ISSN 2004-2965 Energy Proceedings, Vol. 18, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 2, 2021, in Bangkok, Thailand
Paper ID: 760

Hydrogen Hopes for UK Homes? A Theoretical Approach to Breakdown Sociotechnical Barriers

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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. At the national level, hydrogen can help mitigate the carbon footprint of the residential sector, especially in countries historically reliant on natural gas for heating and cooking. Despite cause for optimism, the domestic hydrogen transition faces multiple barriers, which reflect the broader challenges of deploying hydrogen technologies at scale across the industrial, commercial, and residential sectors. However, to date, scholars have scarcely examined how barriers such as safety, costs, and regulation may converge and interact. This deficit is especially pronounced in the case of Hydrogen Homes (HHs), which has a brief research history limited mostly to the UK context. Adopting a sociotechnical transition approach grounded in multi-level thinking, this paper proposes a theoretical framework for addressing the multi-dimensional challenges of the domestic hydrogen transition. Applying this framework to the UK context, this paper highlights distinct interrelationships that cut across sociotechnical dimensions, which will need to be confronted if 'hydrogen hopes' are to be realized.

Keywords: Domestic hydrogen, hydrogen-fueled appliances, Multi-Level Perspective, sociotechnical systems, sociotechnical barriers, hydrogen transition

NOMENCLATURE

Abbreviations	
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
CH_4	Methane
CO_2	Carbon dioxide
EU	European Union
GAD/GAR	Gas Appliances Directive/Gas Appliances Regulation
GHG	Greenhouse gas
GS(M)R	Gas Safety (Management) Regulations
GW	Gigawatt
IEA	International Energy Agency
IED	Industrial Emissions Directive
IRENA	International Renewable Energy Agency
HESs	Hydrogen Energy Systems
HHs	Hydrogen Homes
HyLAW	Hydrogen Law and removal of legal barriers to the deployment of fuel cells and hydrogen applications.
LTS	Local Transmission System
MLP	Multi-Level Perspective
$MtCO_2$	Metric tons of carbon dioxide
NTS	National Transmission System
RETs	Renewable energy technologies
R&D	Research and Development
SMR	Steam Methane Reformation
TWh	Terawatt hour
UKCS	UK Continental Shelf

1. INTRODUCTION

Despite multiple driving forces aligned to climate mitigation and energy security [1,2], the hydrogen revolution has lagged for decades [3]. Hydrogen's

Selection and peer-review under responsibility of the scientific committee of the 13th Int. Conf. on Applied Energy (ICAE2021).

shortcomings as a commercial energy carrier [4,5] 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 [6]. However, as discussed here, there are multiple barriers to the realization of a full-scale hydrogen economy. Although setbacks and barriers to commercialization persist [7], hydrogen has been increasingly recognized as a key pillar of the energy transition [8], leading to a wave of recent investments and a pipeline of global projects [9,10]. Specifically, the use of hydrogen-fueled appliances for domestic space heating, hot water, and cooking [11] is regarded as critical to achieving 'deep' decarbonization in countries with extensive natural gas infrastructure and consumption such as the UK [6,12].

Despite the imperative to decarbonize, potential barriers to the domestic transition remain poorly examined with research efforts largely constrained to the UK context [11,13–17]. Foremost, there remains an underlying knowledge gap regarding the interactions between respective sociotechnical barriers and their contribution to facilitating the deployment of HHs.

Against this backdrop, this study develops a theoretical framework for addressing the multi-level and multi-scalar challenges of the domestic hydrogen transition. To the authors' knowledge, this marks the first attempt to conceptualize the domestic hydrogen transition as a multi-level phenomenon; characterized by complex interactions between multiple sociotechnical barriers which operate across the macro-, meso-, and micro-scales, reflected by impacts at the international, national, regional, and local levels. In doing so, this analysis advances both the theoretical and practical understanding of prospective 'hydrogen futures' [18]; enriching scholarly and policy discussions around HHs as part of the wider energy transitions discourse [19,20].

2. MATERIAL AND METHODS

This paper draws on evidence from a range of sources including academic papers, technical reports, government documents, and survey studies in the grey literature to establish a theoretical framework (see Fig. 1.). Firstly, sociotechnical barriers to the hydrogen economy are identified through an in-depth literature review of academic studies spanning more than a decade [1,6,18,21–25]. The early work of McDowall and Eames including their seminal piece [18] provides a starting point for engaging with the topic; supported by several follow-up studies from the same authors and other pioneers of hydrogen research [26]. Through this snowballing approach, a critical review and synthesis of barriers to the wider hydrogen economy paves the way for understanding the case of HHs. These findings provide the theoretical lens for systematically examining the challenges of deploying HHs at scale according to the interactions between five distinct barrier types: technoeconomic, technical, political, market, and social barriers.

Technoeconomic barriers involve 'energy flows' related to developments around resources and infrastructure [27], which following Crisan and Kuhn [28] represent the "hardware" of the hydrogen transition. Addressing this dimension, this article draws on several studies in the International Journal of Hydrogen Energy which have analyzed data on alternative hydrogen production pathways [1,29–33]. Alongside other findings from the academic literature [34–36], evidence is reviewed from the International Renewable Energy Agency (IRENA) [37–39] and International Energy Agency (IEA) [40,41], together with analysis conducted by governmental agencies [12,16,42–44], the gas industry [15,53], and other key stakeholder groups [46–48].

Technical barriers primarily concern safety issues; investigated according to scientific findings on the impacts of injecting hydrogen into existing gas pipelines [49–52], and the results of experimental tests on representative natural gas cooktop burners running on hydrogen blends [53–55]. Additional technical barriers are reviewed based on international evidence [34,50,56,57] and UK studies [16,58].

The literature on 'sociotechnical futures' [59,60] recognizes the governance of sociotechnical systems as inherently political [27,60], with 'energy futures' examined through a multi-level governance perspective [61,62]. To unpack political barriers, the paper reviews the HyLAW project [63] which aims to reduce regulatory, legal, and administrative barriers to the development of a European hydrogen economy. Specifically, the HyLAW UK National Policy Paper [64] contextualizes the challenges associated with the current regulatory framework, or lack thereof, for hydrogen gas.

A wide range of barriers impact the 'technology readiness', 'market penetration' and 'market growth' of domestic hydrogen [39], which can also be viewed through the lens of barriers to market entry, development, and support [16]. Extensive analysis of both political and market barriers has been undertaken by gauging the perspective of UK manufacturers and trade bodies [16], in addition to work carried out by Policy Exchange, the UK's leading think tank [47].

Finally, accounting for social barriers reflects a growing consensus that social acceptance is a precondition for the successful deployment of low-carbon energy technologies [19,65–68]. Social barriers are reviewed based on surveys and interviews, which have examined the public's knowledge, awareness, and perceptions of hydrogen, and resultant attitudes towards the advent of HHs in the UK [11,13–15,69,70] and Australia [71,72]. Given that research on domestic hydrogen acceptance has a brief history, insights are also gauged from the wider literature on Hydrogen Energy Systems (HESs) [73], principally on public attitudes towards hydrogen transportation [74–76].

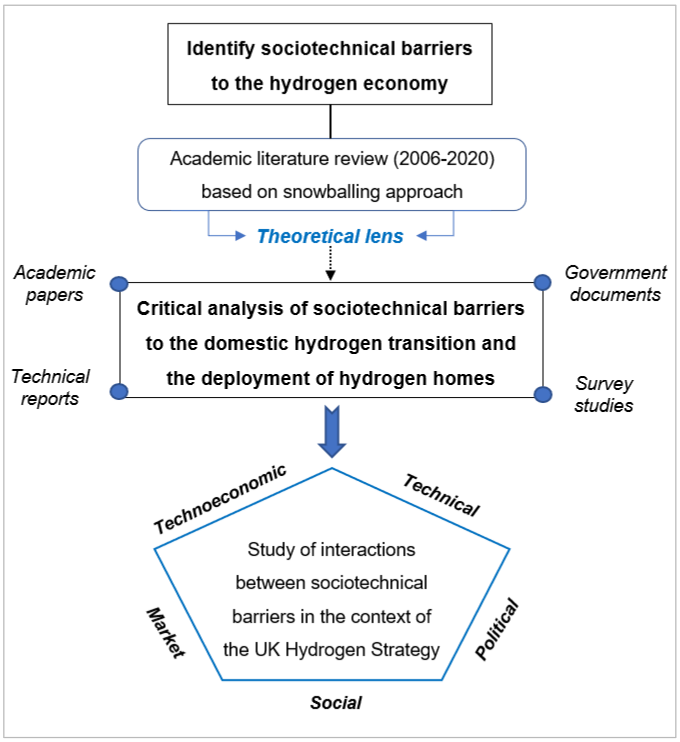

Fig. 1. Research Procedure and methodology

3. CALCULATION

Sociotechnical systems develop through multi-decadal processes [77,78] taking shape through the coevolution of a mix of interdependent technologies, infrastructures, institutions, policies, markets, supply chains, user practices, and cultural meanings [79–81]. Grounded in sociotechnical systems thinking [82,83], Geels [82] advocated for a 'Multi-Level Perspective' (MLP) to examine the emergence of such systems, drawing on insights from divergent fields such as sociology, institutional theory, and innovation studies. The MLP characterizes sustainability transitions are 'non-linear' and 'complex' events; shaped by interactions between technological, political, institutional, economic, and sociocultural dimensions, and through interrelationships between multiple actors [84].

Reviewing the state of the 'hydrogen futures' literature in the early 2000s, McDowall and Eames [18] highlighted a research gap regarding the sociotechnical dynamics of the hydrogen transition, owing to an underlying deficit in existing theoretical approaches. While some studies have discussed the challenges associated with developing a global or national hydrogen economy [21–23,39,85], there remain inconsistencies or even explicit absence regarding the breakdown of sociotechnical barriers [18]. Dissecting sociotechnical barriers is essential for supporting the diffusion of renewable energy technologies (RETs) through effective policymaking [86,87].

A handful of studies have partly addressed this theoretical gap in the context of hydrogen technologies [2,24,25,88,89], however, most of the focus has centered on transport and infrastructure [11,71]. Consequently, exploration of sociotechnical barriers to the deployment of HHs [15,71] remains significantly underrepresented in the energy transitions literature. In response, this study theorizes that hydrogen futures should be examined through a sociotechnical transition framework [27,86,90] grounded in a multi-level approach [84].

Following the method outlined in Section 2, a sociotechnical transition framework is proposed (see Fig. 2.) to capture the complexity and multi-dimensionality of the hydrogen transition; derived according to identified technoeconomic [1,5,6,18,22,33,91–93], technical [1,7,18,21,39], political [1,18,23,38,39], market [5,18,21,23,39], and social [18,21,23] barriers to developing hydrogen technologies.

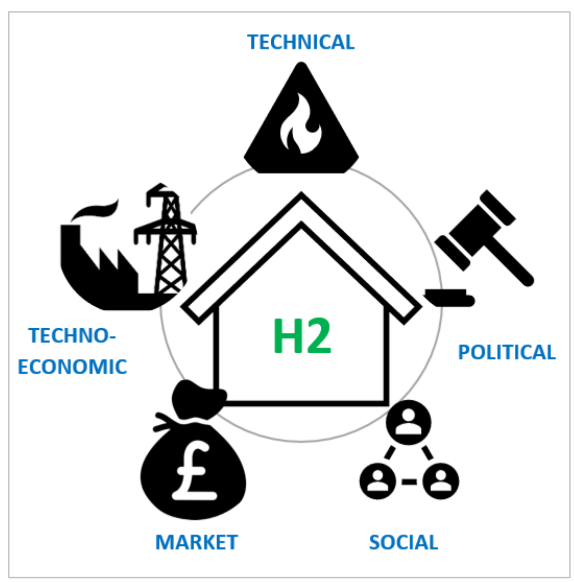

Fig. 2. The five pillars of the sociotechnical transition framework for Hydrogen Homes

4. RESULTS

4.1 Sociotechnical barriers to Hydrogen Homes

Realizing a national energy transition to HHs will require the breakdown and alignment of sociotechnical factors in support of domestic hydrogen acceptance. Based on a case study of HHs in the UK, the following definitions have been formulated to represent the proposed framework:

(1) **Technoeconomic barriers** concerning the development of hydrogen infrastructures and domestic hydrogen appliances, resource availability, investment and cost factors.
(2) **Technical barriers** defined by the safety, efficiency, reliability, and overall performance of hydrogen fuel and domestic hydrogen appliances.
(3) **Political barriers** associated with policy measures, regulatory frameworks, legislation, administrative procedures, stakeholder engagement, and informational flows regarding the domestic hydrogen transition.
(4) **Market barriers** focused on the implications of supply and demand dynamics, availability of skilled labor, market competition, brand loyalty, technology innovation, hydrogen trials and demonstrations, and project management.
(5) **Social barriers** determined by how public awareness and knowledge of hydrogen may influence perceptions and attitudes towards the transition in relation to safety, the environment, costs, social fairness, and behavioral impacts.

4.2 Hydrogen hopes for UK homes

4.2.1 Technoeconomic barriers

The technoeconomic feasibility of constructing hydrogen pipelines is inferior to conventional gas pipelines since the former span about 5,000 km globally compared to 3,000,000 for the latter [39]. Beyond this clear limitation, evidence suggest that the capital, material, and labor costs of hydrogen pipelines will exceed that of methane (CH_4) and carbon dioxide (CO_2) [31,52,94,95]. Although estimates remain tentative [34], the UK government forecasts that the costs of producing and storing large-scale hydrogen are likely to be very substantial, with hydrogen production potentially increasing the annual costs of heating by around £4 billion [12].

The feasibility of building a national hydrogen economy based on Steam Methane Reformation (SMR) combined with Carbon Capture and Storage (CCS) [44,96] is constrained by the progressive depletion of domestic gas reserves in the UK Continental Shelf (UKCS) [97], as reflected by the country's status as a net importer of energy since 2004 [98]. The supply-side demands for developing the country's 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 [99].

Given the UK's comparatively low potential for developing solar power [100], overreliance on offshore wind power may jeopardize the potential for scaling up a green hydrogen production base in proximity to coastal, industrial clusters [101,102]. While more attractive from an environmental perspective, there are also multiple barriers to scaling up electrolytic hydrogen due to high production costs, lack of value recognition, energy losses, and challenges to ensuring sustainability [37].

4.2.2 Technical barriers

A basic tenet of the transition is that 100% conversion to hydrogen networks should ensure at least the same safety levels as natural gas use, however, scientific knowledge on the risks of domestic hydrogen remains low in comparison to natural gas [26]. At present, there is still uncertainty over whether the UK's National Transmission System (NTS) and Local Transmission System (LTS) will be compatible for transporting and distributing 100% hydrogen [17,58]. Furthermore, blending hydrogen into existing pipelines leads to a lower mass flow rate, resulting in less transmitted energy [50]. Additional technical barriers include the need to change measuring instruments, control stations, and compressors [57]. For example, smaller gas meters are required to accommodate hydrogen's volumetric flow rate, while different valves are needed to prevent excess hydrogen flow [16].

Safety measures will be significantly harder to secure for domestic hydrogen appliances compared to industrial applications [56,103]. Hazards and risks are a product of hydrogen's unique physical and chemical characteristics, which engender distinct threats to public safety [11]. At present, explosive risks [104] remain inadequately addressed [11] regarding hydrogen's near-invisible flame [51], and higher flame speed [105] and adiabatic flame temperature than natural gas [106,107].

4.2.3 Political barriers

The flagship HyLAW project identified multiple regulatory, legal, and administrative barriers constraining the development of a hydrogen economy [64]. The UK regulatory framework for the gas industry rests on key legislation passed in 1996, which limits the threshold of hydrogen gas in pipelines to 0.1%vol [64], compared to 6% in France and 1–5% in some other European countries [108,109]. The study also highlighted the case of Scotland as a "regulatory anomaly" since hydrogen production at any scale is categorized as an 'Industrial Activity', adhering to the requirements of the EU Industrial Emissions Directive (IED) [64]. Since National land use planning is uniform for hydrogen production, local producers in Scotland may face unacceptable planning and consent risks, which could prohibit the deployment of small-scale generation sites for electrolysis [64].

The lack of a harmonized policy and regulatory framework between the UK and European Union (EU) [64] may hinder efforts to position Europe at the center of the global hydrogen economy [110,111], while hampering the UK's quest to reap economic benefits as a first mover [112].

4.2.4 Market barriers

It is anticipated that the costs of research and development (R&D), product design, and initial manufacturing for hydrogen appliances will exceed the costs of natural gas appliances [16], creating significant barriers to market entry. Furthermore, there is an information gap concerning the market demands (e.g. gas quality, appliance outputs, thermal efficiency and NOx requirements) for hydrogen appliances [16], which is compounded by the need to adjust manufacturing warranties [47]. Additional market barriers to the deployment of HHs in the UK include deficits across the following areas: financing mechanisms to incentive investment; R&D capacity; supply of skilled labor; appliance manufacturers or business models to support bulk sales; sales and distribution channels; demand for hydrogen appliances; codes and standards for hydrogen boilers; and demonstration projects [16].

Prospects for market growth will remain bleak until a market pull is established to create supply chains and prevent bottlenecks; together with transparent training mechanisms to build a skilled workforce for installing and maintaining hydrogen appliances [16]. By the same token, leading boiler manufacturers will need to align their goals [113] to promote brand loyalty and customer buy-in for hydrogen appliances, as opposed to low-carbon alternatives such as heat pumps.

4.2.5 Social barriers

Mixed methods studies on public perceptions of domestic hydrogen [11,13–15,69–72] indicate that social acceptance may rest on consumer attitudes towards safety, the environment, costs, social fairness, and behavioral impacts. However, perceptions may be based largely on misconceptions due to an underlying lack of knowledge and awareness regarding hydrogen technologies [75,114–118].

Questioning the public about the impacts of hydrogen blending, Scott and Powells [14] found that 69% of online survey respondents envisaged no significant impact on domestic safety, while 35% of paper survey respondents reported positive impacts. In some cases, consumers may have greater concerns about the safety of CCS than hydrogen [119,120].

Evidence suggests that renewable-based hydrogen generation is likely to secure stronger public support than fossil-fuel or nuclear based production methods [14,121]. It follows that non-renewable production pathways may pose a barrier to acceptance, particularly for citizens with strong environmental values [71,121].

Economic concerns include the purchase, running, and maintenance costs of hydrogen appliances [14,15,72], and potential impacts of the switchover on employment, income, property values and rents [15]. Affordability may present the greatest hurdle to social acceptance at the household level [11,14,69], while UK public appears to perceive the impact of domestic hydrogen on the economy to be either neutral or positive [14]. Consumers also recognize the importance of making provisions for vulnerable households [13], especially during the switchover period which could see households disconnected from the gas grid for several days [15,119]. The public is also concerned about the risk of low-income households becoming further disenfranchised if hydrogen adds to energy bills [69].

Finally, the behavioral impacts of hydrogen appliances may prove more pronounced for cooking, since the 'socio-material nature' of cooking practices is more 'visible' and 'foregrounded' compared to heating practices [11]. Overall, consumers are mostly concerned that hydrogen appliances will deliver the same heating and cooking experience as natural gas in terms of functionality, appearance, and maintenance requirements [15] without compromising safety [11,14].

5. DISCUSSION

The proposed theoretical framework for examining barriers to the domestic hydrogen transition is based on the premise that sociotechnical systems entail coevolving dynamics between technology and society [82]; accounting for the critical role of end-users in shaping this coevolution [27,86,90,122–124]. Given this dynamism, there are multiple ways in which identified barriers may interact and evolve.

In respect to technoeconomic factors, the UK's 'blue' hydrogen pathway (via SMR+CCUS) faces a supply deficit which may need to be filled by increasing natural gas imports. If pursued as currently envisioned in the UK Hydrogen Strategy [42], this pathway could expose consumers to commodity price fluctuations and higher energy prices due to increased production costs. The UK already faces a growing fuel poverty crisis, 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. At the same time, the safe capture and sequestration of carbon should also be proven to avoid the risk of public opposition and costly delays [13,119], highlighting the importance of "cross sector technology interactions" [125] and community acceptance.

The economics of hydrogen production are strongly linked to the costs of electricity and gas, and key technical parameters impacting these costs such as conversion efficiencies [40]. This interaction between "economic viability and technical effectiveness" [92] dictates the feasibility of diffusing HHs into the UK housing stock 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 HHs lies with developing codes and standards to accommodate higher volumes of hydrogen in UK gas networks, in addition to standards for the design and development of hydrogen appliances. A national regulatory framework, as well as international agreement around codes and standards, is needed to support market development and best practices for hydrogen safety.

Breaking down political barriers is further required to accelerate cost reductions for producers and consumers through learning-by-doing and a more liquid global market for hydrogen [39]. 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, alongside information campaigns targeted at local officials, stakeholders, and consumers. Hydrogen acceptance also calls for the positive alignment of sociopolitical factors linked to energy justice. UK policymakers should ground their efforts in strengthening procedural and distributional justice throughout all stages of the transition to strengthen 'hydrogen hopes' for UK homes.

Ultimately, efforts to develop safe and efficient hydrogen production clusters and appliances for heating and cooking – yielding net economic, social, and environmental benefits – will be enhanced if government, industry, business, academia, and other key stakeholders can quickly coalesce around a shared set of aims and objectives to confront the sociotechnical barriers discussed here.

6. CONCLUSIONS

This study marks the first explicit contribution to stimulating a much-needed discussion around the interaction of technoeconomic, technical, political, market, and social challenges to the deployment of HHs. By adopting a sociotechnical transition framework grounded in a multi-level approach, this paper has responded to the call for more multi-disciplinary research on hydrogen [100]. Drawing on the foundations of the MLP, the proposed theoretical framework reflects the need for multi-scalar, whole-systems thinking [135,136] to support robust policymaking for the domestic hydrogen transition.

This study has reinforced the need for more integrated research efforts [137] – mobilizing the power of multi-disciplinary insights [138] – to align the deployment of HHs with the pressing need for an accelerated [139] and 'just' energy transition [140]. Ultimately, to strengthen current industry and policy hopes for hydrogen in UK homes, researchers should engage with key barriers through the application of sociotechnical systems thinking. This approach should internalize the importance of social acceptance to the transition, as it has been shown that consumer attitudes towards safety, the environment, costs, social fairness, and behavioral impacts may underpin the feasibility of domestic hydrogen adoption.

ACKNOWLEDGEMENT

This research was supported by the Engineering and Physical Sciences Research Council (EPSRC) Grant EP/T518104/1, and Cadent Gas Ltd.

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