ability to cause embrittlement in metals such as steel [1]. Indeed, the safety credentials of hydrogen have been debated for several decades [4–7] in relation to various sectors and applications [8], including transport, [9,10], power [11–13], industry [14,15], handling and storage [16–20], and more recently, residential use [21–23]. Consequently, hydrogen technology remains a contested topic [24], characterized by blurred representations between myths and facts [25], especially in relation to hazards and risks [4].

As an energy vector with multiple applications across a wide range of energy systems [26][3] hydrogen is highly coveted for its climate change mitigation potential [27,28]. Critically, hydrogen may provide large-scale electricity storage and load-balancing services [29]. In addition to supporting emissions reduction across industry and transport [30–32], hydrogen has also been recognized as a potential low-carbon substitute for natural gas, which may prove critical to decarbonizing the residential heating sector [33]. Hydrogen heating could present an important energy transition pathway in some of Europe's key markets, [34–36], especially those historically reliant on natural gas [37], such as the UK and Netherlands [38–40]. Notably, the Committee on Climate Change (CCC) envisions a role for hydrogen in decarbonizing the UK's residential sector as part of a low-carbon hybrid heating system aligned to net zero [41].

1.1. The UK Hydrogen Strategy

In the run up to the 26th UN Climate Change Conference of the Parties (COP26) in Glasgow [42], the UK released its Hydrogen Strategy [43] followed by the Heat and Buildings Strategy [44], which built off the vision set forward in the Ten Point Plan for a Green Industrial Revolution [45]. As a forerunner to these strategies, the Scottish Government Hydrogen Policy Statement [46] exemplified the UK's push to be at the 'technology core' [47] of the global hydrogen economy. Taken together, these strategies support a 'no and low regrets' approach to developing hydrogen solutions for the residential sector,[4] while confronting "strategic challenges" to realizing a national hydrogen economy [43]. The UK government identified eight main barriers to developing a national hydrogen economy: policy and regulatory uncertainty; technological and commercial risk; production costs; lack of infrastructure; distribution and storage constraints; demand uncertainty; supply and demand coordination; and lack of market structure [43].

The UK Hydrogen Strategy envisions a 'twin track' production approach; combining large volumes of CCUS-enabled and electrolytic hydrogen to help future-proof the country's net zero ambitions by avoiding over reliance on a single technology pathway [43]. Guided by the twin-track approach, the UK hydrogen landscape is rapidly evolving to include a range of industrial, commercial, and domestic applications [43,48]. Following the release of the British Energy Security Strategy in April 2022 [49], the UK government has committed to at least 50% electrolytic hydrogen production (i.e. 5 GW), in parallel to a regional focus on the deployment of blue hydrogen hubs around industrial clusters [50,51].

Critically, the CCC forecasts that hydrogen demand will need to increase from 27 TWh in 2017 to 270 TWh by 2050 to enable the UK to meet its carbon target of net-neutrality by 2050 [52]. This decade, the bulk of hydrogen demand will come from industry (~10–21 TWh), with modest demand potential from the power (~0–10 TWh) and transport (0–6 TWh) sectors [43]. In contrast, demand for low-carbon hydrogen heating in buildings may be constrained to under 1 TWh. Evidently, the feasibility of hydrogen homes is contingent upon developments across other sectors, while the underlying "hydrogen socio-technical system" is embedded within the wider energy transition [26].

1.2. Re-envisioning the hydrogen economy

Against this backdrop of historic, current, and emerging barriers, there is renewed global interest and commitment towards realizing hydrogen's long-held potential for improving local air quality, mitigating climate change [53–55], strengthening energy security [56,57] and improving international competitiveness [55]. Capitalizing on the current "political and business momentum" towards realizing visions for a national hydrogen economy will require coordinated action on at least five fronts: policy frameworks; market structures; technology scale-up; infrastructure development; and costs reduction [58]. At the global level, developing a hydrogen economy will similarly rest on a minimum of five key levers: favorable policy frameworks that create a market pull; new national and international regulatory frameworks to address finance, tax, environment, and safety aspects; stakeholder engagement with public and private actors to deliver a roadmap; demand for energy storage and electricity grid balancing; and sustained commitment to reducing greenhouse gas (GHG) emissions and strengthening energy security [59].

1.3. Research gap, aims, and objectives

Although setbacks and barriers to the commercialization of hydrogen have long persisted [60], with certain aspects catalogued and explored by the research community [1,59,61,62], few studies have attempted to unpack the interactions between socio-technical factors shaping prospective 'hydrogen futures' [55]. Despite the imperative to decarbonize, potential barriers to the domestic hydrogen transition (DHT) remain underexplored [63]. Foremost, there remains an underlying knowledge gap regarding the interactions between respective socio-technical

[1] For example, machine learning research on hydrogen's physical properties [386] and its potential for energy storage [387,388] has its foundations in scientific work from the 1920s [389].

[2] The concept of a global 'hydrogen economy' can be traced back to at least the 1970s [390–392].

[3] See Fig. 44 in Griffiths et al. [26] for an illustration of hydrogen's role in the energy system.

[4] Included are plans for a hydrogen neighborhood and village trial by 2023 and 2025, and potential for scaling up to a hydrogen town trial in 2026 [43,44].

factors and their contribution to facilitating the deployment of 'hydrogen homes'; composed of hydrogen-fueled appliances for domestic space heating, hot water, and cooking [22].

In response, this study sets out to advance the discourse on prospective hydrogen futures by examining the multi-level and multi-scalar challenges of the DHT. Accordingly, the next sections engage directly with sustainable transition researchers, hydrogen experts, energy acceptance scholars, and policymakers through three main objectives. Reflecting the notion that technical change is "an irremediably social process" [64] wherein technology and society co-evolve [65], the first objective is to develop a socio-technical systems framework for examining the DHT. Socio-technical analysis provides a powerful lens for understanding technology deployment in the context of systemic change, wherein the multi-directionality of the transition and role of different actors can be highlighted [66]. Applying the proposed framework, the second objective involves reviewing the main barriers to the DHT. Bridging these contributions, the final objective rests with demonstrating the applicability of the framework by taking the UK as a case study. This three-fold contribution serves to consolidate the nascent literature on domestic hydrogen futures [23,37,67] into a more substantive research area for further exploration.

The paper is structured as follows to fulfil its aim and objectives. Following this introduction, Section 2 describes the materials and methods. Next, Section 3 develops a socio-technical systems framework for examining the hydrogen transition. Applying this framework from a UK perspective, Section 4 reviews the techno-economic, technical, political, market, and social factors shaping the DHT. Section 5 then analyzes the interactions between socio-technical barriers to the DHT in the UK context.[5] The paper concludes by reflecting on the key findings and implications for future research.

2. Methodology and data collection

This paper draws on evidence from a range of sources, including academic papers, technical reports, government documents, and survey studies in the grey literature (see Fig. 1). In deriving a comprehensive socio-technical systems framework, Section 3 engages with the energy transitions and hydrogen future literatures. Taken together, this initial step paves the way for systematically examining barriers to the DHT in Section 4.

Firstly, Section 3.1 contextualizes seminal contributions to the sustainable technology transitions discourse, which can be traced back to Geels' Multi-Level Perspective (MLP) [65,68,69]. Snowballing methods are employed drawing on both early [65,69] and more recent contributions to socio-technical systems thinking [70], including the meta-theoretical study on national energy transitions by Cherp et al. [71]. The rest of section describes the procedures undertaken to complete the theoretical analysis in Section 3 and the review presented in Section 4.

2.1. Hydrogen futures literature and bibliometric analysis

Section 3.2 develops a critical literature review, following a keyword search in Scopus. Scopus provides broader coverage than alternative databases, making it well suited to the study of emerging research topics [72]. The following terms were searched for within the article title, abstract, and keywords: "barriers" AND "hydrogen" AND "economy." The search returned a total of 291 results.[6]

The initial search was narrowed to studies since 2006; coinciding with the seminal contribution of McDowall and Eames [55], which synthesized the early 'hydrogen futures' literature, and in the process, identified at least 17 distinct barriers to the hydrogen economy (see Table S1).[7] This search returned 250 results, of which 39 papers discussed barriers to the hydrogen economy in a detailed way.[8] Employing snowballing techniques (see Section 3.2) led to the retrieval of five additional studies.[9] The final sample size (n = 44) is comparable to recent review papers on the hydrogen economy, such as Kar et al. [73] (n = 53), Emodi et al. [74] (n = 43), and Scovell [75] (n = 27).

Fig. 2 shows that nearly two-thirds of the sample are from 2020 to 2022 (n = 28), with half of these studies published in 2022 (n = 14). This trend reflects historical patterns in developing hydrogen energy technologies (HETs), mirroring the Gartner hype cycle [76]. Once popularized, the notion of a hydrogen economy soon became synonymous with 'hype-disappointment cycles' [77,78], which cast uncertainty over the viability of HETs [79]. Despite earlier decades of false starts [2], the recent increase in studies suggests this decade may prove a critical juncture for shaping the realization of a low-carbon, global hydrogen economy.

Following the database search and snowballing procedure, VOS viewer was used to establish the co-occurrence network of keywords and their clusters across the dataset. VOS viewer provides a powerful tool for generating and analyzing bibliometric networks, such as journals and co-citations [80]. The first step involved creating a network visualization of the co-occurrence between all keywords (i.e. number of occurrences set to one), which resulted in 125 connected items (total 148) made up of 18 clusters (see Fig. 3).[10] The largest cluster contained 12 items, while the smallest cluster contained three items, composed of "non-economic barriers," "power to gas," and variable renewable energy." Interestingly, Cluster 8 included "economic barriers" connected to 7 items mainly associated with the transport sector.[11] Cluster 12 also presented the term "barriers" connected to "geological limitations," "legal framework," "social acceptance," "technical limitations," and "underground hydrogen storage." Clusters containing the items non-economic barriers, economic barriers, and barriers were connected to more recent studies on the hydrogen economy (see Fig. S1).

The next step involved setting the co-occurrence threshold at two, implying that these keywords are repeated at least twice in the title, abstract, or keywords section of the articles. This reduced the previous result from 148 to 17 and produced five clusters. Cluster 1 displayed a strong techno-economic focus, including the word "barriers" and three connected items: "hydrogen economy," hydrogen production," and "hydrogen storage" (see Fig. 4). Overall, the database search and subsequent bibliometric analysis confirmed that the challenges facing the hydrogen transition remain underexplored in the literature; albeit recent trends suggest that this knowledge gap is being increasingly addressed by international researchers (See Section 3.3).

2.2. Literature materials on socio-technical factors and bibliometric analysis

The analysis of socio-technical barriers to the DHT presented in Section 4 follows a non-structured method; according to the guidelines of the 'snowballing' approach and by trial-and-error using keyword

[5] These barriers present an interacting boundary for researchers to interpret, demarcate, and apply accordingly, rather than a definitive classification.

[6] The same search in Web of Science returned 238 results, with no additional studies of interest.

[7] The study in among the top 20 most cited articles on the 'hydrogen economy' [72].

[8] For example, we excluded studies which only mentioned barriers in a generalized way (e.g. [393–395]), as well as highly technical papers which were non-related to our discussion of the hydrogen transition.

[9] Notably, Balat and Kirtay [159] ranks among the top articles with the highest 180 days usage count [72].

[10] Ant colony denotes the use of ant colony optimization (ACO) algorithm [311].

[11] Diesel engines, heavy-duty trucks, hydrogen fuel cell vehicles, hydrogen fuel cells, transport, transition, and low-carbon society,

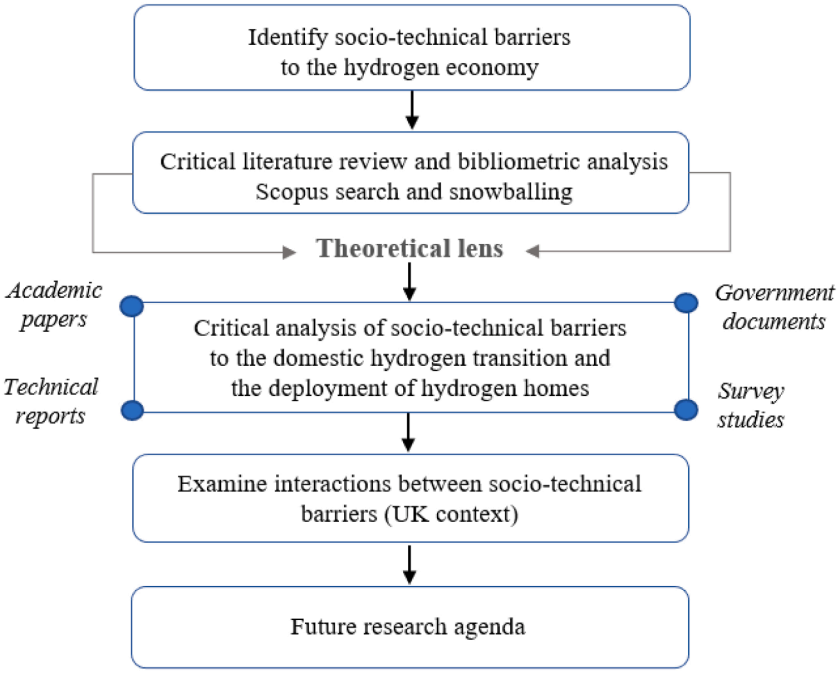


Fig. 1. Research procedure and methodology.

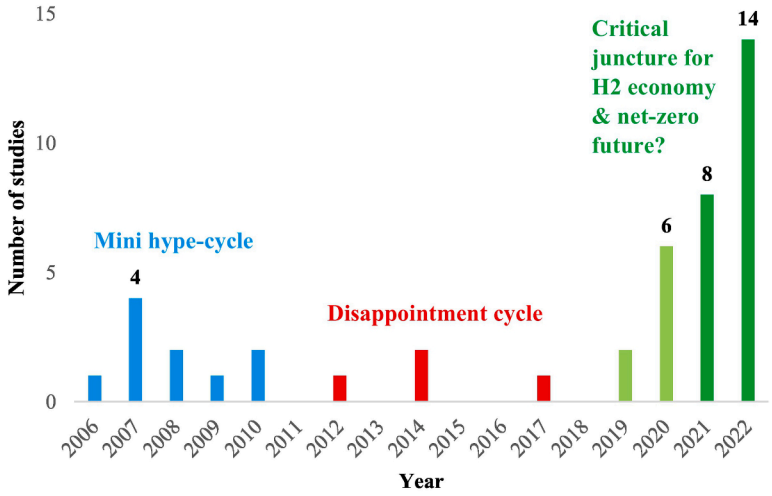


Fig. 2. Number of studies on barriers to the hydrogen economy, 2006–2022.

searches in different databases [81,82].[12] Snowball logic relies on identifying references or citations of interest within already retrieved literature [81,83].[13] This technique is effective for quickly gauging the richness of research materials associated with a given subject area [84] and efficient retrieval of relevant literature [85,86]. Compared to implementing specific search strings to perform a more systematic literature review (SLR), snowballing can help access valuable materials sourced from the grey literature [83,85].

From the academic literature, Section 4 drew on 109 articles with a specific focus on different barriers to the DHT, compared to 44 in the earlier review for building the theoretical framework (see Fig. 5). Of the 109 articles retrieved, 47 corresponded to the techno-economic dimension (43.1%), 30 to the technical dimension (27.5%), 6 to the political dimension (5.5%), 7 to the market dimension (6.4%), and 19 to the social dimension (17.4%). Accordingly, more grey literature materials were sourced to discuss soft barriers to the DHT, compared to techno-economic and technical barriers. Fig. 5 shows that IJHE is the dominant journal in both searches (see Table S4), which is consistent with findings in the bibliometric analysis performed by Kar et al. [72] (n = 1275).[14] IJHE holds around 40% of publications on the hydrogen economy [72], and leads in specific areas of research such as hydrogen storage [87] and microbial electrolysis cells (MECs) [88], making it the pioneer journal for this research field.

[12] These included Scopus, Web of Science, Google Scholar, and the Hydrogen Knowledge Centre.

[13] 'Backward' snowballing involves accessing the reference list of a selected article, while 'forward' snowballing relies on identifying studies that cite the selected article [82,396].

[14] See Fig. 7 in Kar et al. [72] showing "Clusters of journals publishing on hydrogen economy research."

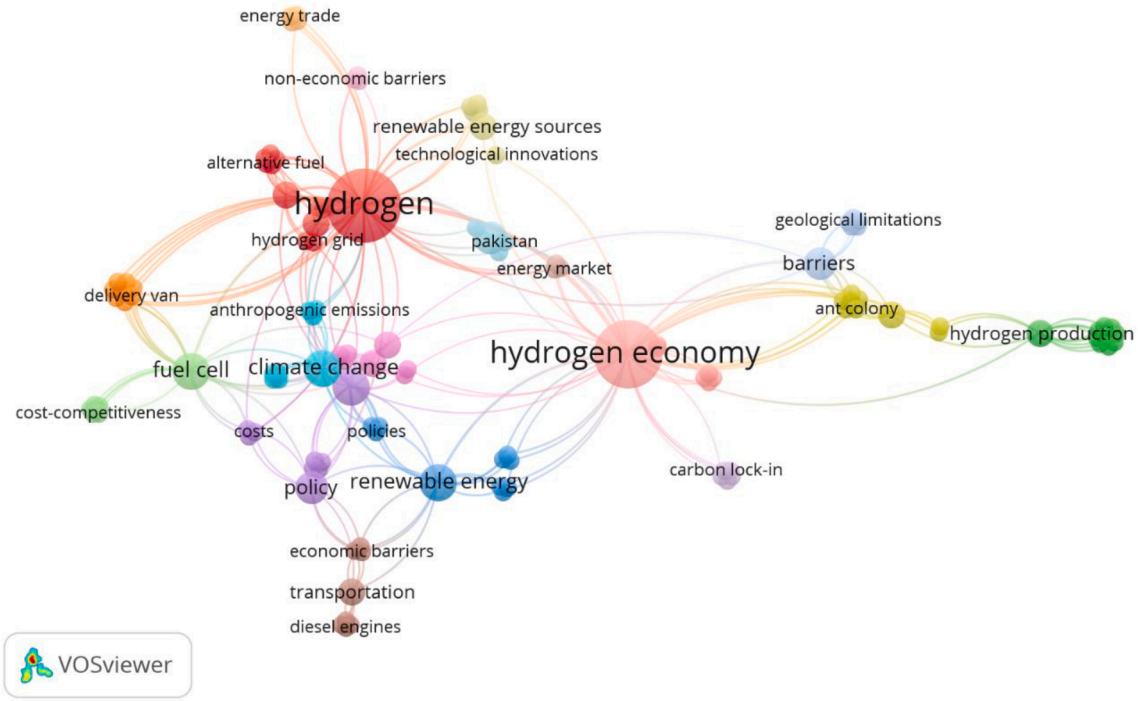


Fig. 3. Network visualization of keywords in Scopus dataset: co-occurrence threshold one.

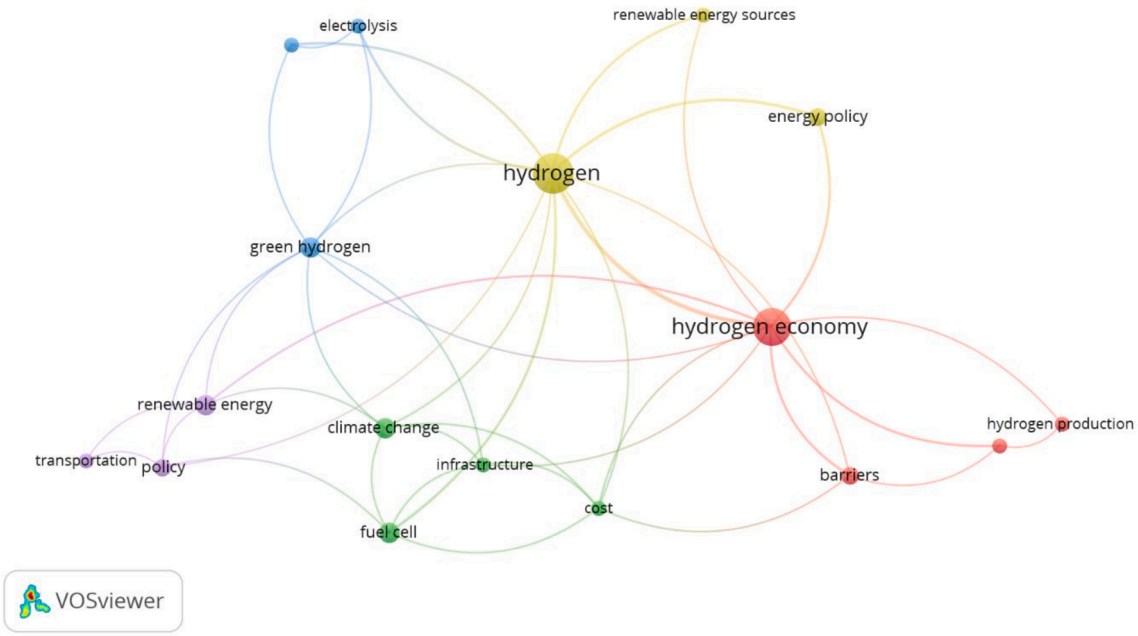


Fig. 4. Network visualization of keywords in Scopus dataset: co-occurrence threshold two.

Drawing on the dataset collected during the snowballing procedures ($n = 109$) (see Sections 2.2.1 and 2.2.2), the earlier procedures using VOS viewer were repeated. Setting the number of co-occurrences to one resulted in 261 connected items (327 total), made up of 24 clusters (see Figs. S2 and S3). By contrast, setting the number of co-occurrences at two resulted in 42 connected items spread across 14 clusters (see Fig. 6). The network visualization highlights emerging research areas aligned to market barriers (e.g. value chain optimization) and social barriers (e.g. public perception, social practices, and energy justice). This finding is consistent with some of the observations presented by Kar and colleagues [72], such as growing research on issues related to public safety.[15]

2.2.1. *Techno-economic and technical factors*

Techno-economic factors involve 'energy flows' related to

[15] See Fig. 9 in Kar et al. [72] for a comparison.

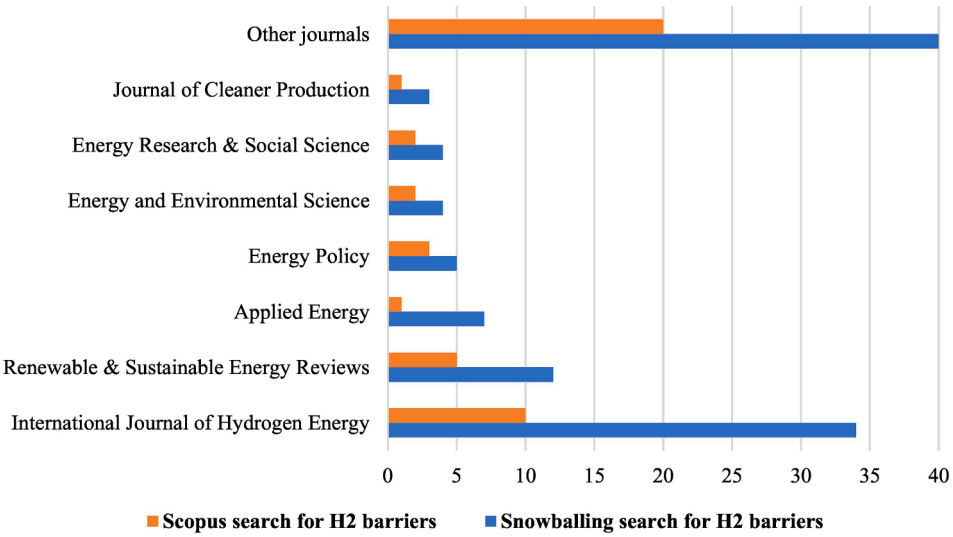


Fig. 5. Comparison between Scopus search and snowballing search for hydrogen barriers.

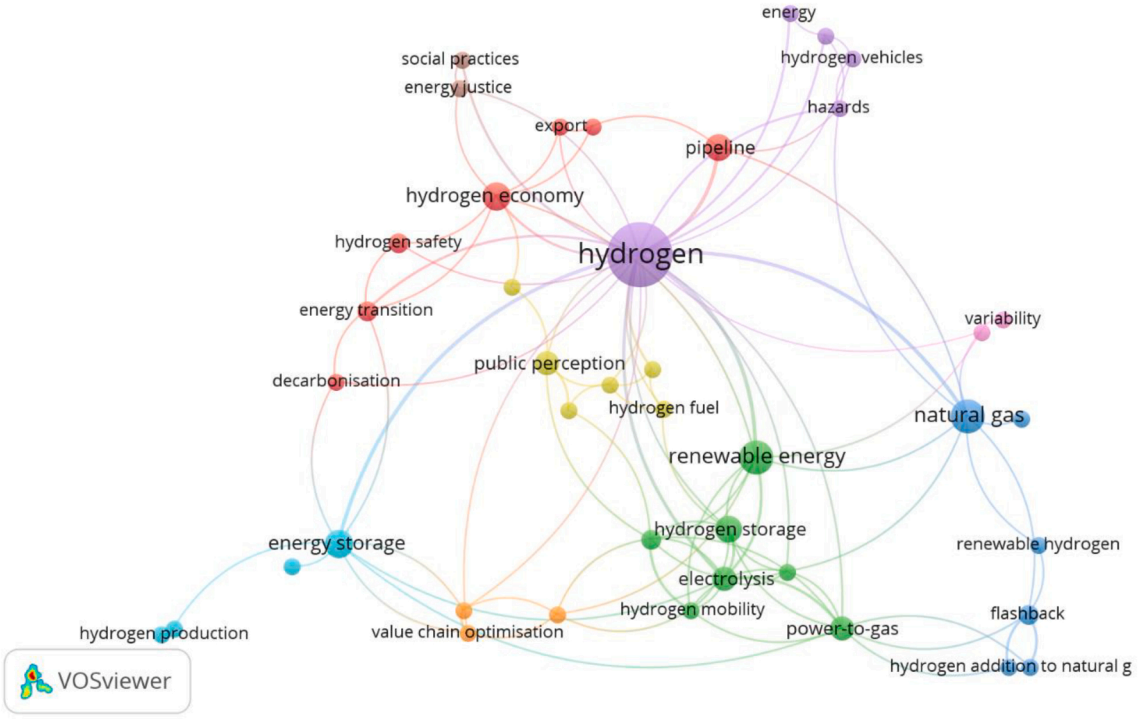


Fig. 6. Network visualization of keywords in articles retrieved through snowballing procedure: co-occurrence threshold two.

developments around resources and infrastructure [71], which following Crisan and Kuhn [89] represent the "hardware" of the hydrogen transition. Addressing this dimension, Section 4.1 draws on a range of studies analyzing data on various hydrogen production pathways and related techno-economic aspects. Several of these studies were retrieved from IJHE [59,90–92]. Following the snowballing procedure, other important materials were sourced from the academic literature [93–95], alongside reports from the International Renewable Energy Agency (IRENA) [96–98] and International Energy Agency (IEA) [57,99], government-led studies [43,49,100], and other key stakeholder groups shaping the hydrogen economy [101–104].

Relatedly, technical factors concern safety issues, the performance and efficiency of hydrogen appliances, and the impacts of hydrogen blending on pipelines. Section 4.2 investigates scientific findings on the technical and safety risks of injecting hydrogen into existing pipelines [105–107], and the results of experimental tests on representative natural gas cooktop burners running on hydrogen blends [108–110]. Hydrogen blending and appliance performance are further reviewed based on UK studies [111,112] and supporting international evidence [106,113,114]. To supplement materials on hydrogen safety factors recently reviewed by the authors [115], two separate keyword searches were performed in Google Scholar using the terms "blending hydrogen into the gas grid" and "hydrogen appliance safety." A highly cited study retrieved from IJHE [116] and Applied Energy Journal [110], respectively, were selected to initiate the snowballing process, which led to inclusion of several articles from these journals, alongside other findings in the academic and grey literatures.

2.2.2. Literature materials on political, market, and social factors

Evidence on political factors was mainly sourced through backward snowballing using the meta-review of Griffiths et al. [26] on industrial low-carbon hydrogen, which cited 718 studies. Section 4.3 reviews the scope of the HyLAW project [117], which aimed to reduce regulatory, legal, and administrative barriers to the development of a European hydrogen economy. Specifically, the HyLAW UK National Policy Paper [118] serves to contextualize the challenges associated with the current regulatory framework, or lack thereof, for hydrogen gas. Further evidence is sourced from government materials [112,119,120], trade bodies such as RenewableUK [121] and the UK Hydrogen and Fuel Cell Association (UK HFCA) [51], and other grey literature [123].

A wide range of factors impact the technology readiness level (TRL), market penetration and growth of domestic hydrogen [96], which can otherwise be viewed through the lens of barriers to market entry, development, and support [112]. Section 4.4 incorporates backward snowballing from the discussion of hydrogen home appliances provided by Scott and Powells [21,22]. Given the limited evidence base available in the academic literature, a specific search was also carried out in the Hydrogen Knowledge Centre database[16] to supplement the data collection through a combination of backward and forward snowballing.[17] In addition to work carried out by Policy Exchange[18] [123], extensive analysis of both political and market factors has also been undertaken by gauging the perspective of UK manufacturers and trade bodies [112].

Finally, accounting for the social dimension of the transition reflects a growing consensus that consumer acceptance is a precondition for the successful deployment of low-carbon energy technologies [124–128]. This dimension broadly reflects factors underpinning the social acceptance of established renewable energy technologies (RETs) [129–131]. Key factors include public perceptions of hydrogen's environmental and safety credentials, together with attitudes towards community-level and behavioral impacts [115,132]. The evidence base on domestic hydrogen acceptance is mostly limited to the UK [21,22], Australia, [23,67], and Europe [133–135]; composed of studies focused on the public's knowledge, awareness, and perceptions of hydrogen, and resultant attitudes towards the deployment of hydrogen homes [115]. Section 4.5 implements a backward snowballing approach based primarily on a recent literature review conducted by the authors [115].

3. Theory

This Section describes the theoretical foundations of the study. Drawing on key examples in the sustainability transitions literature, Section 3.1 introduces the socio-technical transition approach. Section 3.2 contextualizes socio-technical systems thinking to the hydrogen transition. Section 3.3 then summarizes the underlying barriers to developing a hydrogen economy. Finally, Section 3.4 focuses on the DHT and the case of hydrogen homes.

3.1. Socio-technical systems thinking on sustainability transitions

Socio-technical systems [65] develop through multi-decadal processes [136,137], taking shape through the co-evolution of a mix of interdependent technologies, infrastructures, institutions, policies, markets, supply chains, user practices, and cultural meanings [138–140]. Prime examples of large-scale systems serving the needs of society include housing, mobility, heating, and food [139].

Critically, sustainability transitions are 'non-linear' and 'complex' events; shaped by interactions between technological, political, institutional, economic, and socio-cultural dimensions, and through interrelationships between multiple actors [141]. For example, Cherp et al. [71] conceptualize national energy transitions according to the co-evolving dynamics of three types of systems, while Eyre et al. [142] discuss four "categories of change" for deep decarbonization (see Table S2). Adding to this multi-dimensionality, scholars have recently explored technology transitions through the lens of 'evolutionary', 'interpretive and socio-cultural', and 'contested, conflictual' processes [70].

The literature on 'socio-technical futures' – visions or scenarios predicated on prospective techno-scientific and societal change [143,144] – recognizes the governance of socio-technical systems as inherently political [144], with energy futures examined through a multi-level governance perspective [145,146]. Specifically, the "political feasibility" of climate mitigation pathways should be closely examined by contrasting political constraints, characterized as 'soft' and 'probabilistic' in nature, against technical constraints which are 'hard' and 'deterministic' [147]. Such perspectives highlight the purposeful nature of governing large-scale shifts to low-carbon technologies [148], as underpinned by recent country pledges to reach net-zero emissions [149].

3.2. Socio-technical systems thinking hydrogen futures

Reviewing the state of the hydrogen futures literature in the early 2000s, McDowall and Eames [55] highlighted a research gap regarding the socio-technical dynamics of the transition, owing to an underlying deficit in existing theoretical approaches. Addressing this theoretical gap, Eames et al. [24] explored the potential for a hydrogen economy in London by examining visions and expectations through the lens of six competing narratives. The authors concluded that visions of the hydrogen economy are subject to considerable 'interpretive flexibility' [24] – "the capacity of a specific technology to sustain divergent opinions" [150] – which may strengthen hydrogen's potential to compete across a wide range of energy futures [151]. Interviewing key stakeholders within the Danish hydrogen research network, Andreasen and Sovacool [152] similarly uncovered multiple visions for the technology, characterized by "strategic malleability" over which pathways to support and the likelihood of hybridized hydrogen systems. Despite these important contributions, the literature remains dominated by studies engaging with technology roadmaps and transition pathways, mainly limited to the context of hydrogen transport applications [153,154] (see Table S2).

3.3. Socio-technical factors shaping the hydrogen economy

Despite multiple driving forces [55,59], the hydrogen transition is yet to materialize due an array of barriers [1], which must be tackled in parallel to deploy hydrogen at scale [155]. While some of these factors have been discussed in different transition contexts (see Table S3), few studies have examined challenges of a socio-technical nature [63]. To date, techno-economic and technical factors impacting Hydrogen Energy Systems (HESs) have been reviewed in different contexts, such as HFCV technologies in the USA [156], hydrogen production methods in India [157], renewable hydrogen-based systems (RHS) for stationary applications, and renewable or 'green' hydrogen supply at the global level [158]. Several studies have also addressed barriers to developing a global or national hydrogen economy [1,59,61,96]. Nevertheless, there remain inconsistencies or even explicit absence regarding the breakdown of socio-technical factors [55].

For example, Balat and Kirtay [159] discussed the technical factors influencing the hydrogen economy in terms of production, storage, and

[16] https://www.h2knowledgecentre.com/

[17] Using the dropdown menu, the keyword "Hydrogen for Domestic Appliances" and country, "United Kingdom," returned 47 results. Having scanned the titles, the search was then narrowed to more recent publications since January 2018 (38 results) and subject matter "Policy and Socio-economics," which returned 13 results: eight policy papers, three research papers, and two journal articles. Having scanned the abstracts, backward and forward snowballing was conducted on six of these papers.

[18] The UK's leading think tank.

delivery costs. By contrast, in their discussion of power-to-hydrogen (P2H) systems in Italy, Saccani et al. [160] characterized technical factors in terms of "each component and/or the process as a whole that limit P2H efficiency, effectiveness, reliability and safety." The authors classified other factors according to economic, social, and normative/operational aspects [160], whereas without specifying any typology, Garcia [161] identified five non-economic barriers (NEBs) to the deployment of hydrogen technologies and infrastructures in Europe. In a recent perspective on the European hydrogen economy, van de Sperk et al. [155] also provided a comprehensive analysis of techno-economic, legal, and regulatory, and market aspects.

Notably, Griffiths et al. [26] provide an exception to these studies in classifying the hydrogen socio-technical system for industrial decarbonization according to five major areas – production, supply chain, industrial use, institutional drivers, and end-use drivers[19] – which the authors discuss systematically in terms of political, economic, social, and technical factors. Illustrating this diversity and lack of systematic framing, Table 1 summarizes key barriers identified in recent studies at the national, European, and global level.

3.4. Socio-technical factors shaping domestic hydrogen acceptance

Heiskanen et al. [166] were among the first to identify social acceptance factors of low-carbon hydrogen heating solutions according to the following parameters: hydrogen characteristics in terms of safety, cost, usability, convenience and (thermal) comfort; the national and local context; the robustness of supply chains and skilled technicians; and composition of stakeholder engagement. More recently, the feasibility of converting the UK's existing natural gas network to hydrogen has been assessed from a techno-economic perspective through the H21 Leeds City Gate study [167], but remains characterized by deep uncertainties [168]. Additionally, Dorrington et al. [112] identified multiple technical and market barriers to "the development of a hydrogen-fired appliance supply chain," based on the perspective of appliance manufacturers and trade bodies (See Section 4.4).

As with natural gas-based appliances [39], the socio-technical system for hydrogen homes will be sustained by a range of interdependent factors which may accelerate or stifle the transition. However, interactions between respective factors and associated barriers are yet to be examined in detail, characterizing hydrogen homes [169,170] as an underexplored subject in the energy transitions literature. As a way forward, the existing evidence base can be synthesized according to five distinct dimensions: political, techno-economic, technical, market, and social factors. Table 2 identifies each socio-technical dimension, its key factors, and respective parameters and enabling conditions, as operationalized to the context of the DHT. This contribution brings order and clarity to the wide range of impacts discussed across the literature by distinguishing more concretely between technical, economic, and market factors, which are sometimes subsumed under the 'techno-economic' category [71].

Drawing on the findings presented in Table 1 and Table 2, Fig. 7 proposes a socio-technical transition framework; visualized according to identified political [1,55,59,61], techno-economic [13,171,172], technical [55,59,60], market and social factors [55,61,158,160], which together shape the development of hydrogen infrastructure, supply chains, domestic appliances, and social acceptance. Having established a comprehensive socio-technical systems framework for examining the DHT, Section 4 provides a systematic discussion of each of these factors.

[19] Griffiths et al. [26] present an overview of the STS for industrial use of hydrogen in Fig. 9 and a high-level illustration of this framework in Fig. 10 of their study.

Table 1
Barriers to developing hydrogen energy systems and national hydrogen economies.

Study	Context	Scope of study	Barriers identified
[73]	Australia	Developing a national hydrogen economy and hydrogen society	• High cost of hydrogen • Lack of infrastructure • Technological immaturity • Insufficient investment • Low market readiness • Low social acceptance • Negative safety perceptions
[162]	Brazil	Developing a national hydrogen economy, with a focus on the development of a green hydrogen market	• Economic feasibility • Lack of political support and incentives for infrastructure and market creation/expansion • Development of appropriate regulation framework • Research & Development
[163]	China	Development of hydrogen fueling stations (HFSs)	• High initial capital costs • Limited financial channels • Immature hydrogen storage technology • Incomplete hydrogen transportation technology • Lack of relevant standards • Imperfect subsidy mechanism
[157]	India	Commercialization of hydrogen-powered vehicles	• Infrastructure development and delivery • Legislation and regulation • High costs of production, transport, and storage • Uncertainties concerning social acceptance
[164]	Qatar	Developing a multi-sector green hydrogen economy	• Large-scale hydrogen production cost • Infrastructure investments • Achieving bulk storage • Costs and feasibility of transport and distribution • Safety considerations • Matching supply-demand uncertainties
[160]	Italy	Market development for power-to-hydrogen (P2H)	• Efficiency, effectiveness, reliability and safety of components and processes • Impact of economic sustainability on market penetration • Public and individual levels of hydrogen awareness and familiarity
[165]	Eastern Europe[a]	Developing social acceptance of hydrogen as an alternative to traditional fuels	• Lack of public knowledge and awareness of hydrogen technologies • Public fears and insecurities concerning technological innovations and potential social/behavioral changes • Economic risks and increased energy costs

(continued on next page)

Table 1 (*continued*)

Study	Context	Scope of study	Barriers identified
[61]	Europe[b]	Deployment of hydrogen technologies and infrastructures	• Complex legal and administrative procedures among involved authorities • Lack of governments initiatives for increasing the transmission and distribution networks and the use of hydrogen vehicles • Lack of information and assistance to project applicants • Lack of regulations and guidelines for the installation of hydrogen systems • Absence of qualified specialists to manage hydrogen projects • Safety perceptions of the deployment of HESs and HETs
[26]	Global	Industrial utilization of low-carbon hydrogen for deep decarbonization	• Geologic carbon storage potential is geographically specific • CCS applications are expensive to develop and operate • Upstream emissions associated with fossil energy for blue hydrogen pathways are not properly considered • Technological immaturity with emerging hydrogen production technologies (e.g. high temperature electrolysis) still at low TRL • The cost of electrolytic hydrogen is still higher than existing fossil hydrogen pathways

Source: Author's compilation.

[a] Poland, Czech Republic, and Slovakia.

[b] Austria, Finland, Germany, Greece, Hungary, Italy, Norway, Poland, Portugal, Romania, Slovenia, Sweden, Ukraine, United Kingdom.

4. Assessment and analysis of socio-technical factors from a UK perspective

4.1. Techno-economic factors

Given its multi-sectoral applications [173], the role of hydrogen in different energy scenarios is often conflicting, with a lack of specific techno-economic evidence [174]. Following the example of van der Sperk et al. [155], this section provides a 'one-stop starting point' for understanding the techno-economic parameters of the hydrogen economy.

4.1.1. Hydrogen production

At present, 95% of global hydrogen production is sourced from fossil fuels [95,175]. Steam methane reformation (SMR)[20] accounts for nearly half of this production [95,175], while partial oxidation of natural gas and coal gasification account mostly for remaining production [176]. SMR is a mature technology which has been used for decades to handle large capacities of fossil-based ('grey') hydrogen production [177]. Alongside SMR, auto-thermal reforming (ATR)[21] and water electrolysis[22] are commercially mature technologies, capable of producing hydrogen at scale [33,178]. For SMR and ATR to be considered low-carbon or 'blue', high rates of carbon, capture and storage (CCS) are required (>90%) [43,177]. Alternatively, water electrolysis ('green' hydrogen) refers to the process of electrochemically splitting water into hydrogen and oxygen, through the application of renewable electrical energy [179].[23]

Table 2
Socio-technical factors to the deployment of hydrogen homes.

Dimension	Key factors	Key parameters and conditions
Techno-economic	• Resource availability • Production, transport/ transmission, and storage pathways, • Associated cost factors	• Configuration and scale of hydrogen energy infrastructure and scope of project development
Technical	• Safety levels (health and environmental) • Efficiency, reliability, and overall performance hydrogen home appliances	• Practicality of deploying hydrogen energy infrastructure and domestic technologies to meet all engineering, safety, and environmental standards
Political	• Policy measures, regulatory frameworks, legislation, and administrative procedures • Stakeholder engagement and informational flows	• Enabling legal pathways to support a national hydrogen economy and transition to hydrogen homes, predicated on procedural justice
Market	• Investment landscape and market risk • Labor supply and quality of this workforce • Other supply- and demand-side factors	• Competitiveness and commercial feasibility of hydrogen technologies and supply chains for home appliances
Social	• Safety, environmental, and cost perceptions • Social fairness • Behavioral impacts	• Consumer attitudes towards the domestic hydrogen transition and broader hydrogen economy, as shaped by public awareness, knowledge, stakeholder trust, and other social acceptance factors

Source: Authors' compilation.

4.1.1.1. Hydrogen production costs. Despite widespread social and environmental implications [23], the trajectory of competing low-carbon hydrogen pathways may rest principally on cost factors [114,180]. Hydrogen production is a major factor determining overall system costs [181], which requires careful sensitivity analysis due to significant uncertainties [43,182]. While the costs of SMR are well known and modeled according to historical data, there are currently no operational CCS plants within the UK, which makes calculations less reliable [183]. At present, there is less literature on the costs of CCUS-enabled hydrogen compared to electrolysis production methods [182]. Overall, examining the costs and timeline of producing hydrogen is a nascent but growing research area.

[20] Chemical synthesis process for producing syngas from hydrocarbons, whereby steam and natural gas react catalytically at high temperature and pressure [176,194].

[21] Combines endothermic (steam reforming) with exothermic (partial oxidation) reactions within the same reactor [397].

[22] Alkaline electrolyzers consist of electrolyzer cells combined in parallel to build an electrolyzer stack [193].

[23] Alkaline electrolyzers are commercially viable (TRL 9) at the lowest cost; proton exchange membrane (PEM) electrolyzers are nearing commercialization (TRL 8–9); solid oxide electrolysis cells (SOEC) are still under development (TRL 5–6) [217,398]; while biomass-based advanced gasification technology with CCS is at TRL 4–5 [399–401].

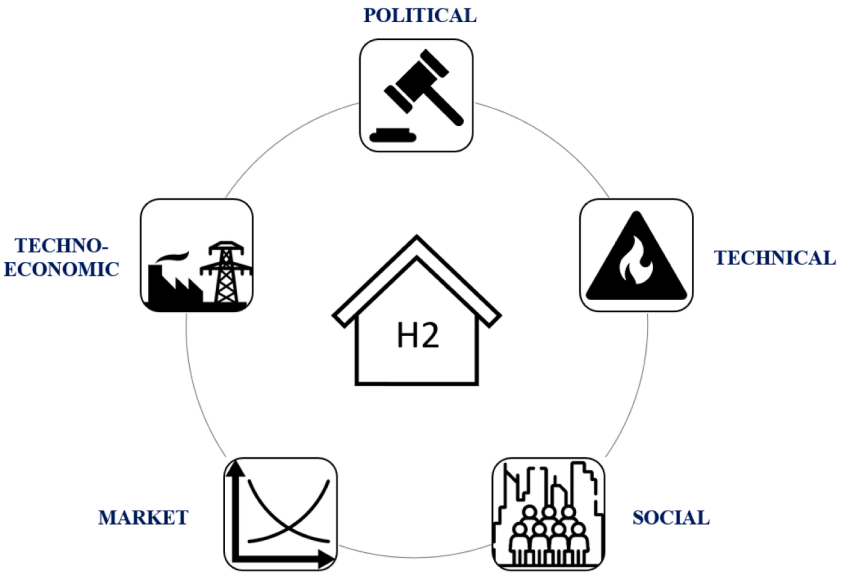


Fig. 7. Socio-technical transition framework for the domestic hydrogen transition.

Although estimates remain tentative [114], the costs of producing and storing large-scale hydrogen are likely to be very substantial [41]. The CCC estimates that decarbonizing heat for buildings through hydrogen and/or electrification could amount to 0.7% of gross domestic product (GDP) in 2050 [41], with hydrogen production potentially increasing the annual costs of heating by around £4 billion [41]. Deloitte UK estimate that hydrogen production technologies alone will require at least £3.5 and up to £11.4 billion by 2035 [183]. Considerable infrastructure investment and engineering capacity are required for developing hydrogen-based technologies [63,112]. Additionally, significant investment is needed to increase testing facilities where hydrogen is produced on-site, while supporting product diversification and efficiency gains [112].

4.1.1.2. Barriers to a blue hydrogen pathway. Fuel costs represent the largest component of hydrogen production costs [57].[24] SMR depends on large quantities of methane (CH_4) [95]; making the natural gas price a major component of overall production costs for blue hydrogen [34]. Coinciding with the COVID-19 pandemic, multiple economic and geopolitical factors [184] caused the price of natural gas to skyrocket in the UK from 36 pence per therm to 290 pence per therm between March and October 2021 [185]. During times of gas crisis, the production costs of blue hydrogen will rise steeply as a direct knock-on effect [186]. Several other factors determine the economics of hydrogen production via SMR: the cost of the reformer; transport and storage (T&S) costs; CO_2 recovery costs; and operational costs for utilizing natural gas reformation together with carbon capture and storage (CCS) [114]. Based on a net-zero scenario, CCS could account for 26%–40% of the total costs for blue hydrogen production [183].

SMR + CCS may accelerate the development of a hydrogen economy by capitalizing on the existing supply chain for natural gas, which can be repurposed for hydrogen production, storage, and distribution. To establish this market, at least three conditions must be satisfied: hydrogen infrastructure to link points of production and consumption; CCS infrastructure to pipe (or ship) the carbon dioxide (CO_2) to storage sites; and large-scale and sustained hydrogen demand [114]. Thus, the economics of a SMR plant depend partly on the CO_2 capture rate [177]. Given that CCS is yet to be commercialized at scale [114], there are multiple unknowns and cost considerations for a blue hydrogen pathway. Notably, storage costs remain highly uncertain and will vary according to geologic location [26,187].[25] Meanwhile, extensive infrastructure will be required to transport CO_2 from inland sites, which will require sizeable investments [114].

At present, the feasibility of establishing a national hydrogen economy partially based on SMR + CCS [180,188] is constrained by the progressive depletion of domestic gas reserves in the UK Continental Shelf (UKCS) [189], as reflected by the country's status as a net importer of energy since 2004 [190]. Increased natural gas imports would be needed to address this supply gap [190,191]. Alongside these challenges, fuel conversion inefficiencies need to be addressed for blue hydrogen production [176].

4.1.1.3. Barriers to a green hydrogen pathway. Water electrolysis may offer an alternative pathway to achieving large-scale renewable hydrogen production with lower carbon emissions [192] and negligible downstream waste [114]. Electrolytic hydrogen can be deployed in proximity to areas of high renewable resource to increase local production from grid-connected electrolyzers [114]. Although more attractive from an environmental perspective and for decentralized applications, especially in proximity to areas of high renewable resource [114], there are also multiple challenges to scaling up electrolytic hydrogen. Barriers include high production costs, lack of value recognition, energy losses and sustainability challenges [98].

Electricity price determines 60%–80% of green hydrogen cost [193], adding to potential market volatility and investment risks. Green hydrogen production costs are driven mainly by the high CAPEX associated with the cost of the electrolyzer [183], which requires high capital investment [181]. Furthermore, converting hydrogen fuel into mechanical or electrical energy is constrained by maximum efficiencies of 50%–60% [176]. The round-trip efficiency of hydrogen is between 15%–30%, therefore, green hydrogen production requires 4–5 times more electricity production compared to direct transmission [194].

[24] Excluding hydrogen produced from coal. For a recent review of hydrogen production costs, see [59] and [158].

[25] The 2016 Department for Energy and Climate Change (DECC) report provided a median cost of £19/tCO_2 for transportation and storage, with high and low sensitivity costs of £31/tCO_2 and £8/tCO_2, respectively [187].

While electrolyzer plant costs remain high, they are expected to fall over time with the experience curve and economies of scale [193].[26]

The UK's offshore wind resource presents an opportunity to scale up renewable hydrogen production [195], with scope for hydrogen hubs in proximity to coastal, industrial clusters [196,197], and export potential to parts of Northern Europe such as Germany, Netherlands, and Belgium [46,198]. Supporting this opportunity and the wider transition to net zero, the UK government has increased its offshore wind target to 50 GW [49] and aims to capture 10 Mt. of CO_2 by 2030 [45]. However, the resource demands for building a national hydrogen economy could prove especially difficult to surmount if an estimated 100–150 GW of gas reforming capacity with 175 $MtCO_2$ per year – equivalent to 300 GW of offshore wind power dedicated to electrolysis – is needed to meet 800 TWh of demand across multiple applications [199].

Overreliance on offshore wind power could jeopardize the feasibility of securing economies of scale for the UK's green hydrogen production base within a net-zero time-horizon. In addition to the uncertainties associated with spatio-temporal variability [200,201], scaling up offshore wind capacity is subject to external factors beyond the UK's borders [202], which may leave the country vulnerable to meeting its renewable targets. Prospects are further compounded by the government's stance towards onshore wind planning [49], which remains hostile and unambitious compared to offshore wind targets. In 2016, the Conservative Party withdrew public subsidies for onshore wind and granted decision-making powers to local communities, which resulted in an effective moratorium [203,204]. Although the British Energy Security Strategy boosted the offshore wind target from 40 GW to 50 GW by 2030, onshore wind policy failed to "introduce wholesale changes to current planning regulations," thereby extending the status quo by leaving "local communities in control" [49].

4.1.2. Hydrogen pipeline construction and transportation

At present, hydrogen pipelines span less than 16,000 km globally [26,174] compared to around 3,000,000 km for conventional gas pipelines [158], highlighting the extreme experience deficit for hydrogen projects. Unlike renewable energy projects such as wind farms and concentrated solar-thermal power (CSP) which have benefited from learning-by-doing (LBD)[27] [205], the economics of hydrogen pipelines are volatile and may fail to reap cost reductions over time [206].

In addition to miscellaneous costs, the construction costs of hydrogen pipelines depend on three main factors: material requirements, labor costs, and right-of-way (ROW) fees [206,207]. All cost categories decrease as transmission length increases, except for ROW cost which remains largely fixed [194]. Schoots et al. [206] found the labor costs of hydrogen pipelines would be 28% higher than natural gas due to more challenging operating conditions [206]. Overall, the construction costs of hydrogen pipelines may exceed that of CH_4 and CO_2 by approximately 19% and 8% [206]. Compared to gas pipelines [63], hydrogen pipelines are more capital intensive as they require greater diameter [208], and are likely to incur higher costs due to greater requirements for compression at several stages of the supply chain, welding procedures, and leak testing [209]. While cost reductions are achievable by minimizing changes in flow velocity between compression stations,[28] the CAPEX and transport costs of hydrogen remain at least marginally higher than natural gas [194] (see Table S6) and can be substantially higher [206,210].

Compressed gaseous hydrogen (CGH_2) can be transported via pipelines, whereas trucks and ships can move CGH_2 or liquid hydrogen (LH_2) [92]. CGH_2 trailers are optimal for small quantities transported over distances up to 200 km, while LH_2 trailers are more economical for smaller volumes and longer distances [92]. However, liquefying hydrogen is an energy-intensive and costly process [92], which makes transport by pipelines a more feasible solution. Furthermore, the transport of hydrogen in the UK is currently restricted, with exclusions on ten tunnels that have category C, D, or E limits on the transit of ADR[29] substances which include hydrogen [118]. While category A tunnels (lowest risk) may be used at any time, category B tunnels may have time restrictions in place, further impeding the logistics of hydrogen transportation. Moreover, there are limitations on the volume and pressure of high-pressure receptacles used to transport hydrogen by road, which makes it unfeasible to deliver bulk hydrogen to large-scale end users [118].

Transport costs are a key component of energy transition pathways, especially when considering scenarios for blue or green hydrogen deployment [194]. Hydrogen transport costs depend on the volume transported, the distance, operating pressure, and pipeline diameter, which are determined by hydrogen mass flow and pressure drop [211,212]. Investments in infrastructure (e.g. pipelines, trucks, ships) should also be added when calculating operational costs (OPEX) [41]. Hydrogen has a comparatively low volumetric density[30] compared to naturals gas,[31] which means that larger volumes will be needed to transport the same amount of energy [158].[32] Although OPEX costs are low, pipeline transport is subject to high capital investment costs at limited flow rates [211]. Using a baseline case of 1000 miles, DeSantis et al. [194] calculated the costs of hydrogen pipelines to be 40% higher than natural gas (See Table S5), while Saadi et al. [210] also estimated that the relative costs of hydrogen pipeline transport would be higher compared to gas pipelines.

4.1.2.1. Repurposing the gas grid to hydrogen. Following the launch of the Iron Mains Risk Reduction Programme (IMRRP) in 2002 [43,213], there is growing interest in repurposing the UK's existing gas network to support hydrogen applications [167]. The IMRRP addresses the failure of 'at risk' iron gas mains, which are to be converted to polyethylene (PE).[33] Critically, PE is a potentially viable material for transporting hydrogen at low pressures within the gas grid over the long term [34,214]. In parallel to the IMRRP, the UK government together with the country's gas distribution network operators (GDNOs) are testing the feasibility of both hydrogen blends and a 100% conversion to hydrogen [43,167,215]. Most notably, Project Union could establish a 2000 km hydrogen backbone linking major industrial clusters and carrying at least 25% of current UK gas demand [215].[34] However, the feasibility of this scenario rests on the scale at which hydrogen blending (up to 20% vol.) is facilitated, which calls for more decisive policymaking and accelerated action from GDNOs.

Compared to natural gas pipelines, the CAPEX of new hydrogen pipelines may prove 10%–50% more costly [104] (see Table S7). By

[26] Cost improvements are anticipated from higher efficiencies, less degradation, higher availability, larger cell sizes, higher operating pressure, and less critical material use together with overall reduced material use [193].

[27] Whereby experience with a technology drives down the unit cost of production over time [402].

[28] Compared to Saadi et al. [210], DeSantis et al. [194] calculate a lower pressure drop for hydrogen transport relative to natural gas, therefore, the volumetric flow is higher in the hydrogen pipelines.

[29] European Agreement Concerning the International Carriage of Dangerous Goods by Road.

[30] 3 kWh/m^3 compared to 10 kWh/m^3 for methane.

[31] However, hydrogen has a higher flow rate than natural gas which may help drive down unit costs through economies of scale [158],

[32] Since hydrogen has a faster flow rate than methane, the pipeline capacity required per unit of energy is only ~20% more [103].

[33] The IMRRP implements a three-tier approach. In Tier 1, 80% of all 'at risk' iron pipes (8 in. or below) are upgraded with PE. The programme is set to conclude by the end of 2032 [213,403].

[34] Project Union aims to decarbonize large clusters of industry, connect to hydrogen storage locations, integrate increasing volumes of electrolytic hydrogen, and could create cross-border markets for low-carbon hydrogen [104,121].

contrast, European transmission system operators (TSOs) estimate that repurposing existing pipelines may prove 10%–25% less costly than building new hydrogen pipelines [104]. Reflecting the lower CAPEX associated with repurposing infrastructure [90,104,216],[35] the European Hydrogen Backbone (EHB)[36] envisions 75% retrofitted pipelines [104].[37] Ultimately, decisions around pipeline construction must be made on a case-by-case basis with involvement from TSOs, GDNOs, and end-users.

4.1.3. Hydrogen storage

Hydrogen storage may prove equally important to production when considering the feasibility of the hydrogen economy. Foremost, large-scale storage is needed to strengthen the flexibility and resilience of the energy system, which can help reduce costs [29]. However, "reliable, safe, effective, and efficient" storage solutions are yet to be established [217]. At the outset, there are significant cost barriers to overcome, given that storage may contribute 24%–35% of CAPEX for a blue hydrogen production plant [177].

CGH_2 can be stored in containers above ground, but higher pressure is needed to contain the equivalent amount of stored energy [103]. Compared to CH_4, storing compressed hydrogen is at least 50% more costly due to its lower volumetric density [96]. Due to operating costs and material properties, large-scale storage of CGH_2 is typically limited to pressures below 100 bar in aboveground vessels and below 200 bar in geological formations [218] (see Table S8). Overall, underground hydrogen storage (UHS) requires significantly less investment costs than large-scale hydrogen storage above ground [219]. Alternatively, liquid organic hydrogen carriers (LOHCs)[38] – relying on hydrogenation and subsequent dehydrogenation of organic molecules – could offer a viable solution for safe and efficient hydrogen storage, alongside more conventional use for transportation purposes [220].[39] Additionally, the potential for flexible linepack storage (i.e. the inherent storage capacity within the gas grid) needs to be carefully considered in energy transition models [155,196].

4.1.3.1. Underground hydrogen storage. Each UHS method entails its own distinct characteristics [31], calling for case-by-case analysis of the geological integrity and techno-economic parameters of each storage site [216]. Although the entire seasonal demand for UK residential heating could potentially be balanced via hydrogen storage in just a few offshore gas fields [33,221], this option presents problems of chemical reactions and environmental pollution, as evidenced by the historic storage of town gas [222]. BEIS concluded that depleted hydrocarbon fields are unsuitable for hydrogen storage due to residual contaminants, such as sulphur compounds [223]. Hydrogen storage in depleted hydrocarbon fields may also result in an unpredictable blend of hythane (methane and hydrogen) [103]. Similarly, in deep seated aquifers, undesirable reactions may produce gases such as H_2S and CH_4 with loss of hydrogen [31], while gas leakage is unavoidable [222]. Notwithstanding, research into the feasibility of these storage options remains nascent [29].

Where geologically viable, salt caverns – artificial cavities built in salt deposits [224] – may provide a preferred option for UHS due to several advantages (see Table S9), including low construction costs, fast withdrawal and injection rates, low leakage rates, minimal risks of hydrogen contamination, and relatively low cushion gas requirements [219,224,225]. Based on the UK and US experience since the 1970s, salt caverns have proved a technically feasible method for achieving large-scale hydrogen storage [31].[40] Notwithstanding, due to the geographic scarcity of salt caverns in the UK [223], transporting this energy to consumers in important demand centers such as London and the Southeast would incur high costs and significant logistical barriers [29].

4.1.3.2. Cost factors for underground hydrogen storage. The cost of UHS consists of construction, operating, maintenance, and decommissioning costs [219,224]. UHS in salt caverns or depleted hydrocarbon fields present more predictable cost estimates than in aquifers, while the costs of the former are expected to be less [224]. Salt caverns offer an economical way to store hydrogen, reducing costs to less than 1% of electricity storage in batteries [193] and allowing for intra-day, daily, weekly, or seasonal operation [223]. The key costs of hydrogen storage in salt caverns include CAPEX for construction by dissolution, and the cost of the gas cushion for maintaining minimum storage pressure [31]. Additionally, the length of the pipeline used to discard the brine is an important cost factor, especially when suitable disposal sites are located far offshore [31,224]. Counteracting these cost barriers, larger cavern size and more favorable geological characteristics may improve economies of scale [31]. Overall, the CAPEX and OPEX of salt caverns are higher than for depleted hydrocarbon fields, but less than in aquifers [31]. However, the costs of salt cavern storage are projected to decrease by one-third [96].

4.1.3.3. Barriers to underground hydrogen storage. Challenges and uncertainties facing UHS remain extensive, as documented in a recent review by Tarkowski and Uliasz-Misiak [226] which identified 25 unique barriers, ranging from geological and reservoir constraints, and technical and safety limitations, to legislation and regulations, potential conflicts of interest, and social acceptance. On the technical side, the unique properties of gaseous hydrogen such as "its high penetrability and negative influence" on steel present barriers to safe UHS [31]. The cost of the borehole injection/withdrawal with its required tubing is much higher than for CH_4, given the need for materials that are impermeable for hydrogen and resistant to embrittlement [31,227]. The behavioral properties of hydrogen may also present additional complexity compared to natural gas when it comes to underground storage [31].

Mathematical modeling has demonstrated that UHS generates CH_4 emissions by behaving like a natural chemical reactor [228], whereby hydrogen acts as "a universal electron donor" for the metabolic activity of different hydrogenotrophic species (e.g. methanogenic archaea, acetogenic archaea, sulfate-reducing bacteria, and iron-reducing bacteria) [229]. Specifically, Hemme and van Berk [230] showed that the generation of hydrogen sulfide (H_2S) and related contaminants by bacterial sulfate reduction presents a risk in salt caverns. Given the co-existence of different microbial species, there is likely to be more competition [229] and resultant loss of hydrogen [31]. In salt caverns, there may be additional risk of impurities in withdrawn gas caused by undesirable reactions between hydrogen and interbeddings other than salt, alongside other limitations (see Table S10). Notwithstanding, evidence on the impacts of subsurface microbial communities and other risks remains limited [155].

Overall, using salt caverns to store hydrogen is not dissimilar to natural gas, in respect to the main risk associated with geological

[35] The levelized cost of transmission (LCOT) for hydrogen is estimated at €3.7/MWh_{H2}/600 km for repurposed natural gas infrastructure, compared to €4.6–11.4/MWh_{H2}/600 km for new hydrogen-dedicated infrastructure Calculations used in these estimates are for the Euro in 2019 [404].

[36] Potentially scaling up from 6800 km in 2030, to 23,000–30,000 km of pipelines by 2040 [104,405].

[37] With diameters ranging between 24 and 48 in., providing 3–13 GW (LHV) transport capacity per pipeline [104].

[38] LOHCs account for all hydrogen storage systems that are liquid in their hydrogen-rich form and can undertake this reversible chemical reaction [181].

[39] See Yang et al. [406] for a recent review of hydrogen storage options.

[40] For example, 1 million m^3 of pure hydrogen (95% H_2 and 3%–4% CO_2) is safely stored at three salt caverns located in Teesside in North East of England, serving as a local industrial feedstock for the production of ammonia and methanol [31].

uncertainty [224]. However, it should be noted that the socio-political acceptance of UHS remains largely unattested [29,226,231], therefore assumptions should not be made that past experience with gas storage will be directly transferable to hydrogen. For example, evidence from Germany highlights public concern over safety and security issues [231], which suggests that gaining a social licence to operate (SLO) hydrogen (and CCS) may prove problematic [232,233]. Even within a favorable socio-political environment, moving from theoretical estimations of UHS to actual site-specific development will require lengthy permitting and planning procedures, which may restrict prospects for cavern development in certain areas and within a net-zero timeframe [29].

4.1.4. Visualizing techno-economic barriers to the domestic hydrogen transition

Techno-economic barriers to the DHT are extensive and cut across all parts of the hydrogen supply chain (see Fig. 8). A multipronged approach is imperative to tackling a range of challenges and issues around energy resources and security of supply, the volatility of gas and electricity markets; alongside the scaling up of low-carbon hydrogen production, transport, distribution, and storage, together with CCS. Each of these components of the HES must be safe and economic. Having dissected the main techno-economic factors shaping the hydrogen economy, the next section discusses technical factors concerning hydrogen safety and appliance performance.

4.2. Technical factors

Technical risks and safety issues impact all areas of the hydrogen economy [55,234]. Potential technical barriers revolve around the inherent hazards and risks of hydrogen fuel, as well as specific issues concerning pipeline integrity, appliance performance, monitoring and metering requirements, and emissions and pollutants. Given that hydrogen has a high sensitivity to detonation [60], risks include potential damage to property such as industrial facilities and hydrogen vehicles, as well threats to health and safety, and the environment [209,235,236].

Despite its risk profile, hydrogen has been used safely across a range of applications [4,60] including aerospace [237,238], petrochemicals [239,240], and electronics [241]. There is a scientific consensus that hydrogen presents no significant additional risks compared to other liquid or gaseous fuels in terms of storage and consumption [60]. Nevertheless, using hydrogen in residential and commercial applications is likely to raise additional concerns [116]. Compared to industrial applications, adherence to safety measures is significantly harder to enforce and monitor [242], for example, in the case of hydrogen fueling stations (HFSs) or HFCVs [243–245] and moreover, in residential applications [22].

4.2.1. Hydrogen detection and monitoring

Despite technical advancements, there is still uncertainty over whether national gas grids, such as the UK's National Transmission System (NTS) and Local Transmission System (LTS), will be compatible for transporting and distributing 100% hydrogen [111,167]. In parallel to testing the compatibility of the gas grid, robust detection and monitoring strategies are needed to minimize the risk of hydrogen leakage [246]. Due to its small molecular weight, hydrogen has a high tendency to leak through pipelines and storage containers [18,247], leaking at a rate of 1.3–2.8 higher than that of gaseous methane and four times that of air [4]. Hydrogen exhibits high diffusivity through a range of materials and is four times as diffusive as CH_4 [247]; calling for constant and accurate monitoring of leaks throughout transport, storage, and use [247]. In typical polymer pipes, permeation rates for hydrogen are about 4 to 5 times faster than for CH_4 [248]. Although hydrogen is not considered toxic in nature, when it releases in confined spaces, there is still a risk of asphyxiation since it can reduce oxygen concentration below 19.5% by volume [18].

4.2.2. Technical risks of hydrogen blending and domestic hydrogen

Investigations into hydrogen blending, whereby small quantities of hydrogen are injected into the existing natural gas grid [21], date back to the 1980s [249]. Notably, the NATURALHY-project (2004–2009) examined the conditions under which pure hydrogen blending could be safely used in natural gas pipelines [250,251]. The project demonstrated minimal impacts on straight pipelines with blends up to 25% [252]. Other estimates are more conservative, suggesting that a hydrogen blend of about 10% has negligible impacts on existing pipelines and appliances [253]. Although a promising steppingstone to the wider transition [43], injecting hydrogen into natural gas networks will present technical and safety challenges [22,116].

Hydrogen has a higher flame speed [107] and adiabatic flame temperature than CH_4 [254,255], which increases the potential for explosive risks [7,256]. As a result, there are additional challenges for handling and storing hydrogen safely [60]. Additionally, hydrogen has a wide flammability range (4.0–75 *v*/v%) in oxygen [90,109] compared to CH_4 (5–15.6 v/v%) [257], with explosive mixtures occurring between

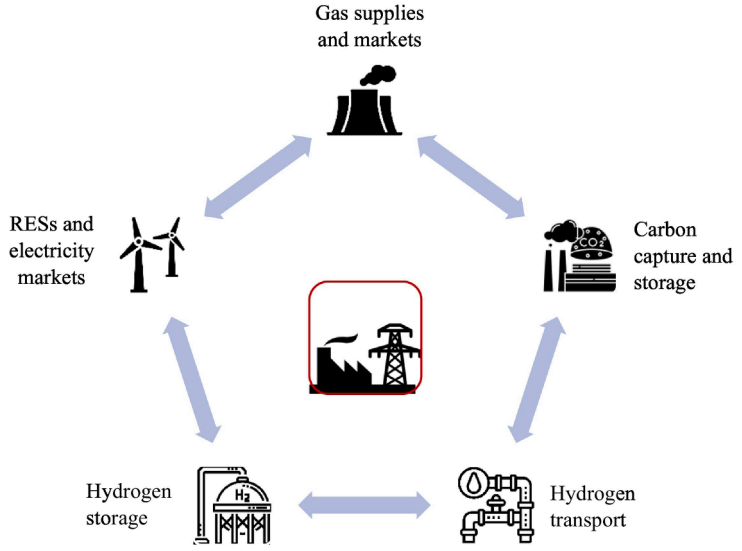


Fig. 8. Interactions between key techno-economic barriers.

concentrations of 18–59 v/v% [18]. These flammability characteristics [9],[109][41] may decrease the lifetime durability of hydrogen appliances, while increasing the need for more frequent and modified maintenance measures [112]. Relatedly, flame flashback – a function of flame speed – is significantly higher for hydrogen compared to CH_4 [110,196]. As the flame burns closer to the gas ring or oven burner [109], the risk of hydrogen flashback increases, which can result in damage to the burner and lead to appliance shutdown [105]. Without prevention from a hydrogen flame arrestor [61], flashback can cause an explosion hazard if the combustible mixture spills over [110]. Critically, de Vries and Levinsky [259] observed that minimizing the risk of flashback and other safety issues concerning hydrogen would require a reduction in the thermal performance of domestic appliances.

Based on experimental tests on a representative natural gas cooktop burner, intermittent flashback occurs when 20% hydrogen is blended with natural gas [109]. Although the overall combustion performance of appliances may not be significantly affected by an addition of about 15% hydrogen [109], it is recommended that the maximum blend should not exceed 15%–20% to prevent downgrading natural gas quality [62]. Zhao et al. [109] concluded that it is feasible to use hydrogen on existing cooking appliances within these limits without the need for technical modifications, while also observing that hydrogen blending reduces pollutant emissions. However, Dorrington et al. [112] highlighted an additional barrier concerning the configuration of new flame retention ports, which act to prevent the flame from lifting off the burner. The authors concluded that converting dual fuel cooking appliances presents a greater technical challenge than boiler conversion, especially given the nature of damage and spoil to cooking apparatus from extensive food spillage [112].

Given that the volumetric density of hydrogen (0.0899 kg/m^3 [247]) is almost three times lower than CH_4 [252],[42] compression energy will be approximately three times greater for hydrogen transmission with the same pressure drop [252]. Consequently, blending hydrogen into the existing pipeline will lead to a significant decrease in mass flow rate, resulting in less transmitted energy [66].[43] Hydrogen blending could also prove technically challenging since different measuring instruments, control stations, and compressors will be required [65]. This includes smaller gas meters to accommodate hydrogen's volumetric flow rate and different valves to prevent excess flow [112], as well as changes to consumer billing (see Section 4.4.3). For example, the GRHYD demonstration project in France [260] found that the presence of 20%vol. hydrogen in gas would cause a metering difference up to 2.5% [252].

In the short-term, blending hydrogen into existing gas networks may provide a viable opportunity to rapidly scale-up hydrogen supply at lower capital expenditure (CAPEX) [103,261]. Evidence suggests that blending percentages of at least 5% and up to 20% hydrogen should be technically feasible with minimal investments [101,103,108]. Notwithstanding, blend concentration, even at fractions of 5%–15%, must be assessed on a case-by-case basis to account for specific end-user typology and variation of natural gas composition within pipelines [123,252,262]. Moreover, moving to higher blending percentages will call for changes to infrastructure and equipment such as different burners [103]. This will increase environmental risks, technical challenges [263,264], and potential costs [123,262]. Notably, regarding emissions, Colorado et al. [263] found that a mixture of natural gas with up to 70% hydrogen promotes the formation of nitrous oxide (N_2O), which is a trend not observed with other gaseous fuel mixtures such as biogas.

4.2.3. Visualizing technical barriers to the domestic hydrogen transition

Despite sustained research efforts and growing technical understanding, a knowledge gap remains regarding the safe transport and use of hydrogen or methane-hydrogen mixtures [116], with scientific knowledge on the risks of domestic hydrogen remaining low in comparison to CH_4 [265]. Clearly, barriers to securing technical feasibility, such as hazards and risks, pipeline integrity, appliance performance and safety will need to be addressed if hydrogen home appliances are to penetrate the UK market at a meaningful scale (see Fig. 9). As a starting point, more experimental studies are needed to bridge the gap between safety levels for hydrogen and hydrocarbon technologies mixtures [116], including research regarding the technical feasibility of hydrogen blends above 20% [266]. Having reviewed the technical aspects of the DHT, the next section introduces the soft side of the transition through a review of political factors [147].

4.3. Political factors

Regulatory engagement is needed across the hydrogen value chain; from safe production, storage, and transportation, to market incentives and business models [118,121] (see Table 3). Critically, regulators should address the lack of harmonization regarding codes and standards for the transport and transmission of hydrogen [118]. For example, the lack of a harmonized policy and regulatory framework between the European Union (EU) and UK impedes ambitions to be reap economic benefits as first movers in the global hydrogen economy [30,267,268]. Notably, there are significant disparities between national thresholds for hydrogen blending, owing to a range of legacy codes and standards [98,118,269,270]. Compounding this issue further, there is still no scientific consensus about safe thresholds limits for hydrogen blending [271].

Thus, identifying 'legal pathways' [272] and implementing adequate policy mechanisms is crucial to enabling transparent procedures for national hydrogen plans, especially renewable-based projects [271]. Establishing international agreements around low-carbon hydrogen standards, as well as future cross-border trade [1], can help support best practices for hydrogen safety, while also accelerating cost reductions for producers and consumers through learning-by-doing and a more liquid global market [96].

4.3.1. Visualizing political barriers to the domestic hydrogen transition

Multiple political barriers inhibit the scaling up of HESs, with most countries yet to develop legal frameworks to support national hydrogen economies [270]. These barriers revolve around the development of international agreements, regulatory frameworks, legal and administrative procedures, codes and standards, and land-use planning procedures (especially for green hydrogen projects) (see Fig. 10). Overcoming deployment barriers to the UK hydrogen economy and the DHT – whether technical, commercial, regulatory, or societal – will require sustained political will. The next section addressed the commercial side of the transition through a review of market factors.

4.4. Market factors

The diffusion of hydrogen appliances will depend on TRL, market penetration, and subsequent market growth [158], which can also be examined in terms of barriers to market entry, development, and support [112]. Overcoming barriers to each stage of the technology curve will hinge on interactions with other socio-technical factors, [273,274] (see Table 4). At present, the global hydrogen supply chain is still in its infancy and faces significant challenges to scale up [57,164,223].

[41] Hydrogen's laminar burning, buoyant, and propagation velocities exceed that of other fuels, while its vapor-from-liquid-generation-speed is higher than fossil based liquid or liquefied fuel [60].

[42] Approximately 3.6 kWh/Nm3 or 12.8 MJ/Nm3 for hydrogen, compared to 11.8 kWh/Nm3 or 42.3 MJ/Nm3 for natural gas [252].

[43] Overall, hydrogen injection increases the upper and lower flammability limits and compressibility factor, whereas both lower and higher heating values, lower and higher Wobbe indices, along with the relative density, decrease [90].

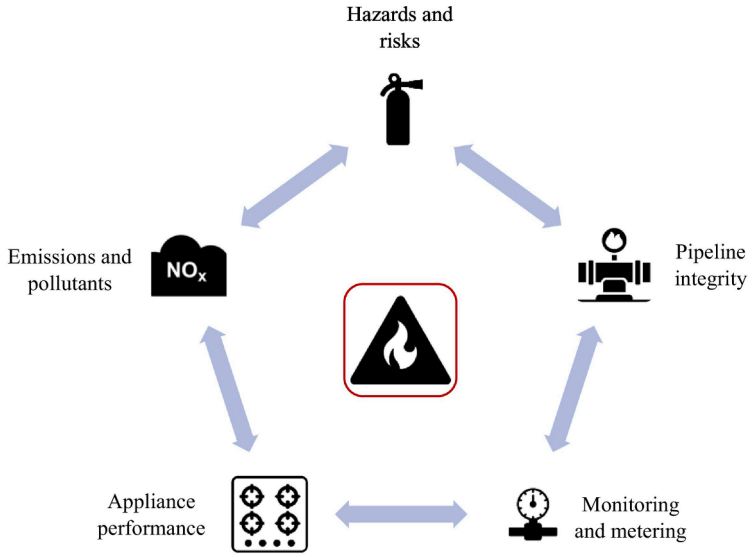


Fig. 9. Interactions between key technical barriers.

Notably, unlike other energy sources and commodities which are publicly traded, hydrogen is currently traded via bilateral agreements between companies [98]. This limitation is reflected by the global hydrogen generation market being valued at about 3% of the global oil and gas market in 2020 [275,276]. The rest of section discusses these market barriers in more detail.

4.4.1. *Supply chain barriers*

The Scottish government has reported underlying deficiencies in areas of design, manufacture, and maintenance for production, storage, and transport of hydrogen, which calls for new skills and training in the workforce [198]. Irrespective of the specific hydrogen production pathway, a greater number of Chartered Engineers and qualified technicians would be needed to deploy hydrogen homes at a large-scale [111], as experienced with the national transition from town gas to natural gas [277,278]. It is anticipated that the UK will face regional constraints for skilled labor when pursuing a transition to domestic hydrogen appliances [223].

In addition to labor constraints, the costs of research and development (R&D), product design, and initial manufacturing for hydrogen appliances will exceed the costs of natural gas appliances [112]. Even when suitable production facilities are in place, bottlenecks are likely to arise when components and materials used in natural gas appliances cannot be transferred to hydrogen appliances,[44] especially if UK manufacturers become reliant on their European counterparts for specific components, such as gas valves, seals, controls, and burners [112]. Walker et al. [223] further highlight that the build rates for several components will depend on unpredictable global supply chains. The green hydrogen supply chain faces similar risks, given that only two electrolyzer factories are currently operational in the UK, both of which are in England [121]. A related barrier concerns "the intertemporal integration" between a prospective hydrogen supply chain and existing supply chains, which is yet to be examined in detail [164].

4.4.2. *Informational barriers*

There is an information gap concerning the market demands (e.g. gas quality, appliance outputs, thermal efficiency and NO_X requirements) for hydrogen appliances [112], which is compounded by the need to adjust manufacturing warranties [123]. Alongside changes to the permissible concentration of hydrogen in the gas network, manufacturing warranties – associated with plant machinery and equipment, and domestic appliances – would also need to be adjusted to support market entry and development [123]. It follows that the appliance industry needs more information about the market requirements for hydrogen products to meet the expectations of both policymakers and consumers [112]. In parallel, leading boiler manufacturers will need to align their goals [279] to compete with low-carbon alternatives such as heat pumps. Alignment between manufacturers is important for promoting brand loyalty and consumer buy-in for hydrogen appliances.

4.4.3. *Barriers to consumer billing*

At present, gas consumption is billed according to an assumed energy content which is held uniform across the gas network [123]. However, should hydrogen be injected into selective regions of the UK, the energy content of mains gas would in turn vary by location [123]. Hydrogen has a lower volumetric calorific value (CV) than natural gas, therefore, gas meters would register a higher volume of use for the same energy input, which would expose consumers to potentially variable and overpriced charges [123]. In response, new methods are required to determine energy content at all points of the gas network [252]. Addressing this challenge would call for a rethink from the Office of gas and electricity markets (Ofgem) about how to bill consumers for gas use [123].

Cadent Gas Ltd., the UK's largest GDNO, has developed the Future Billing Methodology (FMB) project to develop solutions that will enable lower-CV gases such as hydrogen to be embodied accurately into consumer billing. The expectation is that a modification would be required to the uniform network codes (UNC) [123], which govern commercial transactions between gas shippers, transporters, and suppliers. To carry out the hydrogen conversion, hydrogen sensors and new meters would need to be fitted to each home to enable householders to be billed according to CV of gas consumption [214].[45] As supply-side mechanisms develop, market factors will prove critical to determining what tariffs, business models, and other conditions prove acceptable to different consumers.

[44] This may include high temperature seals and gaskets, sizing of various components, and pressure regulators [112].

[45] Based on the UK MARKAL energy systems model (calibrated to UK energy consumption in 2000), this could an additional cost of £230 to £490 per house [214].

Table 3
Impacts of policy barriers to hydrogen development and deployment.

Identified barrier	Implications for hydrogen development and deployment
Regulatory framework for the international transmission of hydrogen (maritime, pipelines) still not harmonized	• Hinders international trade of hydrogen
Emissions reduction schemes and internationally agreed framework for pricing carbon emissions not in place	• Hinders the development of a renewable hydrogen market • Hinders international trade of hydrogen • Hydrogen use remains economically unattractive across multiple use cases
Certification schemes such as Guarantee of Origin (GoO) for renewable hydrogen are still in development	• Hinders the development of a renewable hydrogen market • Constrains the overall environmental benefits of hydrogen across the energy system • Hinders international trade of hydrogen
No common definition of 'green'/ renewable hydrogen in regulatory and policy frameworks	• Divergent national approaches jeopardize the movement of green hydrogen across borders, • Acts as a barrier to the implementation of renewable hydrogen projects • Increases uncertainties associated with production pathways and certification schemes, which may restrict investments
Lack of a 'simplified process' for low volume hydrogen production and storage,[a] as this remains relative to the site and site specific/operational safety risks	• Prevents the easing or removal of some aspects of regulation, compliance, and permitting related to Hazardous Substances, and Control of Major Accident Hazards (COMAH)[b]
Current legal and administrative procedures, including land use planning and associated zoning limitations or exclusions, do not generally distinguish between hydrogen production methods	• Limits the ability for planning authorities to leverage and potentially incentivize production of hydrogen through relatively safe, low environmental impact methods such as electrolysis • Large-scale industrial producers (i.e. SMR-based) and smaller-scale producers using electrolysis face similar planning restrictions, which may discourage investment in local, distributed hydrogen production
Lack of a formal, clear, and coherent payment framework in place across between regions (e.g. UK and EU) for hydrogen transmission; covering connection fees and charges, or covering renumeration for hydrogen supplied/injected	• Limits the business case for hydrogen systems • Delays projects from passing beyond the demonstration phase
Tariffs apply to electricity consumed for hydrogen production	• Increases the relative price of electrolytic hydrogen compared to other hydrogen production mechanisms

Source: Compiled from [26,96,118,123].

[a] Considered as chemical storage of flammable and dangerous (industrial) gases from a legal and administrative perspective.

[b] Hydrogen storage may fall under Hazardous Substance regime at 2 t or under the COMAH Directive at 5 t.

4.4.4. Visualizing market barriers to the domestic hydrogen transition

Early progress has been made on addressing some of the existing market barriers, through innovations such as the FBM, while the boiler industry's 'Big Four' (Worcester Bosch, Vaillant, Baxi, and Idea) have made a price promise on hydrogen-ready boilers [279]. However, overcoming barriers to market entry and development will require increased R&D to increase the TRL of different hydrogen technologies, alongside a massive ramping of the domestic supply chain and a diminishing informational barriers, to enable viable business models for hydrogen home appliances (see Fig. 11).

At the national level, the fragmented structure of the UK gas market [37] – composed of "producers and exporters of gas as a commodity; suppliers and traders of wholesale and retail gas; generation, regasification, and storage asset owners; and network owners and operators" – may also impede coordination across the supply and value chain, should respective actor groups present conflicting motivations and priorities [123]. In addition to the current gas network being much more interconnected and vulnerable to supply disruptions than during the conversion from town gas, the privatized nature of the current gas network presents more of a logistical and financial barrier than during the era of centralization [214].[46] Completing the socio-technical transition framework for the DHT, the next section discusses social factors, which span ethical, environmental, safety, economic, and socio-cultural aspects.

4.5. Social factors

Mixed methods studies on public perceptions of domestic hydrogen [21–23] indicate that social acceptance may rest on consumer attitudes towards equity and fairness, the environment, safety, cost factors, and behavioral impacts. However, existing perceptions of hydrogen technologies may be rooted in misconceptions due to an underlying lack of knowledge and awareness across society [115,243,280]. Against this backdrop, this section provides an overview of prospective barriers to hydrogen acceptance.

4.5.1. Public perceptions of equity and fairness

To date, a limited number of studies have engaged with issues of equity and fairness linked to the DHT. In the UK context, questions of energy justice [281,282] are especially pertinent given the spatial dynamics of the housing stock, where approximately four million households (~15%) are without connection to the gas grid [283]. From an energy equity perspective, these households – typically living in hard-to-treat, off-grid areas [100] – could be doubly excluded from the energy transition if denied access to hydrogen networks or electrification [67]. Both location and housing type present a challenge to achieving energy equity [67] (see Table S11). Furthermore, the UK hydrogen economy is developing in proximity to major industrial zones [284]. Such areas of the country are strongly characterized by disparate economic and social geographies [21], alongside a higher prevalence for fuel poverty [285,21]. This reality exacerbates the challenge of achieving a fair and efficient decarbonization pathway for the residential sector.

4.5.2. Public perceptions of environmental impacts

Public perceptions of environmental impacts have been shown to influence the social acceptance of new energy technologies [286,287]. Whether these perceptions are established on grounds of knowledge and awareness [288,289], or more rooted in culture [290], both the early [291–293] and more recent literature [21,23,294] supports the notion that environmental views are likely to shape hydrogen acceptance. Overall, the literature is quite emphatic on a consumer preference for renewable hydrogen, at least in the long-term [21,295,296]; inferring that non-renewable-based production methods may spark social resistance or opposition, especially across socio-demographic groups that are more culturally, psychologically, or emotionally engaged with environmental issues [23,75,296]. Notwithstanding, the UK public acknowledges an underlying level of uncertainty regarding the timeframes involved in developing infrastructure to produce renewable hydrogen at scale [297].

4.5.3. Public perceptions of cost factors

Evidence suggests that the UK public may perceive the economic impacts of hydrogen at the national or macro-level to be positive or at least neutral [21]. In contrast, at the household or micro-level, cost

[46] British Gas was privatized in 1986 under the Thatcher government [407].

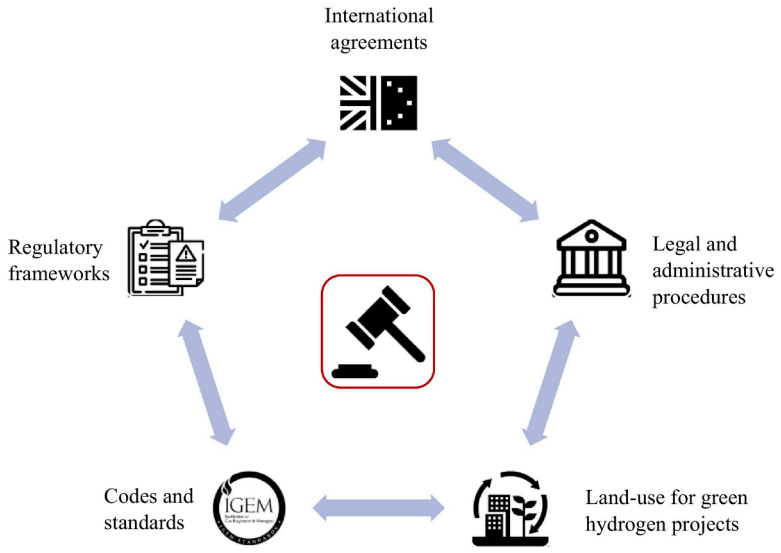


Fig. 10. Interactions between key political barriers.

Table 4
Market barriers identified by UK manufacturers and trade bodies.

Market barrier types	Identified barriers
Market entry	• Lack of necessary codes and standards for hydrogen boilers • Absence of a hydrogen quality standard • Insufficient number of trials and demonstration projects. • Smaller companies and new entrants will need to establish new sales and distribution channels, or cooperate with larger companies with established sales relationships • Lack of consumer awareness regarding the benefits of hydrogen • Lack of confidence in the safe operation of hydrogen appliances
Market development	• Lack of demand for hydrogen appliances • Lack of business models to support hydrogen appliances being sold in volume • Bottlenecks due to deficient engineering capacity • Lack of clear policies incentivising R&D resources to the manufacturing of hydrogen appliances • Limited number of appliance manufacturers, specific product designs, and commercially available products • Competition for R&D capacity and skilled labour
Market support	• Where technical solutions exist, there is no market pull to create supply chains • Financing mechanisms for converting appliances need to be established to resolve uncertainties • Specific training requirements for engineers/installers to install and repair hydrogen appliances

Source: Compiled from Dorrington et al. [112].

factors (i.e. purchasing, running, and potential maintenance costs) present the main barrier to securing consumer support [21,298]. BEIS reported that consumers are highly concerned about the investment, operational, and lifetime costs of hydrogen appliances, with strong interest in how the switchover may impact energy prices and tariff structure [169]. Based on related survey studies conducted in the North of England [22,298], delivering cost-competitive running costs may have a more pronounced impact on social acceptance. In this region of the UK, the affordability challenge looms large, since a combination of high energy bills and low wages have already led to a propensity for fuel poverty [21,22]. In response, there is a strong expectation that government subsidies and financial schemes will be available to encourage technology adoption, which the public expect to be subsidized [295,297]. Beyond these findings, there is limited data on the public's willingness to pay for domestic hydrogen, which presents a significant barrier to developing a comprehensive hydrogen strategy.

4.5.4. Public perceptions of hydrogen safety

As described in Section 4.2, hydrogen has distinct physical and chemical properties which may raise public concerns over safety risks, especially when improperly explained or misunderstood [299]. While most safety-related issues are attributed to hydrogen's volatility and flammability [23,74,299], the production context may also influence safety perceptions [21,22]. For example, in the case of green hydrogen, the Welsh public expressed concerns over explosive risks, which were heightened due to hydrogen's unfamiliarity compared to natural gas [299]. Interestingly, some consumers may be more worried about the safety of CCS for enabling a blue hydrogen pathway [300,301], as opposed to hydrogen-specific risk factors.

Closing social acceptance barriers around safety may prove more feasible if hydrogen first becomes visible in other areas of energy and infrastructure, such as industry and transport [43]. This could prove especially critical if the public has an expressed preference for using hydrogen in commercial applications, as opposed to residential settings [295]. In the same way that blue hydrogen may be viewed as an enabler of green hydrogen [30,302], developing other sectors of the national hydrogen economy may strengthen hydrogen's social standing [303] in the residential context.

4.5.5. Public perceptions of behavioral impacts

Given that very few consumers have seen hydrogen appliances first-hand, let alone tested them at demonstration facilities such as Spadeadam [304], there is scarce data available on potential behavioral impacts. To date, hypothetical studies highlight that consumers value preserving the lived experience of gas heating and cooking, which will require hydrogen appliances to deliver across the board in terms of functionality, appearance, maintenance requirements [169], safety and security [21,22]. Evidence suggests that consumer acceptance would be encouraged if hydrogen boilers can provide a close substitute for gas boilers by providing an efficient, quiet, and minimally disruptive heating system, which has limited impact on domestic energy practices [37,305,306]. However, given the intimate nature of domestic kitchen activities, consumers may have stronger reservations about the 'socio-material nature' of hobs than boilers [22]. Whereas boilers are typically as out-of-sight and removed from day-to-day interactions [22], cooking appliances may bring about undesirable changes to incumbent social practices [37].

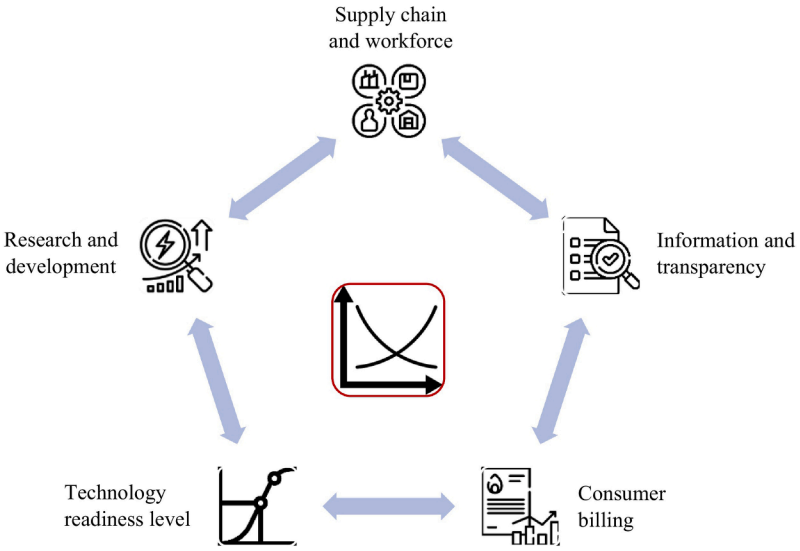


Fig. 11. Interactions between key market barriers.

4.5.6. *Visualizing social barriers to the domestic hydrogen transition*

International research on social barriers to the DHT remains considerably nascent and largely constrained to the UK, European, and Australian context, with several of these studies found within the grey literature [298,307,308]. Notwithstanding, a few articles have recently entered the academic literature [21–23,67], with the available evidence suggesting that social barriers concern the following areas: energy injustice and other social inequities; changes to the lived experience of heating and moreover, cooking; health and safety issues; cost factors; and underlying perceptions of social and environmental impacts (see Fig. 12).

4.6. *Linking socio-technical factors and barriers*

Through identifying the main socio-technical factors impacting shaping the DHT and the broader hydrogen economy, Section 4 enables a more integrated analysis of interactions between different dimensions of the socio-technical system for hydrogen homes. Next, Section 5 explores these interactions in a systematic way by applying the framework to the UK context. In doing so, this analysis advances the discourse around the feasibility of converting natural gas grids to hydrogen [168], accounting for the impacts of both blue and green pathways vis-à-vis the twin track approach [43].

5. Interactions between socio-technical factors: Breaking down barriers to the domestic hydrogen transition

5.1. *Cross-scalar dynamics and policy inadequacies*

The policy environment for supporting HESs is relatively nascent, reflected by a nexus of barriers interacting across different levels of the hydrogen economy. Firstly, policy barriers must be overcome to realize ambitions for aligning mega-projects, such as the UK industrial hydrogen backbone and the EHB, as well as more localized projects. Existing policy mechanisms fail to support strong progress on this front, owing to a lack of codes, standards, or payment frameworks for cross-border transport/transmission. This weakens the prospect of developing international supply chains, which is important for strengthening energy security and international hydrogen trade. Playing out more visibly at the national level, the absence of specific standards for designing or installing hydrogen appliances creates market uncertainty for manufacturers and the wider industry. This deficiency stifles the

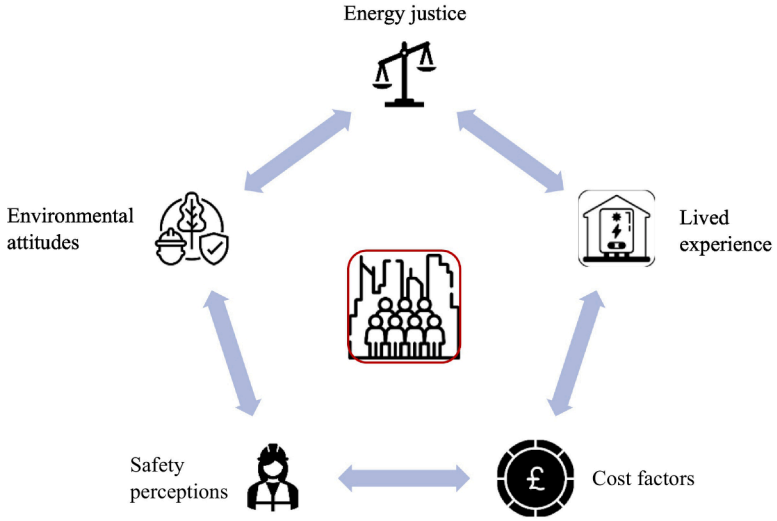


Fig. 12. Interactions between key social barriers.

retraining and upskilling of the UK workforce, which is needed to support a "just transition" pathway [309,310].

The economics of hydrogen production are strongly linked to the costs of electricity and gas, which depends on key technical parameters such as conversion efficiencies [57]. This interaction between "economic viability and technical effectiveness" [311] dictates the feasibility of deploying hydrogen-fueled home appliances in a safe and cost-effective way, which can garner social acceptance at the national, community, and household level. However, one of the preconditions for establishing a functioning market for hydrogen homes lies with developing codes and standards to accommodate higher volumes of hydrogen in UK gas networks [99]. As a starting point, a legal framework is needed to enable the injection of hydrogen into the natural gas grid for distribution and transmission. In the short-term, blending hydrogen at 20% could take advantage of low-hanging fruit for emissions reduction by lowering carbon intensity by up to 7% [99], while helping to mitigate demand risk as the hydrogen economy scales up [167].

A robust national regulatory framework, supported by international agreement around codes and standards, will also help facilitate market development and best practices for hydrogen safety [164]. While negative perceptions of hydrogen's safety credentials appear to be mostly associated with low levels of public awareness and knowledge [22], safety concerns may also permeate the socio-cultural dimension by disrupting the lived experience of heating and cooking [22,169]. Specifically, demography, location, and culture may influence disparities regarding safety perceptions and associated hydrogen acceptance [115]. Coordinated planning and action is required to account for geographic diversities between access to renewable energy resources [312,313] and divergent political dynamics across different parts of the country [314–316]. Otherwise, socio-structural barriers [317] may prove entrenched and challenging to reconcile, as reflected the UK's North-South divide. Thus, availability and access to resources [71], together with institutional factors [26], will carry strong implications for the dynamics of the DHT.

5.2. Dissecting the blue and green of the UK Hydrogen Strategy

While the UK Hydrogen Strategy should be viewed as a major step forward in terms of mapping future pathways and key steppingstones for this decade, some of its momentum and ambition has been curbed by the government's choice to delay strategic decision-making on the role of hydrogen in heating until 2026 [44]. This could potentially offset the scaling-up of demonstration projects [132]. Progress in this area is critical for developing evidence and insights into the regional suitability and feasibility of domestic hydrogen. Trials and demonstrations also lay the foundations for social acceptance [37]. The 2026 decision timeline reduces the likelihood of mandating hydrogen-ready boilers within the next few years [279], which could stall the phasing out of new natural gas boilers by 2035 [43]. Furthermore, policy uncertainty may delay the potential deployment of hydrogen-heat pump hybrids [41,168].

The UK Hydrogen Strategy [43] highlights the degree to which the viability of the DHT rests on parallel, if not significantly faster progress on industrial decarbonization via hydrogen [26], as well as transport and power. Foremost, the nature of these cross-sector dynamics means that the feasibility of hydrogen homes will hang in the balance until tangible progress is made in decarbonizing industrial clusters [232]. Arguably, the very notion of establishing a low-carbon hydrogen economy rests on scaling up blue hydrogen production in the short- to medium-term. However, the blue pathway faces a supply deficit, which could result in greater import dependency for natural gas. If pursued as currently envisioned in the Hydrogen Strategy, this trajectory could expose consumers to commodity price fluctuations and higher energy prices due to increased production costs [318,319]. Currently, parts of the UK population already face a growing fuel poverty crisis [21,285,385], which would be exacerbated if these costs fail to be minimized and socialized equitably.

Doubling down on natural gas via investments in blue hydrogen infrastructure may also prove unpopular with the public on environmental grounds, especially if this route is misunderstood and rejected as a transitional pathway. Arguably, this pathway counteracts the energy transition discourse since it is more emissions-intensive than hydrogen production via wind electrolysis [320], and may lock-in dependence on natural gas for several decades [261]. Notably, the role of blue hydrogen as a transitional fuel and enabler of green hydrogen remains subject to scientific debate, with uncertainties regarding emissions intensity [30,302,321]. Moreover, given that CCS is yet to reach a commercial scale [262], the techno-economic feasibility of blue hydrogen acting as a stimulus for a green hydrogen economy remains unclear. This lack of clarity could derail the foundations for reaching economies of scale for low-carbon hydrogen production.

While the blue hydrogen pathway faces its own set of distinct challenges, existing policy mechanisms designed to support the twin-track approach may diminish prospects for a green pathway. The current playing field for blue and green hydrogen appears unequal, which casts a shadow of doubt over the government's 2030 target for electrolytic hydrogen. The green hydrogen roadmap is less developed than its blue counterpart and faces more pronounced policy barriers, especially given the government's lukewarm stance towards promoting onshore wind projects. While the Ten Point Plan, together with the Hydrogen Strategy, promise to back CCUS alongside a ramping up of renewable energy capacity, conflicting narratives and inconsistent price signals between production pathways may act as a barrier to accelerating a clear, strategic pathway towards establishing a hydrogen economy. This is especially true if "a rhetoric of competition" exists between blue and green hydrogen [322], which could derail the impetus of a twin-track pathway.

As discussion around hydrogen production pathways continue to evolve, the scientific community must commit to a parallel investigation that fleshes out how prospective pathways may impact both environmental and social performance [323]. This is pertinent given that the environmental impacts of hydrogen are only partially understood and remain highly context-dependent [264,324]. Alongside understanding leakage rates [18], accelerated progress is needed in establishing safe NO_x legislation to minimize the risk of undesirable health and environmental impacts [325,326], which could otherwise increase the risk of public backlash and rejection of hydrogen.

5.3. Underground hydrogen storage: From technical feasibility to social acceptability

UHS mirrors many of the challenges faced by CCS [227,327], in terms of socio-technical and socio-spatial barriers [31,328]. The CCS literature demonstrates that these parameters must be addressed to facilitate large-scale implementation [329,330] and social acceptance [331–333]. The safe capture and sequestration of carbon must be proven to avoid the risk of public opposition and costly delays [110,239], further highlighting the importance of "cross sector technology interactions" [334] and community acceptance [335]. Notably, hydrogen remains a significantly less familiar fuel than natural gas for most of the UK public [336]. It follows that inclusive planning and stakeholder engagement will be critical to enabling procedural justice [337], which will require careful consideration of the role of CCS [337].

Prospects for developing full-scale hydrogen storage using salt caverns will depend on further research in at least three key areas: geological surveys during cavern leaching; periodic surveys of changes in the cavern during operation; and detailed characterization of the site storage supported by development of digital modeling [31]. As emphasized by Williams et al. [29], "detailed geological, engineering and techno-economic evaluations" are yet to be undertaken. Such measures will help reduce geological uncertainty by improving the knowledge base on specific salt deposits [177], while making the environmental and safety case clearer4 [29,226].

Reflecting the interactions between different branches of the socio-technical system for domestic hydrogen, converting geological space into hydrogen storage will require long-term commitment from both the public and private sector, with coordinated commitment towards intensive R&D activities [31]. To this end, Work Package 4 of the HyStorPor Project (University of Edinburgh) is engaging civil society with UHS to help couple technical feasibility to social acceptability [338].

5.4. De-risking hydrogen supply and demand

Scaling up hydrogen supply and demand across the UK energy system rests with developing "cost-effective network infrastructure" capable of providing security of supply to offtakers and domestic consumers [29]. By seizing the opportunity to use curtailed electricity from offshore wind farms to scale up green hydrogen supplies [198,339], together with a blue hydrogen production base (i.e. SMR + CCS), multiple producers could potentially supply hydrogen to the grid [43]. If diversity of supply is to materialize, a well-defined legal and regulatory regime must first be established for CCS [51]. This is precondition for enabling early commercial projects to reach Final Investment Decision (FID) [261]. By the same token, projects will need to be de-risked to reduce barriers to investment [123,261].[47] In line with the Ten Point Plan, government investment dedicated to de-risking early hydrogen projects could unlock more than £4 billion of private sector co-investment up to 2030 [43]. Given that the costs of manufacturing for hydrogen-fueled appliances will exceed natural gas appliances, regulatory stability is needed to support a new market [43,112]; wherein informational barriers are reduced to enable long-term investment decisions and market confidence for network expansion and repurposing [33].

Overcoming political barriers is also important for accelerating cost reductions for producers and consumers through LBD and a more liquid global market for hydrogen [34]. As highlighted in the case of Scotland (see Section 4.3), regulatory barriers add to production costs which weakens investment risk appetite, while lack of market confidence has negative spillover effects for developing supply chains to meet future demand for appliances. Thus, ensuring sufficient hydrogen demand is imperative to securing sustained policy commitment and market investment for hydrogen infrastructure. Demand for hydrogen appliances rests on both the safety and business case being made effectively, which is contingent on sustained investments in R&D to support a scaling up of demonstration projects [37]. In parallel, targeted information campaigns about the hydrogen switchover should engage local officials, consumers, and other key stakeholders [132]

Regarding the switchover, consumer buy-in may be hindered if appliances rolled-out during the early stages of the transition have shorter lifespans than existing natural gas or future hydrogen appliances [112]. To counteract this potential market barrier, technical advancements must satisfy consumer expectations. This applies equally to the prospect of hydrogen sensors and new meters [37], which present both a financial cost and social risk. Notably, the UK smart meter roll-out has faced ongoing consumer concerns over operability, reliability, trust, privacy, and data security [340,341], which may set a precedent for the hydrogen switchover. In turn, lessons must be learned to demonstrate that the government has a coordinated, whole-systems approach for residential decarbonization, thereby preempting a scenario in which new metering requirements may otherwise provoke consumer resistance [342,343].

The potential for public backlash looms large in the UK context due to past policy failures for various green technologies [344],[301]. To bolster public support in the early stages of the transition, blending trials and early deployment could be strategically targeted at viable hydrogen communities where there is a prevalence of households with old boiler units approaching replacement age (i.e. more than a decade old). This roll-out pathway would have an important co-benefit in tackling fuel poverty and inequality [345], which is paramount to strengthening socio-political acceptance via distributional justice [346].

5.5. Questioning the role of cooking in a hydrogen home

The notion of a hydrogen home and the current trajectory of the DHT aligns to the prospect of decarbonizing both residential heating and cooking [22,63]. However, hydrogen cooking appliances may present a more significant socio-technical challenge, especially in terms of safety and disruption [22]. Behavioral factors are more likely to pose a significant barrier to market uptake, should the lived experience of hydrogen homes fail to be understood in its totality. Given that compartmentalized transitions will have impacts across the hydrogen socio-technical system and supply chain [26], it remains unclear how a potential divergence between decarbonization pathways for heating and cooking may impact the feasibility and potential speed of the DHT. It should also be noted that domestic cooking is significantly less emissions intensive than residential heating [347], which may see the vision for domestic hydrogen isolated to just low-carbon heating. This is tenable given the lack of focus on cooking in the UK Hydrogen Strategy [43] and the scope of electric alternatives [348] such as induction hobs [349,350], which are currently taking an increased market share due to energy efficiency and safety benefits [350].

5.6. Diminishing socio-technical barriers through stakeholder symbiosis

Developing safe and efficient hydrogen production clusters, in sync with appliances for heating and cooking, necessitates a collaborative effort from government, industry, business, and other key stakeholders [37]. The potential for a national hydrogen economy will be strengthened if such actors can quickly coalesce around a shared set of aims and objectives to confront the socio-technical barriers outlined in this study. Internalizing and actualizing this approach are paramount to ensuring that the hydrogen transition can yield its potential net economic, social, and environmental benefits, while preserving fairness, equity, and safety throughout the process. Optimally, 'multi-regime interactions' [141,351], between the gas industry and the renewable energy sector could facilitate synergistic benefits through symbiosis, as both sides come to reap the mutual benefits of a national hydrogen economy. For such synergies to be realized, multiple barriers will need to be strategically and holistically addressed across the hydrogen supply chain.

In addition to diminishing techno-economic, technical, and market barriers, hydrogen acceptance calls for positive alignment between political and social factors, especially pertaining to issues of community acceptance. Confronting these barriers through the application of socio-technical systems thinking should translate to internalizing the importance of social acceptance, as it has been shown that consumer attitudes towards safety, the environment, costs, social fairness, and behavioral impacts may underpin the feasibility of the DHT. While it remains challenging to reliably forecast and quantify the economic costs of the hydrogen transition [155,206], UK policymakers should nevertheless ground their efforts in strengthening procedural and distributional justice throughout all stages of the transition to help realize 'hydrogen hopes for UK homes' [352].

6. Pathways to domestic hydrogen acceptance

As argued throughout this paper, the socio-technical feasibility of the DHT rests on overcoming multiple policy, techno-economic, technical, market, and social barriers. While all five dimensions are interconnected (see Fig. 7), Fig. 13 provides a clearer visual representation of how different socio-technical factors interact both within and across

[47] De-risking measures may include capital grants, feed-in-tariffs (FITs) and premiums, tax incentives, R&D funding, and loan guarantees [96].

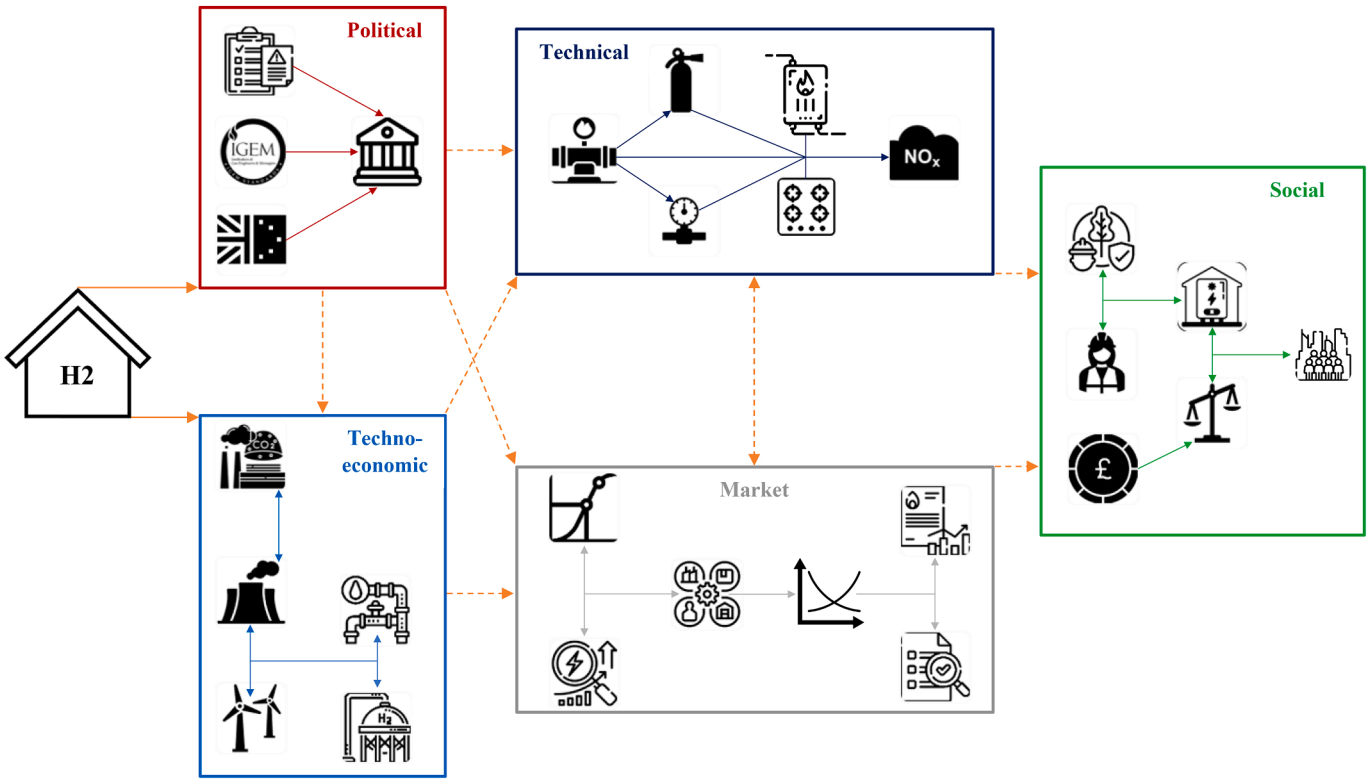


Fig. 13. Interactions between socio-technical dimensions and key factors for enabling domestic hydrogen futures.

Table 5
Key relationships between socio-technical factors within each dimension.

Socio-technical dimension	Summary of observed relationships within dimensions
Techno-economic	• Blue and green hydrogen resources and their respective production costs are interrelated to gas and electricity markets, with blue hydrogen and CCS sharing a direct interaction, which together shape the dynamics of hydrogen transport/transmission and storage (light blue box)
Technical	• The testing of hydrogen blending in existing pipeline infrastructure and optimally, construction of new hydrogen pipelines, advances the deployment of monitoring and metering equipment, and risk assessment practices, which is critical to developing safe, low-carbon hydrogen home appliances (dark blue box)
Political	• Regulatory frameworks based on codes and standards, as well as related international agreements, support legal pathways towards enabling the development of hydrogen projects (red box)
Market	• R&D into hydrogen technologies and parallel development towards higher TRLs support the building of corresponding supply chains and a hydrogen workforce; facilitating the conditions for market demand, as information and price transparency develop, alongside new methods of consumer billing for domestic hydrogen users (grey box)
Social	• Positive environmental and safety perceptions of hydrogen contribute towards behavioral acceptance, while distributional justice and cost factors further shape hydrogen acceptance at the national, community, and moreover, the household level (green box)

Table 6
Summary of interactions between political, market, and social factors.

Political	Market	Social
• A legal and regulatory regime for CCS incentivizes market investment in blue hydrogen projects, and related policy mechanisms (for blue and green hydrogen)	• Help reduce cost barriers and risk for investors • Provides a critical juncture towards building supply chains and a corresponding hydrogen labor force • Enables a consumer market for domestic hydrogen appliances	• Can help support a social acceptance through a just, low-carbon energy transition initiated around industrial towns
• Codes and standards facilitate a legal pathway towards hydrogen blending for short-term emissions reduction	• Hydrogen blending enables the demonstration and early commercial uptake of hydrogen home appliances, including new metering devices	• Can help can offset potential risks of low behavioral acceptance, while supporting social acceptance through positive safety and environmental perceptions

dimensions. Table 5 summarizes the observed relationships between the five dimensions, while Table 6 provides further examples of the interactions between soft barriers to the DHT (i.e. political, market, and social factors).

In the top half of Fig. 13, tackling political barriers (red box) helps overcome technical barriers (blue box), which is needed to enable positive public perceptions of key factors, such as hydrogen safety and environmental impacts (green box). In the bottom half, addressing techno-economic barriers (light blue box) is critical to scaling up the hydrogen supply chain and diminishing other key market barriers (grey box), which together shape important aspects of social acceptance, such as cost-competitiveness and energy justice (green box). Notably, the production costs of blue and green hydrogen will influence wider techno-economic feasibility (transport/transmission and storage), as well as technical feasibility in terms of safety levels, and perceptions thereof, which is a critical determinant of social acceptance.

The dashed orange lines depict the interactions between political,

technical, and social barriers (top half), and techno-economic, market and social barriers (bottom half), in addition to the following four relationships: (1) political factors influence techno-economic factors (red box to light blue box); (2) political factors influence market factors (red box to grey box); (3) techno-economic factors influence technical factors (light blue box to dark blue box); and finally, (4) technical and market factors interact bi-directionally (double-headed arrow between dark blue box and grey box). Taken together, political, techno-economic, technical, and market factors shape the configuration of social acceptance (green box), through a series of direct and indirect interactions.

7. Conclusions

To date, a limited number of studies have addressed specific dimensions of the DHT; rarely connecting the interactions between barriers to sustained political support, low-carbon production, cost factors, technical feasibility, technology innovation, market development, and social acceptance. In response, this analysis set out to enrich scientific and policy discussions around the role of hydrogen in the broader energy transition [38,125,353], through advancing both theoretical and empirical understanding on the topic.

As key stakeholders continue to shape the configuration of prospective hydrogen futures across different geographical scales, more integrated research efforts [354] are required to mobilize the power of multi-disciplinary insights [355], in alignment to the pressing need for an accelerated [356] and just energy transition [26,309]. By adopting a socio-technical transition framework – grounded in a multi-level approach – this paper has responded to the call for more holistic research on HESs [63,75], which is critical to comprehensively assessing barriers to the hydrogen economy [357]. Ultimately, this contribution reflects the need for multi-scalar, whole-systems thinking [358,359] to support robust energy governance for the DHT and the wider energy transition.

Section 3 provides the research community with a clear and comprehensive framework for engaging with socio-technical systems thinking in a more tangible way, which has been put into practice in Section 5. The findings affirm that the socio-technical feasibility of low-carbon energy transitions rests on overcoming hard and soft barriers in parallel [89,147], with the aim of coupling techno-economic feasibility [71] to social acceptance [132]. The pathways identified in Fig. 13 hold equally for several other emerging RESs and RETs, whereby effective policy mechanisms are needed to drive early upscaling and market formation; helping to facilitate business models and market acceptance towards an optimal balance between supply-push and demand-pull measures [360,361].

Importantly, observations presented within this analysis can provide critical lessons for developing HESs in other countries. The UK case study, through its twin-track context, can help accelerate the learning curve for other nations that are potentially well-suited to pursuing a blue hydrogen pathway due to aging natural gas infrastructure, such as the Netherlands [362] and Italy [363]. Similarly, European nations with stronger prospects for green hydrogen such as France [364], Germany [302], and Spain [365] can take stock of the identified barriers to scaling up electrolysis production, and related challenges around the green hydrogen supply chain [366]. In either scenario, where feasible, governments must seek pathways to accelerating the pace and scale of domestic hydrogen production, infrastructure development, and demonstration projects, while also engaging the public in developments around these activities.

The study has also drawn significant attention to the conundrum around hydrogen storage, which is often overlooked in discussion around production targets. By accounting for the wider aspects of the techno-economic dimension, policymakers yet to launch their national hydrogen strategies can (re-)evaluate their country's respective potential for developing a hydrogen economy, and what configuration (sectors and scale) and color (blue, green, or other) this may entail. Other key players shaping the prospective global hydrogen economy – including frontrunner countries that otherwise dwarf the UK such as Australia and Canada – can likewise benefit from adopting a multi-level and whole-systems approach when assessing the viability of hydrogen for domestic decarbonization and other uses across different regions [73,367], which may include industrial clusters, urban areas, and off-grid locations.

Finally, many of the findings presented here are directly transferable to other emerging low-carbon energy sources and technologies. For example, the market for domestic micro-generation technolgies [370,371] such as heat pumps [368,369], as well as energy storage technologies [372,373] and innovative energy services (IES) [381], face many of the same barriers discussed throughout this paper [368,369].[48] Acceleration the market diffusion of heat pumps is crucial to the UK's decarbonization agenda; reflected by a national target of 600,000 installations per year by 2028, equivalent to a 20-fold increase compared to installations in 2019 [44]. While the UK is a notable laggard in heat pump adoption, parts of Europe face similar hurdles to increasing the market penetration of heat pumps, as well as solar photovoltaic (PV) panels [374]. Given the fundamental importance of UHS to the fulfilment of national hydrogen strategies [383,384], it is also evident that identified barriers and risks will apply to different extents for other subsurface activities linked to heat decarbonization, such as geothermal energy [375,376], and as previously discussed, CCS.

7.1. Limitations of study and future research agenda

Energy scholars can build on this analysis by testing the proposed framework in different national contexts, as well as other sectors of the hydrogen economy. To proceed with this task, it is important to first recognize the limitations of the study, which also helps identify areas for future research. As discussed in Section 2, one notable drawback is the lack of academic studies on soft barriers to the DHT, especially political and market barriers. Encouragingly, research on the social acceptance dimension is on the rise, although public and consumer awareness remain largely overlooked in the UK Hydrogen Strategy.[49] Relatedly, the review of market barriers in Section 4.4 draws partly on the 2016 report prepared for the Department of Energy & Climate Change (DECC)[50] [112], which is now somewhat outdated given the recent proliferation around hydrogen. In response, a similar study engaging with appliance manufacturers and trades bodies should be undertaken to reassess stakeholders' perspectives. Beyond some limitations related to the literature review materials, this paper lacks a significant contribution in, at least, the following three areas:

- While the UK Hydrogen Strategy frames much of the discussion, this study does not provide a one-to-one analysis to measure the extent to which different barriers have been engaged with by policymakers to date.
- The spatial dynamics of the hydrogen transition are acknowledged, but no in-depth analysis is provided to flesh out key implications based on primary data, such as geospatial maps and regional census statistics.
- Although the importance of environmental impacts is highlighted in several places, there is limited comparative evidence presented to better contextualize the implications of different hydrogen production pathways.

In addition to addressing these limitations, moving forward, researchers should aim to advance knowledge on at least four important

[48] See Fig. 6 in [368] for a visualization of barriers to heat pump deployment.
[49] The topic is discussed briefly in Section 2.5.3 of the strategy.
[50] Merged with the Department for Business, Energy & Industrial Strategy (BEIS) in 2016.

aspects of the socio-technical transition to domestic hydrogen:

(1) Distilling how barriers to respective hydrogen production pathways (e.g. blue and green hydrogen in the UK) can be tackled in a holistic way that promotes synergies which yield net benefits for the hydrogen economy and society.
(2) Mapping interactions between socio-technical factors and key actors to understand HETs at a whole-systems level [382], which is critical to facilitating stakeholder symbiosis.
(3) Examining the potential convergence and divergence of decarbonization pathways for heating and cooking according to space, scale, and geography [377,378], and how this configuration may (re-)define the concept of a hydrogen home.
(4) Conducting comparative cross-country studies of socio-technical barriers to gauge how international hydrogen backbones can be established and consolidated, especially in view of the current geopolitical landscape around natural gas supplies [379].

This final objective is a clear by-product of advancing knowledge on the first three fronts. It presupposes that comparative research will first be carried at the national level, for example, across different UK industrial clusters. In view of the emerging 'techno-socio-economy nexus' for HESs [380], international case studies should become a clear focal point for energy transition scholars and the wider research community.

This study was motivated to engage energy transition scholars, hydrogen experts, and policymakers interested in the socio-technical parameters of the DHT and broader hydrogen economy. As HESs continue to be re-envisioned by technologists, scientists, and other parts of society, all sides of the actor-network must learn from the past to ensure that this era makes the 'true dawn' of the global hydrogen economy. Above all, realizing domestic hydrogen futures will require a radical repurposing of pipelines, policies, and public perceptions.

CRediT authorship contribution statement

Joel A. Gordon: Conceptualization, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualization, Writing – review & editing, Supervision. **Seyed Ali Nabavi:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary material

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Socio-technical barriers to domestic hydrogen futures: repurposing pipelines, policies, and public perceptions

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