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Beyond the triangle of renewable energy acceptance: The five dimensions of domestic hydrogen acceptance

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HIGHLIGHTS

- Social acceptance research should be critical, systematic, and holistic.
- Domestic hydrogen acceptance is shaped by the interplay of five distinct dimensions.
- Hydrogen acceptance hinges on cognitive, sociopolitical, and sociocultural legitimacy.
- Hydrogen acceptance is composed of a rich matrix of potential consumer responses.
- Overcoming attitudinal and behavioral barriers is critical to the hydrogen transition.

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ABSTRACT

The 'deep' decarbonization of the residential sector is a priority for meeting national climate change targets, especially in countries such as the UK where natural gas has been the dominant fuel source for over half a century. Hydrogen blending and repurposing the national grid to supply low-carbon hydrogen gas may offer respective short- and long-term solutions to achieving emissions reduction across parts of the housing sector. Despite this imperative, the social acceptance of domestic hydrogen energy technologies remains underexplored by sustainability scholars, with limited insights regarding consumer perceptions and expectations of the transition. A knowledge deficit of this magnitude is likely to hinder effective policymaking and may result in suboptimal rollout strategies that derail the trajectory of the net zero agenda. Addressing this knowledge gap, this study develops a conceptual framework for examining the consumer-facing side of the hydrogen transition. The paper affirms that the spatiotemporal patterns of renewable energy adoption are shaped by a range of interacting scales, dimensions, and factors. The UK's emerging hydrogen landscape and its actor-network is characterized as a heterogenous system, composed of dynamic relationships and interdependencies. Future studies should engage with domestic hydrogen acceptance as a co-evolving, multi-scalar phenomenon rooted in the interplay of five distinct dimensions: attitudinal, sociopolitical, community, market, and behavioral acceptance. If arrived to, behavioral acceptance helps realize the domestication of hydrogen heating and cooking, established on grounds on cognitive, sociopolitical, and sociocultural legitimacy. The research community should internalize the complexity and richness of consumer attitudes and responses, through a more critical and reflexive approach to the study of social acceptance.

1. Introduction

In 1970, Professor John Bockris introduced the term 'hydrogen economy' [1] to describe "a system of industry, transportation, and household energy" based on piped hydrogen fuel [2]. In a 'post-Paris Agreement' world [3], there is renewed interest in realizing this vision following the launch of hydrogen strategies across parts of Europe, Asia, America, and Oceania [4]. Hydrogen is attracting attention from policymakers due to its promise of delivering synergies with other low-carbon technologies for mitigating climate change [5,6]. In response, some nations are already engaging in 'hydrogen diplomacy' [7], while energy modelers are intensifying efforts to map the "feasibility space" [8] of hydrogen systems [9,10]. Notably, low-carbon hydrogen could help contribute to the 'deep' decarbonization of residential heating. Reducing global carbon emissions from this sector is critical to the

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Nomenclature

ANT	Actor-Network Theory
ASHP	Air source heat pump
BEIS	Department for Business, Energy & Industrial Strategy
CCC	Committee on Climate Change
CCUS	Carbon capture, utilization and storage
CBM	Contingent Valuation Method
CBA	Cost-Benefit Analysis
DESs	Distributed energy systems
EJM	Energy Justice Metric
EU	European Union
FCEVs	Fuel Cell Electric Vehicles
GDNs	Gas Distribution Networks
GHG	Greenhouse Gas
GSHP	Ground-source heat pump
GW	Gigawatt
HETs	Hydrogen Energy Technologies
HHP	Hybrid heat pump
HSE	Health & Safety Executive
IEA	International Energy Agency
LADs	Local Authority Districts
LPG	Liquified petroleum gas
MLP	Multi-Level Perspective
NIA	Network Innovation Allowance
NIC	Network Innovation Competition
NIMBY	Not In My Back Yard
NGO	Non-governmental Organization
NGN	Northern Gas Networks
NZHF	Net Zero Hydrogen Fund
Ofgem	Office of Gas and Electricity Markets
PEM	Proton Exchange Membrane
R&D	Research and Development
RETs	Renewable Energy Technologies
SMR	Steam Methane Reformation
SPT	Social Practice Theory
SRP	Social Representations Theory
SST	Social Shaping of Technology
STS	Science and Technology Studies
SDGs	Sustainable Development Goals
TPB	Theory of Planned Behavior
TWh	Terawatt hour
WTP	Willingness-to-Pay

climate change effort [11,12] and already a priority for meeting European targets [13]. In response, recent forecasts from the International Energy Agency (IEA) [12,14,15] and other reports [16–18] include a potential role for hydrogen in the global buildings sector [14].[1] Moreover, alongside the European Union (EU), countries such as Japan, Australia, Germany, the Netherlands, and UK foresee a role for low-carbon hydrogen in domestic heating [15,18,20,21], with parallel interest in hydrogen appliances for cooking [22–25].

Hydrogen has become a focal point of UK energy policy [26–29], given that the country has an ageing housing stock with a poor efficiency performance by European standards [30]. Compared to countries such as Germany [31], the UK has made limited progress in retrofitting homes with poor thermal performance, due to the failure of a number of policy initiatives including the Green Deal [32]. Although the UK power sector has undergone rapid decarbonization following the phase out of coal and the scaling up of wind energy and other renewables, the residential sector has seen only minimal reductions in greenhouse gas (GHG) emissions over the last three decades [33]. In response, the Committee on Climate Change (CCC) has stated that "coordinated central decisions must be taken on the balance between electrification and hydrogen" [34].

Following the government's renewed commitment to reach 'net-zero' by 2050[2] and a more ambitious target to curb GHG emissions 78 % by 2035 [36], there has been growing policy interest in repurposing the UK's national gas grid to hydrogen [37]. Supported by a £240 million Net Zero Hydrogen Fund (NZHF), the UK Hydrogen Strategy announced a roadmap: a 'Hydrogen Neighborhood' by 2023; a village trial by 2025; scaling up to a 'Hydrogen Town' before the end of the decade [26]. The UK is seeking a front runner position through its 'twin-track' strategy, which supports both electrolytic ('green') and carbon-capture (CCUS)-enabled (blue) hydrogen production, with growing intertest in other potential production pathways [26]. In turn, investments in research and development (R&D) activities are scaling up to support this policy push towards a national hydrogen economy [38]. Moreover, the British Energy Security Strategy recently doubled the low-carbon hydrogen production target to 10GW by 2030, affirming a commitment to at least 50 % electrolytic hydrogen [28].[3]

Despite increased interest from the gas industry in (re-)introducing[4] hydrogen-fueled appliances to UK homes for heating and cooking purposes [42] and strong signals of political commitment towards this pathway [28], there is limited data on whether the public would support this decision and accept the switchover [43]. Public perceptions cannot be overlooked since it has been demonstrated that in addition to techno-economic, socio-technical, and political factors [44], socio-cultural factors may prove equally critical to achieving national energy transitions and climate change targets [45]. As technological innovation has accelerated, social and behavioral scientists have increasingly focused on understanding the factors that shape social acceptance [46–48]. In parallel, case studies of historical and emerging national energy transitions [49–51] have demonstrated the importance of social acceptance for supporting effective policies and strategies [48,52] to help accelerate the uptake of renewable energy technologies (RETs) [41]. As global renewable energy deployment has scaled up [53], such perspectives caution against viewing the energy transition narrowly as a "function of technological optimization and economic feasibility" [54]. In response, social acceptance is widely viewed as a "prerequisite for the adoption and introduction of new technologies" [55]. Notably, Australia's National Hydrogen Strategy [56] highlights the need to prioritize "socially responsible practices and policies" [57] and community acceptance [58]. It follows that understanding the "human dimension" of the hydrogen transition is critical to driving the large-scale adoption of hydrogen home appliances [59]. Arguably, social acceptance may present the greatest barrier to developing national hydrogen economies [60].

Despite some advancement towards more critical research approaches [61], the 'social acceptance matrix' [62,63] of domestic hydrogen – the configuration of potential consumer responses [61,64] to

[1] For example, under a scenario where 30% hydrogen is blended into city gas, Chapman et al. [19] estimate that hydrogen could account for 2% of global energy consumption.

[2] The Climate Change Act 2008 (2050 Target Amendment) Order 2019 [35].

[3] The UK's Gigastack project is currently the largest planned electrolyzer factory in the world [39,40].

[4] Before natural gas became commonly used in the UK after the mid-1970s, the main gas used in homes and businesses was a manufactured mixture called town gas, composed of coal and up to 50% hydrogen [41].

the proposition of 'hydrogen homes' [43,65] – remains underexplored in the literature.[5] In part, this is due to the nascency of the technology, reflected by only a handful of available studies in the academic [22,42,66–69] or grey literature [23,41,57,59,70–75]. Moreover, this deficit reflects how scholarship on the social acceptance of RETs is yet to evolve into a coherent, multi-dimensional body of research [76]. The lack of coherence and integration regarding the development of social acceptance frameworks [76] is especially pronounced for emerging energy technologies, such as distributed energy systems (DESs) [54,77] and hydrogen-fueled appliances for the home (i.e. boilers, fires, hobs, and ovens) [38]. In view of this knowledge gap, this study constructs a conceptual framework for examining the consumer side of the domestic energy transition by applying 'critical approaches' [61] to the study of domestic hydrogen acceptance. In doing so, three research questions are tackled:

- What is the current state of research on the social acceptance of the RETs?
- What are the main factors underpinning the social acceptance of domestic hydrogen in the UK?
- What are the conceptual dynamics of domestic hydrogen acceptance?

Following this introduction (Section 1), the study follows the structure illustrated in Fig. 1. Section 2 further contextualizes the study through a review of critical junctures in the field of Science and Technology Studies (STS), which have contributed towards "three waves" of social acceptance research [61]. Following Batel [61], Section 3 systemically reviews each wave of social acceptance research, spanning normative, criticism, and critical approaches, respectively. Next, Sections 4.1 and 4.2 examine the social acceptance of hydrogen energy technologies (HETs), leading to the more in-depth focus on domestic hydrogen acceptance in Section 4.3. Drawing on the findings, Section 5 presents a novel conceptual framework for exploring domestic hydrogen acceptance through five distinct dimensions. Finally, Section 6 provides recommendations from the research and concluding remarks.

2. The human factor in household energy adoption

During an influential period in the development of Science and Technology Studies (STS), the Social Shaping of Technology (SST) framework [78,79] argued that technological design and implementation [80] are shaped by "social processes, actions, and structures" [81]. Coinciding with this framework, sociologists began to explore how processes of innovation and knowledge diffusion could be understood through the lens of Actor-Network Theory (ANT) [82,83]. Notably, this approach has helped advance the study of energy transitions [84,85]. Early STS research revealed the importance of macro socio-economic forces and actor-networks in shaping technology deployment, and the role of consumers as technology adopters. In turn, scholars posited how technology is a cultural phenomenon subject to social appropriation, yet firmly rooted in political and economic ideologies [78]. Accordingly, consumers "may reject technologies, redefine their functional purpose, customize or even invest idiosyncratic symbolic meanings in them" [78].

Adding to this scholarship, domestication theory describes the process of technology adoption through four specific steps: appropriation (i.e. technologies are taken home) [86]; objectification (i.e. how a technology rearranges or constructs a physical environment) [87]; incorporation; and conversion [88,89]. As with the SST approach, consumption is seen to have an active nature, whereby households choose to incorporate a new technology into their family routines [80], until it takes on symbolic meaning and becomes normalized within a familiar setting [90]. Ultimately, if incorporation resonates at an emotional and economic level, conversion can take place through identity creation and shifts in perception of status. Indeed, in cases where new technologies have been embraced by the public, research has highlighted the importance of active end-user participation and social acceptance throughout the deployment process [91].

Focusing on the importance of the 'human factor' in household energy consumption, Lutzenhiser [92] followed in this tradition by exploring the importance of social and behavioral dimensions in terms of both 'macro-social' and 'micro-behavioral' aspects of energy use. His framework included the following factors: behavior and variability in consumption; public opinion and conservation attitudes; price and information; billing and rates; consumer knowledge and the social contexts of consumption; micro-behavioral studies of actor-building-technology systems; and macro-social organization of energy use. The author's integration of scales, and multiple behavioral, attitudinal, economic, and socio-cultural factors remains critical to better understanding the role of consumers in the renewable energy transition, as visible in the last three decades of social acceptance scholarship [61] (see Section 3). For example, two decades later, Kowsari and Zerriffi [93] proposed a 'three dimensional energy profile' framework to assess household energy use, composed of multiple exogenous (i.e. external conditions) and endogenous (i.e. household characteristics) factors. In a similar vein, Steg et al. [94] set out a future research agenda for examining "the human dimensions of a sustainable energy transition." Countering the techno-economic approach, the authors argued that alongside contextual factors, knowledge and motivations determine the feasibility of sustainable energy transitions [94].

Despite advances in the social sciences, techno-economic thinking has long dominated the academic discourse, even in the field of domestic energy studies [95]. This is striking since sociological research provides a better lens for unpacking the motivations and meanings of energy behaviors and practices [96]. Against this background, Section 3 discusses the current state of research on the social acceptance of RETs to better understanding the conceptual foundations of critical approaches towards the study of domestic hydrogen acceptance.

3. Three waves of social acceptance scholarship

As technology innovation and the pace of renewable energy diffusion has accelerated, social and behavioral scientists have increasingly focused on understanding the factors that shape social acceptance [46–48]. Social acceptance studies aim to support the clean energy transition by understanding which processes may counteract the grip of institutionally 'locked-in' fossil-based energy systems [76,97]. Key conditions for social acceptance may include support for the technology from policymakers and experts, and a lack of resistance from the NGO community, residents, local policymakers, or other representatives of public interest [98,99].

Reviewing historical developments in social acceptance theories, Batel [61] recently systematized the literature according to three waves of research (see Fig. 2). Rooted firmly in the risk perceptions literature of the 1980s and early 1990s [100–104],[6] the first wave (*Normative approaches*) focused primarily on the social side of RETs by investigating NIMBY (Not In My BackYard) syndromes and responses to the siting of renewable energy projects such as onshore wind farms [61]. Following extensive critique of the NIMBY theory throughout the early 2000s [106–109], the second wave (*Criticism approaches*) [61] was inaugurated in 2007 by Energy Policy Special Issue on the *Social Acceptance of Renewable Energy Innovation*, crystallized by Wüstenhagen et al's [110]

[5] This study uses the term social acceptance to discuss consumer attitudes and public perceptions of the domestic hydrogen transition, based on literature review findings (see Section 4).

[6] See Bickerstaff [105] for a review of psychological studies of risk perception.

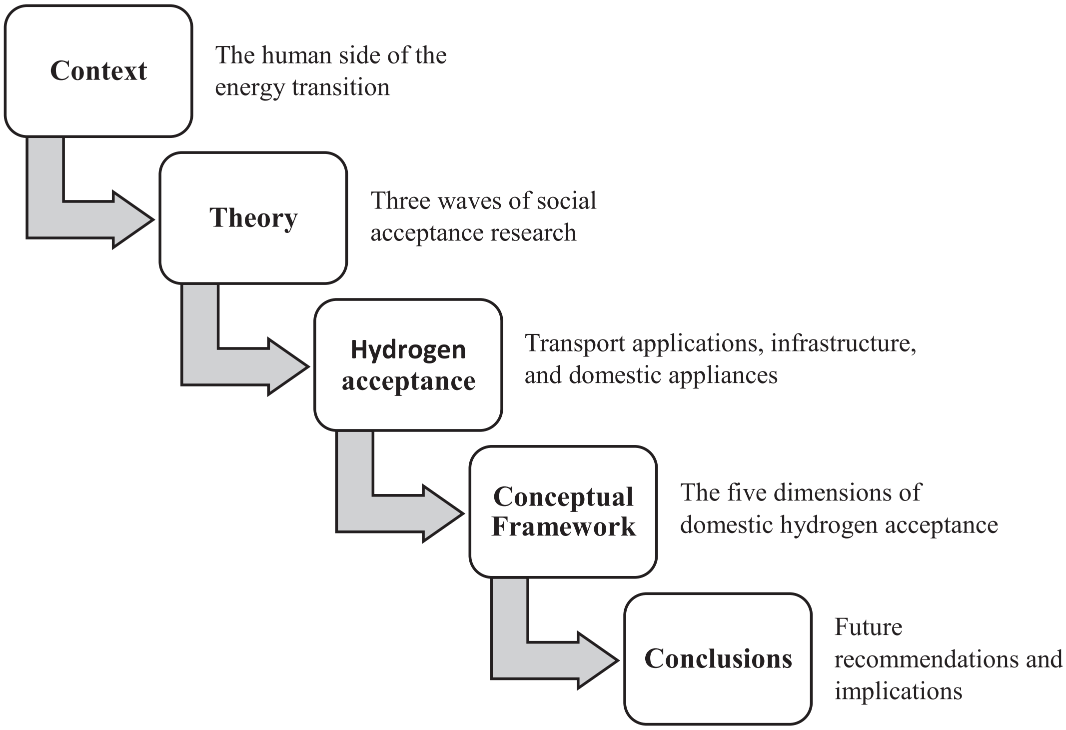

Fig. 1. Structure of the study.

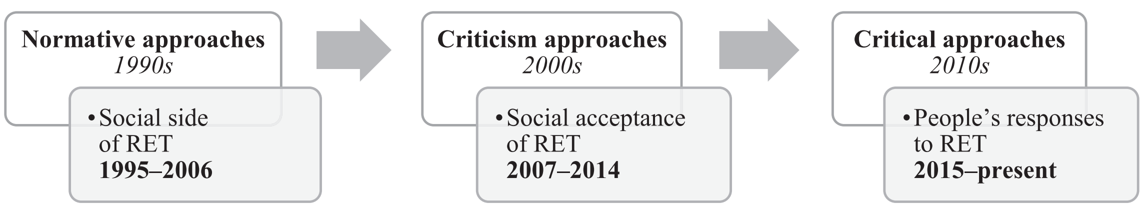

Fig. 2. Overview of the three waves of research on the social acceptance of RET, adapted from [61].

conceptualization of "the triangle of social acceptance of renewable energy innovation.".

During this second wave, acceptance studies presented a stronger focus on actor-networks and scales beyond the community-level [48,99,111], incorporating deeper socio-psychological explanations [52,94,112–115]. This approach engaged more meaningfully with aspects of procedural [63,109,116,117] and distributional justice [63,116], among other factors such as perceived risk and benefit, and social trust [112,118]. Building on this literature, leading scholars have increasingly turned their attention towards better understanding people's reactions to renewable energy deployment [61]. Here, studies grapple more directly with issues of energy injustice and power relations, while communicating the "socially embedded" [61] and co-created nature of social acceptance [64] in view of socio-historical and spatio-temporal factors.

Following Batel [61], Fig. 2 provides a simple systematization of the evolution of social acceptance scholarship on the renewable energy transition over the last three decades (*italics*). This study demarcates each wave around the seminal contribution of Wüstenhagen et al. [110] (**bold**), yet retains, the original conception that these waves/periods are neither independent nor consecutive, rather they are interacting and overlapping. While criticism and critical approaches remain normative, the first wave aligned more directly to what was considered institutionally normative and mainstream thinking at the time.

3.1. Wave 1: Normative approaches – The social side of RET

Drawing on the findings of Batel [61], the first wave of social acceptance research can be loosely traced back to the mid-1990s, cemented by Gordon Walker's review paper [119] on public attitudes towards four types of RETs (hydroelectric power, geothermal, tidal, and wind). Responding to a deficit in understanding "the perceptual and social dimensions" of renewable energy deployment, Walker called for more research dedicated to providing "…a clearer, harder and more sensitive and sophisticated awareness of public attitudes…and a greater understanding of how attitudes are formed, changed and developed," with experience and over time [119]. Additionally, the article highlighted the extent to which studies on the public acceptance of RETs remained dwarfed by research on nuclear power [119], concentrated foremost on risk perceptions of radioactive waste [101,102,120–122] and the NIMBY phenomenon [123,124], to which Wave 1 owes its foundations [61].

3.1.1. Not in My back Yard syndromes and responses

NIMBY 'syndromes' [125] and 'responses' [126] – whether rooted in the selfish pursuit of maximizing personal-utility [127] or rational acts of 'place-protection' [108] – have often been cited as one of the prevailing reasons for public opposition to energy projects and technologies [107]. 'NIMBYism' takes effect when citizens object to energy projects being sited in proximity to their property or local area [108,128], which typically supersedes general support they may otherwise hold for the project [107]. NIMBY objections may be strongly linked to visual intrusion, especially in the case of wind farms [129], while noise and effects on biodiversity are other motivational factors [106].

NIMBY attitudes have been linked with opposition to windfarm planning applications in England and Wales during the early 2000s [130]. Based on a more recent dataset (2012–2018), Roddis et al. [131] found that rural communities located close to onshore wind and fracking installations were more opposed to these technologies than people living in urban areas. A wide range of case studies present similar findings on the prevalence of NIMBY [128,132,133]. For example, Mueller et al. [134] observed that proximity to high-voltage transmission lines in Lower Saxony, Germany, led to increased risk perceptions and decreased citizen support for grid expansion. In the case of hydrogen refueling stations, Iribarren et al. [133] found that Spaniards were supportive of the infrastructure, but objected to these facilities being located within residential zones. Notwithstanding, contradictory evidence suggests that spatial determinism may be a weak explanation for the NIMBY phenomenon [108]. Alternatively, researchers have shown that some energy projects including wind farms may give rise to an 'inverse NIMBY syndrome' [135], which sees local support positively correlated with spatial proximity to the project site [106].

Marking a departure away from early thinking on the social side of RETs [61], the notion of NIMBY became a highly contested factor of social acceptance [107]. In turn, most schools of thought moved from questioning to debunking its validity as a concept [106]. Writing in 2006, Wolsink [136] memorably argued that "the application of the NIMBY argument as a tool for analysis is scientifically perilous, and it should be abandoned." His critique concluded that NIMBY "obscures the real motives and impedes our understanding of what is really happening in facility siting conflicts" [136], announcing the imminent shift towards a new wave of social acceptance research.

3.2. Wave 2: Criticism approaches – The social acceptance of RET

The second wave marked a departure away from engaging with questions of social acceptance through the lens of NIMBY. Instead, scholars such as Devine-Wright [107] and Walker et al. [137] turned their attention to examining actor-networks and scales that extend beyond the local level, while also investigating socio-psychological and contextual aspects linked to perceived benefits, costs, and risks. Section 3.2.1 outlines the first focus area with a brief discussion of 'post-NIMBY' theories [107], while Section 3.2.2 details the other prominent 'strand' of the criticism approach [61] through an overview of socio-psychological and contextual factors.

3.2.1. Post-NIMBY theorizing: Place attachment and place identity

The discussion of social acceptance in relation to spatial factors and the associated critique of NIMBY has been enriched by nuanced analysis of the role of 'place attachment,' which corresponds broadly to "one's emotional bonds with the local area" [52]. Emotional bonds may develop in the form of 'place inherited' and 'place discovered' attachment, or otherwise be absent in the case of "non-attachment" [138,139] (see Table 1). Place attachment is positively correlated to the duration of this relationship [108] and gives rises to 'place identity' [140], which Proshansky et al. [141] define as "a cluster of positively and negatively valenced cognitions of physical settings." Accordingly, place attachment should be considered as both a socio-psychological and geographical factor of social acceptance [111].

Moving beyond NIMBYism by uniting these streams of thought, Devine-Wright [108] attributed local resistance to the disturbance of "pre-existing emotional bonds," which threatens place identity and motivates 'place-protective' actions [140]. Exploring the interactions between place attachment and place identity in relation to the construction of high voltage power lines, Devine-Wright [140] found that individuals with ties to their surroundings in the form of 'place discovered' attachment were less likely to express technology acceptance,

Table 1
Theories of place attachment.

Source	Type of place attachment	Core foundations	Operational significance
[298]	Place inherited/ traditional	Rooted in dailyness and familiarity	• Surroundings taken for granted • Deep connections sustained to place of residence
[298]	Place discovered/ active	Rooted in the conscious decision to live in a specific location	• Active interest in surroundings • Strong sense of ideological identification
[138]	• Place alienation • Place relativity • Placelessness	Rooted in non-attachment to place of residence	• Dislike and estrangement to place of residence • Ambivalence and conditional acceptance • Indifference to surroundings and no desire for developing emotional bonds to place of residence

Source: Authors' compilation.

most likely stemming from finer attunement to the potential negative impacts of energy-related infrastructures on their community. Additionally, the study reported that project-related variables such as perceived impacts, procedural justice, and trust were more significant in explaining public opposition than place attachment or socio-demographic variables.

Geographical factors such as "place, landscape, distance, decay, and territory" may have a significant impact on social acceptance, especially at the community level [142]. More specifically, it has been argued that spatial proximity and scale are potential determinants of community support, which result in "heterogenous patterns" of acceptance [54]. Supported by an associated study on the local acceptance of wind power projects [109], Wüstenhagen et al. [110] suggested that community acceptance follows a U-shaped curve, which sees acceptance go from high to relatively low during the siting or construction phase, before reaching a higher level of acceptance once the project becomes operational.

While such studies and related post-NIMBY theories typically look at a specific energy project or technology, it has also been argued that place attachments and identities may prove influential to how society responds to the climate change crisis [143]. Place attachment need not be limited to one place and to the local scale but can extend to the 'poly-local' and 'polyscalar', which may motivate public engagement in climate change action vis-à-vis the adage, "think globally, act locally" [144]. The shift towards 'polycentric'[7] modes of thinking about social acceptance [76,145] and the governance of energy infrastructure [146] coincides more concretely with the ongoing wave of scholarship (see Section 3.3). Notwithstanding, in both political and public discourse, there is still a prevailing tendency towards bracketing issues of community acceptance under NIMBYism.

3.2.2. Socio-psychological and contextual factors

As conceptualized by Stephenson et al. [147] in their 'Energy Cultures' framework, there is a relationship between "cognitive norms" (i.e. beliefs and values), "energy practices" (i.e. activities and processes), and the surrounding material culture associated with a technology and where it is used. More systematically, the Theory of Planned Behavior

[7] Referring to "the many different centers of decision-making at different scales" [145].

(TPB) posits that behavioral intentions are determined by “attitudes toward the behavior, subjective norms, and perceived behavioral control,” which together with consumer perceptions “account for considerable variance in actual behavior” and decision-making [148]. Moreover, environmental psychologists have documented how a discrepancy often exists between stated values, beliefs and intentions, and observable behavior, resulting in a ‘value-action gap’ [149,150], otherwise often discussed in terms of an ‘intention-behavior gap’ [151] or ‘knowledge-action gap’ [152].

In addition to reconceptualizing the notion of NIMBY and highlighting the importance of ‘space and place’ to the study of low-carbon energy transitions [108,142,153], the second research wave developed a more explicit focus on how social acceptance is configured by interactions between socio-psychological [115] and contextual factors [52] (see Table 2). Socio-psychological factors depend on individual subjectivity and personal values, which may also explain public attitudes towards climate change [154] and the sustainable energy transition [155]. While classifications of these factors vary somewhat within the literature, socio-psychological factors are regarded to shape public perceptions of contextual factors [52]. Furthermore, Wolsink [76] posits that contextual factors reveal the impact of external conditions which may drive, trigger or block technology acceptance.

During the period of post-NIMBY theorizing, socio-psychological and contextual factors were mainly analyzed through the lens of perceived benefits, costs, and risks [112,114,156,157]. At the individual level, “perceived benefit” relates to the probability that a given action or behavior will yield positive results [157], whereas “perceived risk” refers to perceptions regarding the uncertainty and potential negative effects of a specific action or behavior. As argued by Wüstenhagen et al. [110] and Steg et al. [94], social and community trust influence how the public perceives the costs and benefits of low-carbon energy transitions.

Focusing on ‘controversial’ electricity generation sources, Bronfman et al. [118] constructed a “causal-trust acceptability model” in which acceptability is determined by social trust in regulatory authorities, in addition to perceived risks and benefits. Investigating the relationship between benefit and risk judgements for hydrogen transport (cars and buses) in the Netherlands, Montijn-Dorgelo and Midden [158] found that consumers are more likely to perceive stronger benefits and lower risks when they trust the actors involved in hydrogen projects. Interestingly. Gupta et al. [113] found that *perceived risk* was the most frequently investigated determinant of public acceptance, followed by *trust*, *perceived benefit*, and *knowledge*.[8]

Table 2
Socio-psychological and contextual factors underpinning renewable energy acceptance.

Socio-psychological Factors	Contextual Factors
• Place attachment	• Fair procedures
• Place identity	• Environmental impact
• Trust	• Energy price
• Values	• Quality of supply
• [52]	• Location
	• Objective dimensions of energy goods [52]
• Beliefs and attitudes	• Performance
• Motives and intentions	• Cost
• Perceived behavioral control	• Fashion
• Cost-benefit appraisals	• Familiarity
• Personal and social norms	[176]
[299]	

Source: Authors’ compilation.

Illustrating the importance of these factors in the context of energy-producing systems, Sjöberg [159] showed that perceived risks were regarded as more important than perceived benefits, except in the case of wind power. However, in the absence of perceived benefits, consumers are less likely to tolerate even minor levels of risk [160]. Furthermore, it remains critical that benefits flow to the public and the environment [52], as opposed to industry or specific stakeholders, unless these stakeholders can better represent marginalized social groups such as those in fuel poverty [160]. While risk perceptions strongly influence public support for the building of large-scale infrastructure projects such as a nuclear power plant, perceived benefits may prove to be the “key predictive factor” when considering the social acceptance of new sources of electricity generation [118] or low-carbon heating technologies [98].

Under the worst-case scenario, Cohen et al. [161] state that, social acceptance should correspond to a “welfare neutral” outcome for each agent involved, whereby the negative and positive aspects of new energy infrastructure projects are balanced out. Although welfare neutrality may not necessarily secure higher welfare for society, this economic framing is suggested to counteract definitions of social acceptance that impart excessive agency on members of respective social units [48]. At the collective level, cost-benefit evaluations and risk perceptions reflect societal implications such as public safety and environment health, whereas individual implications involve personal resources such as time, money, and comfort [52]. While technical experts employ detailed risk assessments to arrive to their conclusions, the decisions of the public regarding perceived costs, benefits, and risks are influenced by non-technical sources of information such as media representations, and ordinarily based on prior experiences and emotional factors [100,162,163].

3.2.3. *The triangle of social acceptance of renewable energy innovation*

During the early 2000s, scholars such as Devine-Wright [107] had underscored the multi-dimensionality of social acceptance, for example, by examining physical, contextual, political, and institutional, socio-economic, social and communicative, symbolic and ideological, local and personal dimensions in relation to wind farms. In 2007, Wüstenhagen et al. [110] consolidated the criticism approach by expanding on the importance of the institutional and social environment [76]. The authors proposed a tripartite framework for understanding the social acceptance of renewable energy innovation, composed of socio-political, community, and market dimensions [110]. The framework added a distinctive ‘multi-level’ element to the study of social acceptance, characterized by dynamic interactions and co-evolving processes [76], somewhat comparable to the Multi-Level Perspective (MLP) framework [164]. The MLP explains technological transitions according to the interplay of processes across three distinct levels: the socio-technical landscape (macro-level); the socio-technical regime (*meso*-level); and the niche (micro-level) [165,166].

Socio-political acceptance is the broadest of the three dimensions, operating at the macro or national level [48]. This dimension encompasses how the public and other stakeholders view the policy environment surrounding the deployment of new energy technologies, which is typically gauged through opinion polls [110]. The implementation of effective policies by regulators and policymakers is recognized as a key mechanism for fostering market and community acceptance [167]. Market acceptance “operates at a *meso*-level between national politics and local communities” [167], involving industry actors such as incumbents, small and medium-sized enterprises (SMEs), and intermediaries [168]. At this level, investors typically act as energy suppliers and consumers as technology adopters [167], although households may be regarded as both investors and consumers when they purchase energy appliances [110]. The investment landscape shapes the potential for social acceptance by directing how companies and consumers contribute towards technology adoption [55].

In contrast to market acceptance, which is linked to how transition

[8] *Individual differences*, *attitudes*, negative affect, technology characteristics and *the* role of societal actors were other relevant determinants, albeit less frequently reported.

Table 3
Actors and factors behind social acceptance of renewable energy technologies.

Acceptance dimension and definition	Scale	Actors	Factors
Sociopolitical acceptance The ability for regulators, policymakers, and other key stakeholders to craft effective policies or frameworks that effectively foster and enhance community, market, and public acceptance of RETs [110,167]	**Macro** Supply-side acceptance of RETs at the policy or national level [48]	• Regulators	• Technology type, scale, and context
		• Legislative authorities • Policy actors • Key stakeholders • General public [76,167]	• Legal and regulatory frameworks • Institutional capacity • Political commitment [111,167]
Community acceptance The extent to which new renewable energy projects or appliances are invested in or trusted by local stakeholders, and the scope of justice (procedural and distributional), trust and legitimacy [110,167]	***Meso*** Acceptance of new renewable energy infrastructure, facilities, and technologies at the local level [48]	• Local stakeholders	• Infrastructure and resource availability
		• Local authorities • Residents • End-users [76,110,167]	• Historical and cultural heritage • Place attachment • Participatory project siting • Transparent communication and planning procedures • Local stakeholder engagement • Recognition of externalities [110–111,142,167]
Market acceptance The extent to which investors want to support the manufacturing and use of RETs, and the level of market uptake [110,167]	***Meso*** Acceptance of a renewable energy technology or application at the household and organization level [48], which operates at a *meso*-level between national politics and local communities [167]	• Incumbents	• Competitive installation and production costs
		• Small and medium-sized enterprises (SMEs) • Producers • Consumers • Distributors Investors • Other intermediaries [76,167,168]	• Cost-competitiveness of the technology for consumers • Financing mechanisms for producers and consumers • Business models and tariffs • Mechanisms for information and feedback [167,168]

Source: Authors' compilation.

and transaction costs compete against alternative technologies [167] and gauged in terms of adoption, community acceptance is contingent upon the willingness of local stakeholders to invest in new energy projects or appliances and measured according to participation in planning processes [110]. This willingness depends partly on how local citizens perceive levels of disruption or inconvenience [169]. Moreover, community acceptance rests on whether costs are perceived to be distributed equitably, alongside fair decision-making processes, characterized in terms of procedural and distributional justice (see Section 3.3.2), and trust at the community level [110]. When planning processes are non-participatory and lack transparency, and costs and benefits are distributed disproportionately, social acceptance is more likely to waver [132,170,171]. Finally, trust depends on how the local community perceives the intentions of investors and external actors, and whether they consider information to be reliable [172]. To promote fairness and equity for all stakeholders, it follows that the low-carbon transition should actively engage with issues of energy justice and trust [171], which has become a pillar of the third wave of research (see Section 3.3).

When distributional costs are accounted for, residents are more likely to have positive views of perceived energy justice, as exemplified in the context of landmark renewable energy projects in Denmark and Germany [173]. Such projects highlight the importance of bottom-up consultation processes and information dissemination as key mechanisms for securing energy justice and social acceptance [173]. Public perceptions of transparent and participatory energy-system implementation processes increase social acceptance [174]. Conversely, social acceptance appears to decrease when the public has pronounced reservations about the profit motives of energy companies [41,175] and the legitimacy of government pledges [41,59,74]. Ultimately, social acceptance is more likely when institutional frameworks and business models foster stakeholder participation and transparent communication procedures [176], with citizens assured that technology adoption will provide local economic, environmental or social benefits [77,98] without disenfranchising vulnerable members of society [160].

Representing the contribution of the criticism approach, Table 3 provides a high-level overview of the scales, actors, and factors of each social acceptance dimension based on the original conceptualization [110], and subsequent modifications and additions to the framework, and applications to different renewable energy contexts.

3.2.4. The transition from criticism to critical approaches

Following the seminal contribution of Wüstenhagen et al. [110] and growing interest in themes of energy justice [171], several studies [62,145,174,177,178] have demonstrated the importance of multiple social acceptance factors (see Table 4), while enriching theoretical perspectives. Notably, in 2008, Devine-wright [111] called for more "interdisciplinary research…with a greater emphasis upon the symbolic, affective and socially-constructed nature of beliefs about renewable energy technologies." Having examined the investment and community acceptance side of wind and solar systems during the early decades of

Table 4
Applications of social acceptance approaches, 2008–2018.

Study	Social acceptance dimensions and factors	Details of study and key findings
[111]	**Personal** Age Gender Class Income **Social-psychological** Knowledge and direct experience Perceived fairness and levels of trust Political beliefs Environmental beliefs Place attachment **Contextual** Technology type and scale Institutional structure Spatial context	• Builds on theories developed from the field of environmental psychology [54] • Places a more direct focus on the consumer in terms of socio-demographic and socio-psychological factors • The contextual and spatial focus extend the analysis to the macro-level, with the contextual category echoing the socio-political dimension described by Wüstenhagen et al. [110] • Highlights how support for RETs may vary across geographical scales
[167]	**Socio-political** Strong institutional capacity Political commitment Favorable legal and regulatory frameworks	• The framework separates the political from societal/community aspects [168] • Explains faster diffusion and stronger domestic markets for wind energy in Denmark compared to India, and for solar power in Germany compared to USA during the 1990s and 2000s
	Community acceptance Prolific community and/or individual ownership and use Participatory project siting Recognition of externalities Positive public image.	• Denmark satisfied every criterion except for that of transparent regulatory changes, and Germany satisfied every criterion except for competitive installation/production costs • India and USA satisfied only three of the criteria
	Market acceptance Competitive installation and/or production costs Mechanisms for information and feedback Access to financing	
[62]	**Project specific and technical** **Ecological** **Social, societal, and emotional**	• Locals frequently have rational arguments for their resistance to high voltage lines and wind farms
	Procedural and formal **Political** **Macro-economic/national/spatial**	• Mistrust among stakeholders significantly hampers the progress of negotiations and participatory processes
		• Standards for participatory processes and quality standards should be implements by project planners • Consumer attitudes are often intractable, therefore, comprehensive information about project proposals should be disseminated to the public as early as possible
[168]	**Governance and regulation** (i.e. socio-political)	• Unpacks the interrelations between these dimensions across different geographical scales (international, national, and local)
	Socio-cultural and public acceptance (i.e. community)	• Argues that the belief systems or social representations of key actors operating at different scales are critical to the process of social acceptance
	Markets and innovation (i.e. market)	• Analyzes the role of 'middle actors' in driving technology diffusion and acceptance • Middle actors play an important role in mediating processes of change between scales
[179]	**Material arguments** Aesthetic factors Environmental factors Economic factors Project details	• Material arguments (i.e. impact on wildness, project size and visual impacts) were more significant factors of community acceptance for onshore wind and solar farms than attitudinal/social influences
	Attitudinal/social influences Demographic factors Political factors Temporal factors Geographical factors	• Visibility (aesthetic), installed capacity (project details), social deprivation (demographic) and year of planning application (temporal) were statistically significant factors for both technologies
		• Solar farms are more likely to be sited in deprived areas • Onshore wind farms are more likely to be sited in wealthier areas

Source: Authors' compilation.

market deployment, Sovacool and Ratan [167] argued that each acceptance dimension should be met "holistically in order for investors and users to embrace renewable energy." Applying an energy justice lens, Roddis et al. [179] investigated the impacts of community acceptance on planning applications for onshore wind and solar farms in Great Britain between 1990 and 2017. Such studies reflect a recent observation by Busse and Siebert [180] in the context of renewable energy projects with land use impacts, namely, that "trust, participation, knowledge, prior experiences, and economic, and visual aspects" are frequently cited as the influencing factors of social acceptance.

Above all, the conceptualization of social acceptance proposed by Wüstenhagen et al. [110] and subsequent modifications to this framework [48,167,168], reinforce the extent to which social acceptance may hang in the balance due to deficits within a specific factor; or be undermined by a combination of deficiencies across multiple factors and dimensions. Furthermore, the same factors may play out differently and carry different weight according to the energy technology in question.

3.2.5. Ten years on from the triangle of social acceptance of renewable energy innovation

Despite progress in some respects, ten years on from the three-dimensional framework [110], Devine-wright et al. [168] observed that few studies had succeeded in addressing the multi-dimensionality of social acceptance. On the one hand, this is striking since over 400 studies had cited Wüstenhagen et al. [110] by the end of 2016. However, equally noteworthy is that over 800 additional studies have cited the seminal work since 2017, according to the Web of Science database (see Fig. 3). While encouraging in terms of numbers, to the authors' knowledge, no attempt has been made to identify how many of these studies fall within the scope of critical approaches. Notwithstanding, it is evident that criticism approaches remain the most prolific wave of research on social acceptance to date.

Writing in 2017, prior to an overall surge in social acceptance studies, Devine-wright et al. [168] advanced the research domain by examining the importance of "social representations held by key actors…where a polycentric perspective places particular emphasis on ways that middle actors mediate processes of change between scales" [168]. Expounding on this shift towards polycentric thinking and associated critical approaches to the study of social acceptance, Section 3.3 systematically describes the ongoing research wave, following the contributions of Batel [61], Batel and Devine-Wright [64], and one of protagonists of the second wave, Maarten Wolsink [76,181].

3.3. Wave 3: Critical approaches – People's responses to RET

As described in Fig. 2 and internalized throughout this historical analysis vis-à-vis Batel [61], each research wave is neither strictly independent nor consecutive, but rather interconnected and overlapping.

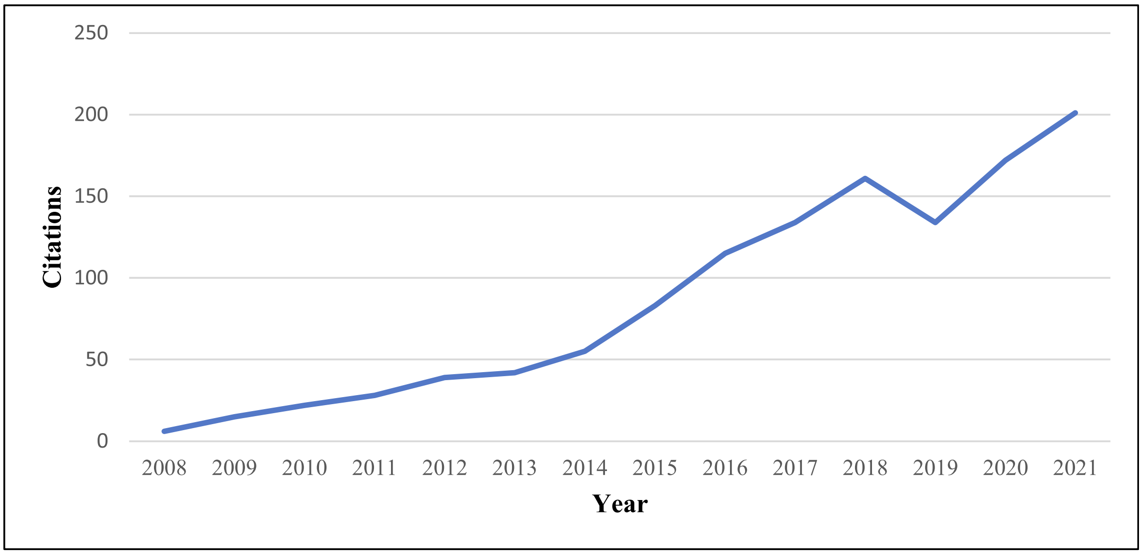

Fig. 3. Citations per year for the "Social acceptance of renewable energy innovation: An introduction to the concept [110,296], as of Web of Science database [296].

Notwithstanding, it is instructive to link the start of each wave to a key contribution to the literature, such as Walker [119] for Wave 1 in 1995 and Wüstenhagen et al. for Wave 2 in 2007 [110]. Coinciding with recent critical junctures in political and environmental history,[9] Wave 3 can be traced back to 2015 when Batel and Devine-Wright [64] set out to establish "a better understanding of people's responses" to RETs by drawing on insights from Social Representations Theory (SRT). Thereafter, Batel and colleagues [185] linked together theories of behavior, practice, and social representations by merging Social Practice Theory (SPT) [186,187] with SRT in a single framework. The framework proposed a more comprehensive way to understand different junctures of the "social change process" towards a sustainable energy transition and low-carbon society. In parallel, Miller et al. [188] proposed the "socio-energy systems" policy framework, predicated on the notion that energy transformations co-evolve within and shape the fabric of society, culture, and politics, wherein "people and organizations are complex entities – with histories, identities, and cultures – that require careful and sophisticated analysis."

Whereas some technologies such as nuclear power have traditionally been associated with political elitism [189] and technocratic ideologies [190], renewable-based energy systems may present opportunities to create a more democratic, decentralized and community-based energy future [191]. This prospect has seen 'clean energy' politics increasingly associated with the notion of 'energy democracy' [192–194], demonstrating the far-reaching implications of energy choices on the socio-political landscape [195]. Contrary to this line of thinking, critical approaches depart from previous scholarship by unpacking how RET deployment and the decision processes behind it are "often apolitical, unjust and undemocratic, or just another materialization of the neoliberal capitalist system" [61]. While the third wave is multifaceted with several emerging themes [61], it has materialized around at least four key areas which are further taken up in this analysis (see Table 5).

This focus brings new insights to the socio-spatial, socio-cultural, contextual, and attitudinal (i.e. socio-psychological) dimensions of social acceptance, while retaining a multi-dimensional approach towards rigorous inquiry. For example, in the context of DESs, Von Wirth et al. [54] underlined how social acceptance studies should examine spatio-temporal factors "to detect socio-spatial patterns," alongside "an in-depth actor analysis and temporal analysis of the diffusion process."

[9] Foremost, the passing of the United Nations 2030 Sustainable Development Goals (SDGs) [182–184] and the Paris Climate Agreement [3].

Table 5
Four pillars of critical approaches to the study of social acceptance.

Scope of pillar	Perspective and framing	Key studies
Exploring the spatial dynamics of social acceptance through relational frameworks	Social acceptance is viewed as a multi- and cross-scalar phenomenon, operating within the energy production-consumption nexus	[76,153,202,300]
Examining the impacts of pursuing 'just' energy pathways	Social acceptance contends against a pandemic of energy poverty rooted in the prevailing socio-political landscape	[171,173,179,198,301,302]
Exploring the influence of temporal and socio-historical factors on the energy transition and community acceptance	Social acceptance is linked to time, place, and space, such as the legacy of industrial heritage and absence/presence of regional energy cultures	[131,222,223,225,226,303,304]
Overcoming the reductionist nature of previous research waves (i.e. normative and criticism approaches)	Social acceptance is characterized by a matrix of potential attitudes and responses, reflecting the complexity and often paradoxical nature of human emotion	[54,76,243,305]

Source: Authors' compilation.

The next Sections (3.3.1–3.3.4) tackle each of the four areas in turn.

3.3.1. *The spatial dynamics of social acceptance: macro-, meso- and micro-scales*

Social acceptance is governed by complex and multi-layered interactions between multiple stakeholder groups [168] and involves "mutually influencing processes" that cut across national, communal, and local scales [76]. These processes – whether scientific, technical, institutional, socio-economic, cultural, or organizational – are context-specific and polycentric in nature [76], with several governing authorities operating at different scales [196,197]. As low-carbon transitions play out within dynamic 'territorialities' [153] and across different geographies, changes are thus "modulated by uneven spaces and scale" [198].

There are three specific geographical scales or levels at which these processes interact: the macro-, *meso*-, and micro-scale [48,168]. The macro-scale represents "the general, policy or country level" [48], characterized by large-scale infrastructure projects that directly impact national energy supply, such as the building of nuclear power plants or offshore wind farms. The *meso*-scale refers to how energy projects develop through mechanisms at the local, community or town level, while the micro-scale is relevant to technology implementation at the building, household, or organization level [48,111]. Further unpacking the characteristics of the micro-scale, Després [199] described the household as a "material located" and "political-economic" entity, where "continuity and permanence" reside; reproduced by the activities, relationships, ideas, and values of its occupants. As the modern, domestic environment becomes increasingly populated by smart home technologies and devices [200], this social reproduction of continuity and permanence may be reconfigured along new contours. Optimally, this reconfiguration should reflect changing values and priorities aligned to environmental citizenship and energy conservation [150,201].

Illuminating the differences between these scales and their respective links to economic, political, and social dimensions of technology acceptance in the context of wind energy projects, Fournis and Fortin [202] proposed the following analytical levels: macro-economic, *meso*-political, and micro-social. At the micro or micro-social scale, acceptance is determined directly by the decisions of end-users [203], as they choose to support and adopt, or resist and reject energy technologies for different motivations [115]. After all, even the best technology serves little purpose unless people genuinely use it [115,204] and preferably as intended by its designers [205].

Broadly speaking, energy transitions involve simultaneous shifts across all three scales: at the macro-scale through changes in electricity and gas networks; at the *meso*-scale as interactions between consumers and suppliers are altered; and at the micro-scale as households change their technology preferences. Accordingly, energy researchers should adopt a sensitive multi-scalar perspective [206] to reveal information about individual perceptions and attitudes toward clean energy technologies [207,208] and their land-use impacts, which should be examined "case-to-case with data-driven impact evaluation" [209], incorporating a direct focus on social aspects and environmental justice implications [210].

Table 6
Definitions and implications of energy and fuel poverty.

Energy Poverty	Fuel Poverty
• Lack of access to energy infrastructure, especially electricity and modern cooking fuels, and affordability challenges for securing energy goods and services [306]	• Households cannot afford adequate domestic energy services given their current income level [308]
• Gives rise to reliance on traditional use of biomass for heating and cooking [211,271,307]	• Forced to spend more than 10 % of household income on basic energy costs [212]
• Households may be forced to forego essential services or capabilities, or choose between eating or heating [211,271,307]	• Households have higher than average fuel costs but lower than average income [309]

Source: Authors' compilation.

3.3.2. Just transition pathways: Fuel poverty, energy justice, and social acceptance

Households facing energy poverty and/or fuel poverty are often victims of pervasive energy injustice and inequality. While these terms should be differentiated according to context, they share similarities in terms of distributional injustice (see Table 6). Bartiaux et al. [211] describe the source of energy poverty as "a lack of material resources and economic power," which can corrode a wide range of physical, sensory, psychological, intellectual, emotional, and spiritual capabilities. Energy poverty remains a systemic issue in the UK, since England's flagship fuel poverty program – the Warm Front Home Energy Efficiency Scheme which ran between 2003 and 2013 – while successful in reducing the level of fuel poverty for 2.36 million homes, failed to lower the national rate of fuel poverty [212]. In response, Demski et al. argue that a more salient approach considers energy as "a need and basic right" [207], thereby seeking explicit provision and protection for vulnerable parts of society. Sovacool and Brisbois [213] have likewise drawn attention to the importance of protecting human rights throughout the production and consumption of energy.

Against this backdrop, energy justice has developed into a prominent interdisciplinary research area [171,214], strengthened since 2015 by the passing of the United Nations 2030 Sustainable Development Goals

Table 7
The Energy Justice Framework.

Energy justice tenet	Premise and focus	Operation and application
Procedural	Focuses on the decision-making and informational aspects of energy developments to achieve social goals [171,215,216,310]	Examines how stakeholders participate in the planning of rules and laws, exploring the configuration of stakeholders involved in influencing decision-making processes [171,215,216,310]
Distributional	Depends on how the social goods and ills of a new technology are distributed across the population [170–171,311]	Calls for more robust quantitative and qualitative exploration of the co-benefits and externalities of renewable energy deployment [171][1]
Recognition	'Post-distributional' in the sense that inequalities should be contextualized and understood according to their societal impacts [312]	Aligned to fair representation, freedom, and safety for all individuals [313]
Cosmopolitan	Applies procedural and distributional justice to the global scale, based on the premise that every individual has intrinsic worth that should be safeguarded [216]	Promotes a collaborative approach towards recalibrating energy cultures in a direction aligned to positive global change [217]
Restorative	Focuses on repairing the damage inflicted on society or nature [218]	Offers a built-in mechanism for safeguarding the welfare of local communities and nature by obligating decision-makers to factor in the long-term social and environmental costs of energy-related activities [218]

Source: Authors' compilation.
[1] Cautions against overreliance on CBA as a tool for judging the equitability of energy projects [171].

(SDGs), especially SDG7 targeting "Affordable and Clean Energy"[10] [182–184]. McCauley et al. [171] describe energy justice as "a conceptual, analytical and decision-making framework" designed for understanding the temporal and spatial dynamics of ethical issues related to energy activities. The framework strives to secure a sustainable energy system rooted in fairness and equity [179] by identifying which stakeholders should be involved in resolving such issues [171]. Formally, the framework includes three core tenets – procedural, distributional, and recognition justice [215] – which are increasingly discussed alongside two additional dimensions, namely, cosmopolitan [216,217], and restorative justice [218] (see Table 7). Notably, Applied Energy Special Issue on "Low Carbon Energy Systems and Energy Justice" highlighted the importance of merging energy justice with other theoretical frameworks such as social acceptance to drive a more nuanced understanding of a 'just' energy transition [171].

The links between fuel poverty, energy justice, and social acceptance have recently been explored across a range of national contexts and scales, with social science researchers applying multiple theoretical approaches [171,179]. For example, Heffron et al. [219] proposed the Energy Justice Metric (EJM) to provide a more representative measure of energy justice than offered via on cost-benefit analysis (CBA). The EJM accounts for the full energy lifecycle of a technology, adopting an "inequality-correcting" approach that enables decision-makers to proceed more responsibly when assessing technology pathways. The modeling tool operates by quantifying the energy justice performance of different countries based on data from national governments and international institutions. Sareen and Haarstad [198] examined the socio-technical and energy justice aspects of sustainable transitions in terms of "the co-evolution of institutional, material and relational change," accounting for the 'cross-cutting' implications of 'multiple spatialities' and normative effects. Such approaches espouse the use of innovative, multi-scalar research methods to advance knowledge on "societal transitions and transformation" that are just and sustainable [198].

Drawing on data from the Townsend Index score of deprivation for Local Authority Districts (LADs) in Great Britain, Roddis et al. [179] demonstrated the impacts of social capital on the community acceptance of renewable energy project siting and equity. For solar farms, a unit increase in the Townsend score – representing a more deprived area – increased the likelihood of planning approval by 15 %, while the opposite trend was reported for onshore wind applications, with the likelihood of planning approval decreasing by nearly 11 %. The authors linked these findings to the impact of social capital on planning processes, suggesting that wealthier communities consider wind farms to be a more acceptable land use than solar farms, leading to lower acceptance rates for solar projects in more affluent areas [179].

Viewed through an energy justice lens [220], these results indicate that affluent communities have greater capacity to oppose unwanted energy projects than poor communities, exemplifying a case of procedural injustice. When procedural injustice takes effect, the conditions for distributional injustice are also exacerbated, whereby material benefits, or public resources and negative externalities, are unevenly allocated [216]. Under such conditions, disparities in social capital may result in deprived areas becoming soft candidates for an influx of certain renewable energy projects [179]. Specifically, rural areas, lying beyond a thriving commuter belt and with an industrial heritage, present prime sites for RE projects due to their low landscape value [221].

3.3.3. *Temporal and socio-historical factors*

Following a case study analysis of national energy transitions in the United States (nuclear power), Brazil (sugar cane ethanol for vehicles), and Sweden (biomass fuel), Malone et al. [222] highlighted the importance of "political-social-cultural national narratives" to the technology diffusion process and socio-political acceptance. This observation can also be extrapolated to the *meso*-scale (regional/local scales) and processes of community acceptance. According to van Veelen and Hagget [223], the commonplace narrative around community renewable energy projects is that "local action can and will be effective, that communities can function as the site of cooperative action as well as being the recipient of collective benefits." Whether such a notion comes to fruition is deeply entrenched in the pervading history and culture of the community in question, wherein energy futures become shaped by the totality of multiple and often competing place identities and place attachments, both at the community and individual level [223]. As discussed here through examples of industrial towns, past energy cultures may be sources of pride and joy, or trauma and stigma, but usually prove difficult to categorize in overtly binary terms.

Engaging with the theme of stigma in the UK context, Parkhill et al. [224] highlighted how historical associations of "risk and threat, pollution and dirtiness" are especially pronounced in the case of nuclear and coal-fired power stations, and more recently fracking [225]. Despite strong political backing, public support for fracking decreased between 2014 and 2018, with a mean score of just 22 %. This rating was significantly lower than the next most unpopular energy technology, nuclear power, which had a mean score of 37 % between July 2012 and April 2018 [131]. Short et al. [226] suggest that public resistance originated and subsequently escalated due to a "collective trauma" being inflicted on communities in the North of England during the planning process. The "stigmatization effect" [225] was further amplified by risk perceptions concerning drinking water, environmental degradation, and distributional injustice [227]. Prolonged procedural and distributional injustice [227] resulted in widespread public distrust, leading to sustained, active resistance across Lancashire [226,228] throughout the 2010s and arguably, de facto national opposition to fracking [131]. Nevertheless, it took until 2019 for the UK government to impose a moratorium on the technology, which was seen by many as act of political opportunism [225]. These findings serve as a case in point of the potentially far-reaching implications of historical associations and recent environmental legacies, albeit in a non-renewable energy context. Furthermore, the case of fracking in Lancashire and moreover, the legacy left behind by coal mining demonstrate the scope for enacting restorative justice.

At one extreme, stigma and trauma may lead to strong community opposition, however, these same inflictions may also numb deprived or geographically vulnerable communities from the potential adverse impacts of energy activities to some degree [229]. At the same time, it should be borne in mind that deprived communities often have muted voices as stakeholders [230], reflecting a tendency towards procedural injustice. Interestingly, examining the controversial aspects of renewable energy siting, van der Horst [221] reported that communities with an industrial legacy or mining history are more attuned to the reality that electricity comes from a production site and involves complex transportation networks and storage activities. Such communities may be more acute to recognizing the "embedded" [231,232] or "invisible" [233] nature of electricity consumption, whereby consumers are increasingly distanced from modern production sources [234]. Given this attunement, people in communities associated with a legacy of heavy industry and subsequent pollution and stigmatization, such as Teesside in the North East of England [230], may have higher tolerance for the potential negative impacts of energy generation than residents in wealthier communities [221]. Notwithstanding, such communities remain more likely to welcome energy projects that reduce social and environmental blight [229].

In this sense, there is a certain paradox at play regarding the thresholds and desires of people living in areas characterized by a legacy of social deprivation and environmental degradation. Further illustrating this argument, proposals for onshore wind farms in the early 2000s near the Corus steelworks in Teesside, and Goole in Yorkshire, were largely welcomed by locals due to positive perceptions of economic

[10] SDG7 aims to "ensure access to affordable, reliable, sustainable and modern energy for all.'.

benefits [235]. In the Yorkshire case, the importance of socio-economic factors was especially pronounced in the community of Old Goole, the nearest village to the windfarm site.[11] By contrast, Haggett [177] described how a proposal for an offshore wind farm located off the coast of Teesside sparked somewhat unexpected resistance from protestors advocating for the rights of people living near hazardous industry.

Such case studies suggest that communities characterized by an industrial past may sometimes rally to protect those areas yet to be spoiled by polluting activities [177], as opposed to passively accepting proposed socio-economic benefits. While environmental issues, especially concerning air pollution and water contamination present potential grounds for community resistance to energy developments in deprived areas, there is usually greater scope for opposition when projects fail to prioritize employment opportunities for the local community [177,230]. Critically, when considering community acceptance, the cost-benefit and risk perceptions side of energy projects should be examined within the broader context of temporal and socio-historical factors, and related energy cultures.

3.3.4. The social acceptance matrix

A focal point of recent social acceptance research builds off the recognition that many studies have lacked a sound theoretical or conceptual foundation [180]. For example, reviewing 132 publications on acceptance studies regarding the impacts of renewable energy projects on land use, Busse and Siebert [180] found that only one-third of researchers adopted a theoretical approach in their studies. This deficit has resulted in conceptual 'fuzziness' [181] by failing to reflect the multi-dimensional, co-evolving nature of social acceptance and the interrelations between its key dimensions [111,236]. Consequently, a comprehensive understanding of the dynamics of social acceptance remains 'elusive' [111] and challenging [98], with several analytical areas in need of further exploration [48].

This elusiveness is strongly rooted in terminological ambiguity, owing to range of similar terms that can be easily misconstrued given that the boundaries of interchangeability are poorly defined [161]. When examining how the public perceives new energy technologies, 'social,' 'societal,' and 'consumer' acceptance are some of the common terms adopted by researchers. However, such concepts have been frequently applied to various phenomena with different definitions [98]. Similarly, the terms 'social acceptance' and 'social acceptability' have been used inconsistently,[12] which has led some authors to advocate for differentiating between the concepts [180,202]. In linguistic terms, L'Orange Seigo et al. [237] suggest that "acceptance refers to the act of accepting, whereas acceptability is a property of the item to be accepted." The risk acceptance literature further distinguishes between 'expressed' and 'revealed' preference [238].[13]

Compounding matters further, the study of public acceptance also includes a range of relevant terms such as "public perceptions, public opinion, public beliefs, public awareness, public understanding, social representations or risk perceptions" [111]. Reflecting this diversity, Gupta et al. [113] incorporated seven terms[14] for their key word search when reviewing the public acceptance of ten 'controversial' technologies with 'transformative' potential. Clearly, the social acceptance literature presents a distinct lexical richness owing to a plethora of relevant phrases. However, this richness is characterized by notable ambiguity, most visible in the need to distil the blurred boundaries between social and public acceptance [161].

In a recent critique of Gaede and Rowlands [46], Wolsink [76] reviewed conceptual developments in the study of social acceptance since its inception in the 1980s. In the context of studies on energy technology and fuels, he argued that public acceptance is an invalid proxy for social acceptance [76]. Acknowledging that individual acceptance has a specific 'internal structure,' "composed of attitudinal elements (attitudinal acceptance), behavioral intentions, and actual behaviors (behavioral acceptance)" [48], Wolsink [76] redefines public acceptance as "the aggregate degree of acceptance by individual citizens" according to attitudes, behaviors, and tolerance. In contrast, social acceptance "concerns not only the public, but all relevant actors, and not primarily actor positions, but processes" [76].

Although a wide range of concepts and definitions have been proposed in the literature to date, there is underlying consensus that social acceptance studies should aim to capture the multiple dimensions of technology adoption and use [46,76]. Furthermore, it has been emphasized that the interrelations between consumer values, perceptions, attitudes, behaviors, and actions should be at the forefront of such analysis [48,111]. Personal values impact "beliefs, attitudes, preferences, and norms related to environmental behavior" and other actions [52], which in turn affects consumer willingness to adopt low-carbon energy technologies.

To capture its full richness, social acceptance should therefore be viewed as "a socially constructed outcome" – as opposed to a "one-way process" of adoption or rejection of technology innovation – in which interests become "mutually aligned" [236] and complement existing socio-cultural structures [98] (see Fig. 4). Furthermore, the object of social acceptance research should be "new phenomena, new ideas, policies, and projects" [181]. This reconfiguration of the key components of social acceptance, marking an explicit distinction from public acceptance, exemplifies the self-reflective nature of third wave scholarship and the drive towards more integrated research approaches [239]. The next Section (3.3.5) further reflects on 'questionable' and 'disturbing' trends in the literature [76], foremost identified by Maarten Wolsink, and increasingly discussed by other energy transition scholars [48,62,63,114,168,180,202,203].

3.3.5. A spectrum of positive–negative and active–passive potentialities

Wolsink [76] exposed questionable and concerning trends in the literature, reflecting a tendency towards conceptual misrepresentation and simplification. Owing to a wide range of individual research perspectives [54], the term social acceptance has been used in a variety of ways and taken on different meanings according to specific cases of technology diffusion. When social acceptance towards an emerging technology has an active element, consumer responses may be 'favorable' or 'positive' [48]; transmitted through "endorsement, approval, approbation" or equivalent expressions [114]:

Energy-technologies acceptance may be defined as an affirmative reply or a positive attitude …that is likely to lead to supporting behavior for the respective technology if necessary or requested [54].

Roche et al. [162] describe social acceptance in terms of consent or active support, which is established when multiple social interests are coordinated in a way that serves to promote the technology transition, as well as the interests of the public [98]. When this 'alignment' is reached, the significance of technology adoption and associated actions are institutionalized both within and between stakeholder groups [98]. While different meanings have been explored by some researchers, conceptualizations of social acceptance remain 'narrow' and 'problematic' within the energy transitions literature [240]. To date, only a handful of researchers have approached and understood social acceptance beyond a single discipline such as psychology, sociology, or innovation research [180], stifling the pursuit of more integrated and

[11] Citizens of Old Goole hoped the project would help bridge the economic gap with their more affluent neighbors residing in 'New' Goole.

[12] See Table 1 in [180] for a comprehensive review of definitions used in the literature.

[13] Expressed acceptance is reflected by agreeing with a statement such as "I would accept a hydrogen fueling station in my community," whereas revealed acceptance is represented through non-engagement in the activities designed to promote or prevent such a project [238].

[14] "Consumer acceptance OR consumer response OR consumer acceptability" AND "societal response OR societal acceptance OR societal concern OR social acceptability.".

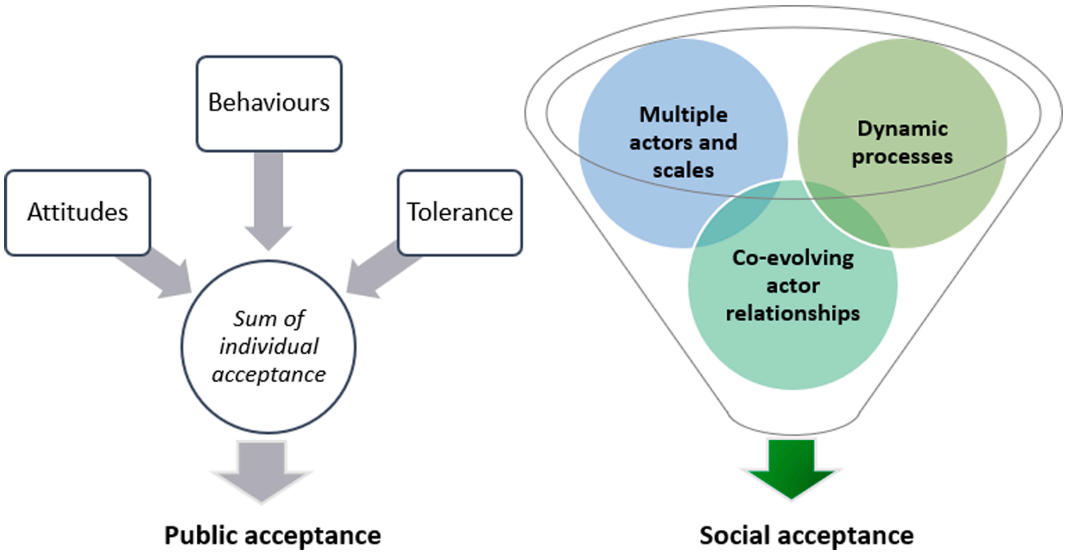

Fig. 4. The components of public and social acceptance based on [48,76].

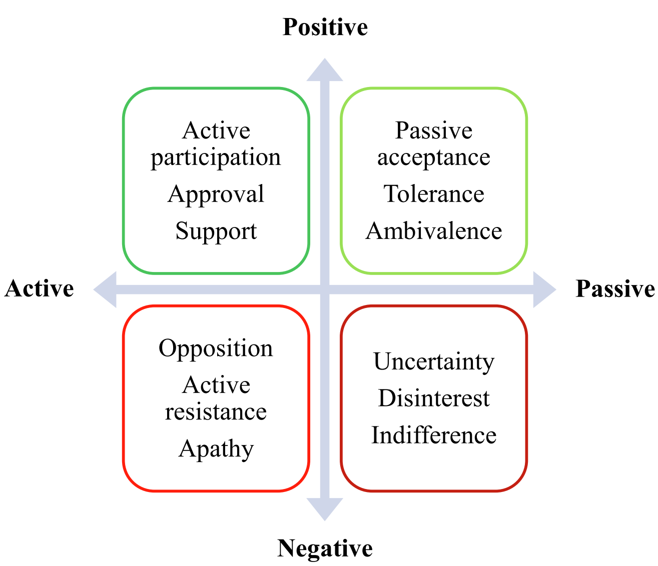

Fig. 5. The social acceptance matrix based on [48,62,63,76,114,168,203].

richer research questions [76]. As Von Wirth et al. [54] reflect, "a coherent overview of this knowledge across scientific disciplines is nonexistent."

In most studies, the term 'acceptance' reflects a passive tolerance for technology adoption [203]. Passive tolerance usually corresponds to an absence of public resistance based on perceptions of low risk levels [240]. Such representations fail to recognize social acceptance as a multi-dimensional phenomenon [48] with complex psychological components [76]; shaped by active and passive reactions to new technology, and positive and negative valuations [236,240]. As conceptualized by Schweizer-Ries [63] and expounded on by Friedl and Reichl [62], these opposites form an acceptance 'matrix', consisting of a wide 'spectrum' of potential responses (see Fig. 5) such as support, uncertainty, ambivalence, tolerance, resistance, or opposition [76,203]. Consumer responses can fluctuate freely between positive–negative and active–passive ends of this spectrum, corresponding to the adoption or rejection of new behaviors and practices [62].

This turn towards a deeper understanding of emotional responses [241] and affective evaluations [242], as captured in the social acceptance matrix, epitomizes the third wave of thinking. For example, Martiskainen et al. [243] reported that positive emotions associated with hydrogen technologies may include desire, joy, gratitude, and

Table 8
Key aims and attributes of the three waves of research on the social acceptance of RET.

	Wave 1 (~1995–2007)	**Wave 2** (~2007–2014)	**Wave 3** (~2015–present)
Approach	Normative approaches	Criticism approaches	Critical approaches
Main assumptions regarding local opposition to RET	Examining NIMBY syndromes and responses	Criticizing NIMBYism and proposing alternative theories and explanations	Focusing on how spatial dynamics, energy justice, power relations, and historical factors shape people's responses to the development and diffusion of RET
Main lines of enquiry	Characterizing opposers and supporters	Examining which socio-psychological and community factors affect opposition to RET, especially in terms of procedural and distributional justice	Adopting a critical approach at *ideological* (e.g. revealing and contesting RET as business and usual), *theoretical* (e.g. applying agonist approaches to community engagement), and *methodological* levels (e.g. using discourse analysis)
Anticipated societal implications	To overcome local opposition to RET	To understand public resistance and ease the transition to RET	To question if opposition to RET should be reduced/overcome
Examples of key studies	[119]	[110–112,145,167]	[54,61,64,76,180,181,243]

Source: Authors' compilation based on [61].

pride, while negative emotions include fear, anger, and greed. However, it should be noted that even at the dawn of Wave 1, Walker [119] had flagged how public attitudes "can be highly variable, dynamic and sometimes contradictory." In this sense, recent theoretical and conceptual advancements mark an uptake in response to an argument some three decades in the making.

3.3.6. Social acceptance as a cross-scalar and multi-actor process

Having reviewed theoretical and conceptual developments presented within the energy literature, there are a multitude of factors that shape social acceptance: legitimacy, trust, and justice [110,167,168]; socio-political, demographic, cultural, psychological, and contextual factors [52,111,240]; and perceptions of costs, benefits, and risks [112,118,156]. In sum, social acceptance is a 'complex' and 'dynamic' phenomenon [76,111] driven by a diverse range of technical, political, economic, and social factors [167]. Compared to earlier waves of research (see Table 8), studies in the third wave stress that the 'positions' of respective actors are dynamic and continuously evolving [76]. Social acceptance is a thus a process where "the question of acceptability is at stake" for each decision-maker [110] and should be examined as a 'cross-scalar' [244,245], 'multi-actor' [48] phenomenon that accounts for "the intrapersonal characteristics of individual acceptance" [54]. In response, acceptance studies should account for how society encounters technology within a unique historical, geographical, socio-cultural, institutional, and economic setting [64,80,98,168]. At the same time, attention should be also paid to whether the scale of technological change itself impacts social acceptance [246]. In view of these findings and the inherent theoretical challenges associated with the study of social acceptance to date, the remainder of the paper answers the call for a clear conceptual approach to the study of domestic hydrogen acceptance [22,42,69,247,248].

4. Social acceptance of hydrogen energy technologies

4.1. Research areas and approaches

The early scholarship on hydrogen perceptions reflects a mix of theoretical dimensions proposed in the social acceptance literature [42]. In the context of hydrogen transportation, Roche et al. [162] identified three main approaches taken by researchers: general attitudinal surveys; non-market economic valuation studies; and risk perception studies. Additional methodological approaches that fall outside these categories include studies based on semiotic theory [162], and experimental or activity analyses [249]. Scott and Powells [22] also classify the hydrogen acceptance literature into three 'strands' of studies: hydrogen for transportation; consumer willingness to pay more to support the introduction of hydrogen technologies[15]; and consumer perceptions of risk and safety.

Most acceptance studies have focused on transport, with primary interest in hydrogen-powered buses, cars and refueling stations, and some emerging interest in hydrogen-fueled shipping and aviation [70]. Hydrogen acceptance has been examined through a socio-technical lens, with several survey studies on hydrogen fuel-cell vehicles and related infrastructure, carried out in countries such as the UK, USA, Netherlands, Germany, Spain, and Japan [57,70]. In general, public support for hydrogen technologies appears to be somewhat positive yet largely reserved, owing to limited awareness and moderate concerns about safety [162]. Reviewing the literature on hydrogen as an energy carrier in transport, Hujits et al. [250] concluded that social acceptance is unlikely to be a major barrier for deploying hydrogen buses, highlighting a potential divergence between public and consumer-facing technologies. In line with the criticism approach, the study highlighted the importance of technology, location, and other contextual specific factors. Notably, prior knowledge also has been shown to act as a driver of hydrogen acceptance [251], especially in the context of transportation [252].

Broadly, this early wave of hydrogen acceptance studies [253–257] – based on both assessments of measured knowledge [253,255], and the effect of information provision [256,258] – suggested that men, younger people, the highly educated, and those in full-time employment are more likely to be better informed about hydrogen technologies than other socio-demographic groups. Furthermore, hydrogen acceptance appears to be positively correlated with environmental awareness [133,253,257] and trust in technology [256], while men are typically more supportive than women [254,257].

4.2. Factors of hydrogen acceptance

Reviewing the social acceptance of low-carbon heating solutions based on a *meta*-analysis of European projects, Heiskanen et al. [98] suggested the following factors as the key determinants of hydrogen acceptance: its 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 the composition of stakeholder engagement. Capturing the complexity and interrelatedness of social acceptance, scholars have theorized that support for hydrogen energy technologies may depend on socio-economic, demographic, geographic, situational, psychological, cultural, and knowledge-related factors [98,112].

Working with several focus groups across the UK, Flynn et al. [150] showed that motivation to adopt hydrogen technologies is strongly linked to economic considerations, usability, convenience, safety, and environmental benefits. Based on a review of seven hydrogen studies, Gupta et al. [113] found that *attitude* (positive and negative), *technology characteristics*, *individual differences* (i.e. socio-economic and demographic factors), *perceived benefits*, and *knowledge* ranked as the key determinants of social acceptance. Anticipating the shift from criticism to critical approaches, Heiskanen et al. [98] linked hydrogen acceptance to the "historical and accumulated experiences" of comparable renewable energy projects, while Flynn et al. [150] argued that hydrogen-fueled technologies must align with established socio-cultural practices and socio-political views.

Subsequent studies in the UK have echoed the importance of these factors. For example, Fylan et al. [75] identified six themes reflecting the public's main uncertainties and concerns: the justification for a hydrogen conversion; the source of hydrogen and its production methods; cost factors; safety factors; practicalities; and the time scales and unknowns involved in the conversion; and behavioral factors such ease of operation and thermal comfort. To better understand hydrogen acceptance, recent studies have further examined attitudinal and behavioral factors [23], together with safety perceptions, economic factors, user experience and technical support, stakeholder engagement, and public trust to understand hydrogen acceptance [23,41,59]. Researchers in Australia have also explored similar themes and reported similar findings [69–70,72,247,248]. While early strides have been taken, more insights are required to better understand the determinants of social acceptance for hydrogen technologies across the transport, power and residential sectors, and the interrelation between key psychological, demographic, situational and knowledge-related variables [250].

4.3. The social acceptance of domestic hydrogen

Research on the social acceptance of domestic hydrogen for heating and cooking applications remains largely underexplored by energy scholars [41]. The hydrogen literature has mostly focused on its use for transport and related infrastructure [178], leaving a significant research gap for understanding the social acceptance of stationary applications

[15] These studies usually employ econometric methods such as Willingness-to-Pay (WTP) and Contingent Valuation Method (CVM).

Table 9
Summary of UK hydrogen trials.

	H21	HyDeploy 1&2	Hy4Heat	H100
Project lead	Northern Gas Networks (NGN)	Cadent Gas	Department of Business, Energy & Industrial Strategy (BEIS)	SGN
Funding mechanism(s)[1]	NIC and NIA	NIC	NIC	NIC, Scottish Government, and UK Gas Distribution Networks (GDNs)
Duration	Jul 2018–Dec 2021	Apr 2017–Mar 2023	Nov 2017–Mar 2021	Apr 2021–Mar 2027
Hydrogen scale	100 % conversion	20 % blending	100 % conversion	100 % conversion
Social acceptance context	Dimension of social science research	First demonstration of hydrogen use (2018); first public demonstration of hydrogen use (2020)	Engagement regarding home conversion	Engagement with host site

Source: Authors' compilation based on [270,314–318].
[1] The main funding mechanisms for these projects is via two pathways: (1) the Network Innovation Competition (NIC) in which gas network companies compete for higher levels of funding from energy regulator, Ofgem, to develop and demonstrate new technologies; and (2) the Network Innovation Allowance (NIA), which allocates funds directly to gas networks for smaller projects [105].

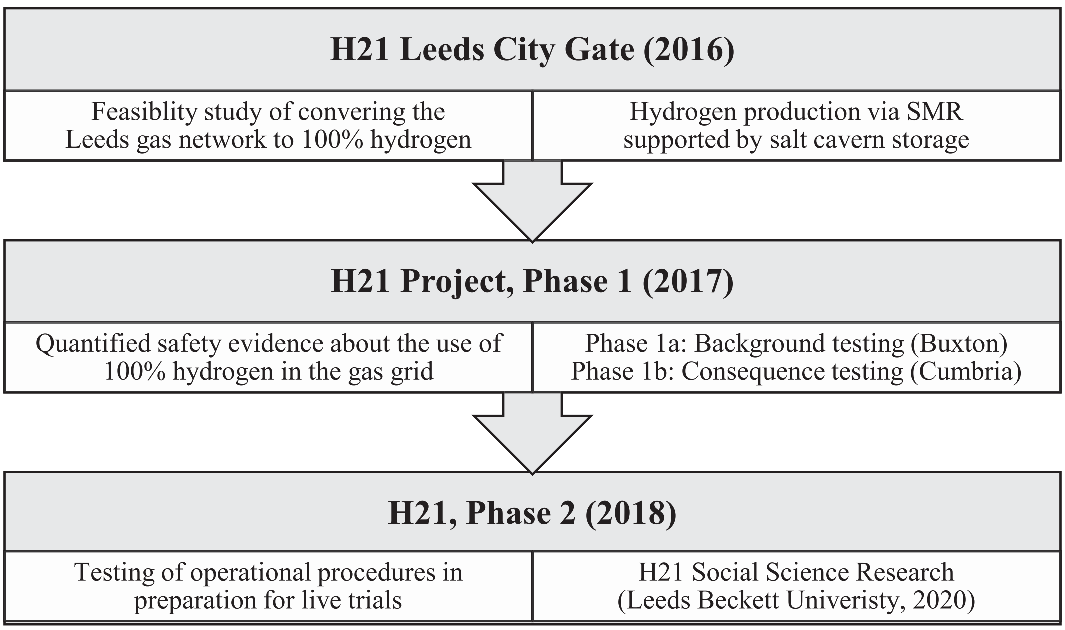

Fig. 6. Timeline and details of H21 Leeds City Gate project [75,262,263].

for the home such as hydrogen boilers and hobs [22,68]. This scarcity is reflected by hydrogen's status as a niche technology in the early stages of development and innovation [259], with few pilot projects or relevant case studies for commercial applications [178]. This point is especially true for domestic heating, which is characterized as "a new and untested proposition" [59]. By contrast, hydrogen fuel cell technology has a long history spanning two centuries [260], with ongoing efforts to deploy fuel cell electric vehicles (FCEVs) in recent years [261]. To date, few survey studies have focused on the social acceptance of domestic hydrogen [247]. Most of the existing research is limited to the UK context [22,23,41,42,59,73,75], reflecting activities around four key projects: H21, and its sub-project Hy4Heat, HyDeploy, and H100 (see Table 9).

4.3.1. H21 Leeds City Gate: Converting the gas network to 100 % hydrogen

The first feasibility study on domestic hydrogen can be traced back to the H21 Leeds City Gate study in 2016. On behalf of Northern Gas Networks (NGN), Sadler et al. [262] set out to determine the feasibility of converting the Leeds gas network to 100 % hydrogen. In 2017, the H21 project secured £9m of NIC funding to make the safety case for hydrogen [263] (see Fig. 6). As part of the H21 evidence base, Fylan et al. [75] conducted an online survey (N = 1027) representative of the first areas to be converted to hydrogen homes, which included Leeds, Monmouthshire, and Birmingham. This selection mirrors the unique spatial dynamics of the hydrogen transition, reinforcing that social acceptance studies should account for the corresponding geographic and community context [57]. The results indicated the scope of the emerging social acceptance matrix for domestic hydrogen, spanning responses such as acceptance, cautious support, disinterest and skepticism, reluctance, and rejection [75].

4.3.2. HyDeploy blending trials and community trials

Hydrogen blending – the injection of small quantities of hydrogen into the existing natural gas grid [42] – has been promoted as a 'practical' and 'non-disruptive' pathway towards securing emissions reduction in residential heating [264]. As a transition mechanism, the government is considering injecting hydrogen (20 % by volume) into the natural gas grid to help reduce short-term carbon emissions [12], which is expected to strengthen the foundations for a future hydrogen economy [265]. The first hydrogen blending trial took place on the Keele University private gas grid in Staffordshire, whereby 20 vol% hydrogen was injected successfully without compromising safety standards or modifying household appliances [41,266] (see Fig. 7).

Subsequently, HyDeploy Phase 2 was launched to extend the evidence base for hydrogen blending by moving the trials to public networks situated in the North East and North West of England [41]. This

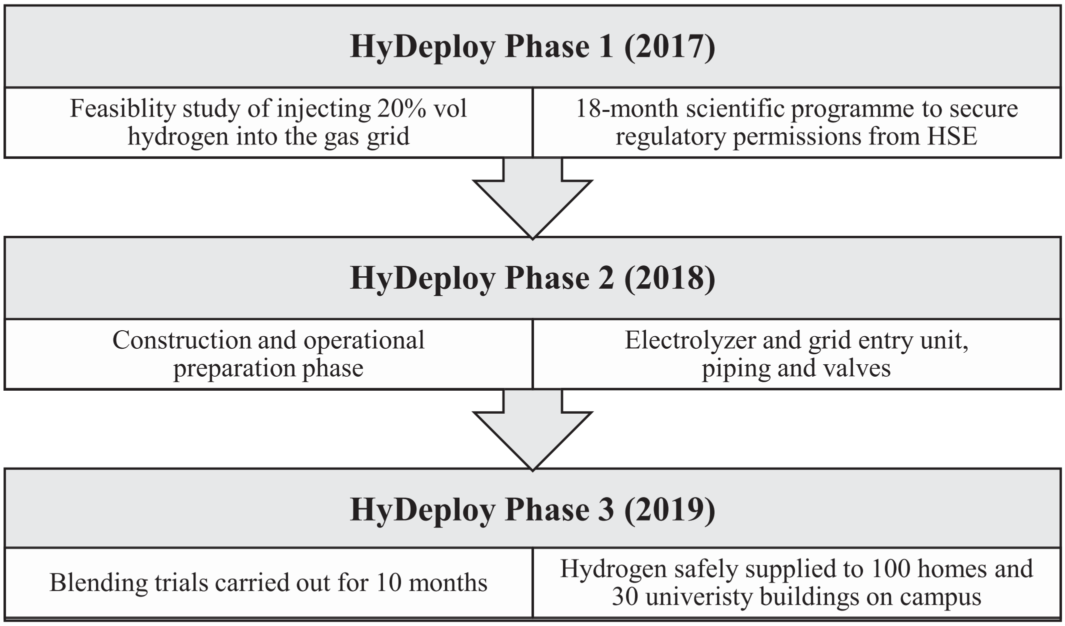

Fig. 7. Timeline and details of the HyDeploy project [41,266,297].

phase delivered its aim to "bring hydrogen injection to the same level of regulatory approval as biomethane injection" [266], through a trial of 670 houses, as well as a church, primary school, and several businesses in Winlanton, Gateshead [267]. In parallel, Scott and Powells published three studies on hydrogen acceptance in relation to HyDeploy (see Table 10), which included an online survey (N = 700) focused on the North of England [42]; a region representative of the HyDeploy trial areas and characterized by "uneven economic and social geographies" [22]. Reflecting the relevance of SPT to the study of social acceptance, the authors argued that the "analytical focus" should be shifted to capture how people are likely to behave, as opposed to what they may think or feel" [22].

Hydrogen pilot projects such as HyDeploy are critical to raising public awareness and increasing trust, while demonstrating the safety case and technical feasibility of domestic hydrogen. At NGN's Low Thornley site near Gateshead, boiler manufacturers Baxi Heating and Worcester Bosch, with support from Cadent Gas and the Department for Business, Energy & Industrial Strategy (BEIS), are showcasing their respective hydrogen heating technologies in two semi-detached modular homes [268]. The Hy4Heat project (part of H21) is the first of its kind, allowing members of the public to interact with hydrogen-fueled appliances to see how they function in comparison to natural gas appliances [268]. Test sites of this description are a critical step to providing information on aspects of behavioral acceptance, which to date has been limited mostly to the results of Scott and Powells [22].

Scaling up from activities at Low Thornley, the H100 Fife project led by SGN[16] is the world's first community trial of green hydrogen [269]. Following the literature review and focus group study commissioned by BEIS on a hypothetical hydrogen trial [59], the trial offers an opt-in process to enable around 300 homes in Levenmouth to switch their gas supply to hydrogen produced via electrolysis from Scottish offshore wind power [270]. The pre-study confirmed that "there is a strong human and social dimension" to converting households to hydrogen, which given the diversity of the UK housing stock and associated social grades, creates a wide range of potentially incompatible individual and communal needs [59]. Together with the logistical challenges of replacing appliances,[17] there is a need to integrate social, cultural, and psychological factors into the planning mechanisms of community trials.

4.3.3. Governance aspects of the UK domestic hydrogen transition

At present, a distinct set of policy, industry, and business actors are spearheading hydrogen development and deployment [179], composed of the companies who own and manage the UK's national and regional Gas Distribution Networks (GDNs), government actors such as the BEIS, boiler manufacturers, and industrial and business players, including members of the Hydrogen Taskforce, a coalition of the hydrogen industry's largest organizations [271]. UK homeowners may be quite familiar with their boiler manufacturer and energy supplier; however, most domestic energy users are unlikely to know much about the operations and territories of GDNs. Bridging this knowledge gap may prove critical to decarbonizing residential heating, since GDNs are the primary group driving innovation in network management and current R&D activities, in turn influencing the spatial dynamics of early hydrogen development and deployment across the UK (see Fig. 8).

Regarding trust in GDNs, Scott and Powells [41] caution that survey participants in the HyDeploy demonstration project raised concerns about the underlying motives of the gas industry, as well as the central government. Demski et al. [175] also found that the UK public considered energy companies as accountable for helping to lead the energy transition, but viewed their contribution to date as insufficient, especially given their ability to invest sizeable capital in low-carbon energy infrastructure and technologies. Evensen et al. [272] further highlighted that public willingness to help fund the energy transition rests strongly on perceptions of procedural and distributional justice regarding the role of government and energy companies.[18]

Based on the literature review findings, citizens appear willing to trust in gas companies in terms of providing safety and risk management, reflecting a degree of socio-political acceptance. However, consumers lack confidence in the commitment and ability of the same

[16] Formerly, Scotia Gas Networks, Scotland Gas Networks and Southern Gas Networks.

[17] For a detailed discussion of these logistics, see [25].

[18] Respondents assigned most responsibility to energy companies (45%), followed by the government (32%).

Table 10
Studies on the social acceptance of domestic hydrogen in the UK, 2018–2020.

Study	Location, research type, and sample size	Approach and research scope	Findings
[23]	a) Nationally representative online survey UK; N = 1029 b) Four focus groups London and Edinburgh; N = 29	• Assesses the public acceptability of hydrogen heating, relative to that of heat pumps • Examines household preferences and barriers to consumer acceptance, with a focus on attitudinal differences between socio-demographic groups[1]	• Knowledge and awareness of both technologies is low • Preferences depend mainly on how respective advantages and disadvantages are communicated • 45–55 % of respondents had no clear preference towards either hydrogen heating or heat pumps throughout most stages of the surveyAt the end of the survey (stage 6), • 63 % of consumers expressed a preference for heat pumps • Hydrogen boilers had a higher perceived installation burden
[59]	4 focus groups with consumers from different housing segments connected to the gas grid[2] England: Manchester and Birmingham; N = 39	• Assesses consumer perspectives on the disruption and costs impacts of a hypothetical hydrogen conversion trial for approx. 300 homes[3] • Focuses on logistical and welfare issues, stakeholder groups, and how participation and communication can be promoted	Skepticism, concerns, and doubts regarding several key areas: Potential cost-neutrality of the hydrogen trial Benefits of the switchoverThe duration of the switchover period (3–4 days) Disruptive impacts Adequacy of proposed incentive schemes and/or compensation packages Loss of equivalence compared to natural gas
[41]	Nationally representative online survey UK; N = 742	• Designs and deploys an online survey,[4] collecting quantitative data on public perceptions of hydrogen and hydrogen blending • Based on initial perceptions, values, and knowledge of hydrogen; the possibilities and pitfalls of hydrogen blending; public trust; and participants' overall support for hydrogen	• Public knowledge and understanding of hydrogen are low • Neutral perceptions of hydrogen's suitability for the domestic environment • Support levels increased when participants were informed about hydrogen's environmental benefits • Perceived cost proved the most significant barrier to social acceptance
[22]	Paper-based survey and in-person interviews (cafés/coffee shops) 10 different locations in the North East of England; N = 100	• Adopts a SPT approach[5] and employs a 'talking' methodology • Examines how the physical and chemical properties of hydrogen may impact the 'gas-energized' social practices of cooking and heating	• Cooking practices more likely to be disrupted than heating practices die to hydrogen's flame characteristics (i.e. near invisibility) • Most participants envisaging hydrogen bringing positive environmental benefits, without compromising safety and user experience, or hampering the economy • It is imperative to develop a suitable colorant for hydrogen-fueled appliances
[42]	a) Online survey, representative of the HyDeploy2 trial areas North of England; N = 700 b) Paper-based survey conducted in cafés Nine towns in the North of England; N = 102	• Employs a mixed methods approach – integrating spatial, quantitative, and qualitative analysis based on the principles of 'grounded theory' [319,320] • Elicits and evaluates public perceptions of hydrogen and hydrogen blending in the UK, in relation to theories of social practice, energy justice, and place attachment	• Respondents were concerned that hydrogen could increase their energy bills and/or taxes, and exacerbate existing problems of fuel poverty • Acceptance is likely to hinge on what hydrogen can deliver to the local community in terms of social and economic benefits • The transition is set to engender complex and unpredictable disruptions and enhancements to people's feelings of place attachment
[75]	Nationally representative online survey UK: Leeds, Monmouthshire, and Birmingham; N = 1027 b) Discovery interviews N = 12 c) Deliberative workshops[6]	• Explores public perceptions of changing the domestic fuel supply to 100 % hydrogen • Examines beliefs about the environment, inconvenience and costs, safety, and potential economic impacts	• 28 % of respondents supported changing to hydrogen gas and using it for heating and cooking • 20 % were more cautious about the use of domestic hydrogen and concerned about potential disruptions • 30 % were disinterested in and skeptical of the hydrogen conversion due to underlying uncertainties and information gaps • 10 % were unconvinced about the conversion • 12 % rejected it outright

Source: Authors' compilation, adapted from [43].

[1] Technical stimulus materials were developed to explain the heating technologies in simple terms, using real life scenarios, while attitudinal differences between demographic groups were gauged according to housing tenure, level of education, location, and age.

[2] Two with owner-occupiers, one with private landlords, and one with a mixture of tenants.

[3] The conversion scenario required no financial investment from households. Although participation was mandatory, households could choose to op-out by disconnecting from gas and switching to electric heating. After the trial, a decision would be made about whether the community would use hydrogen or natural gas.

[4] Based on a review of existing academic and policy literature on the public acceptance of renewable energy and hydrogen technologies.

[5] Participants were provided with simple pieces of information regarding the material and socio-technical properties of hydrogen and asked how these properties might impact their existing hob and boiler practices.

[6] Assessed the public's ability to understand and communicate information about the hydrogen transition.

companies to promote community engagement and trust, through transparent and participatory planning processes [43]. This is reflected by an underlying sense of skepticism or uncertainty regarding the actions of both the gas industry and government, in part owing to poor reputation linked to past policy and business failures [41,59,73,74]. Such a situation undermines the potential for "strong socio-political acceptance," [54] which is critical to "implementing innovations" [97], and supporting community acceptance through trust mechanisms [172,273] and participatory processes [274,275].

Alongside the government, the role of the gas industry in managing a just transition cannot be overlooked, especially since community acceptance is likely to hinge on the level of disruption associated with changes to pipework and other infrastructural upgrades at street level, and how these disruptions are communicated and justified [23,59]. Critically, GDNs, together with energy suppliers, will need to pay careful attention to how they plan, promote, and execute roll-out strategies to secure trust and fairness throughout the hydrogen transition, which should also be enshrined in policymaking. Building off these findings, Section 5 fulfils the main research objective by conceptualizing the social acceptance of domestic hydrogen.

5. Conceptualizing the social acceptance of domestic hydrogen

5.1. Defining the triangle of social acceptance for hydrogen households

If hydrogen homes are to become a reality, the technology will need to secure socio-political, community, and market acceptance from end-users, which represent co-evolving layers of social acceptance. First, it must be clarified what these dimensions mean for prospective hydrogen-fueled communities and households. This calls for clear understanding of the main actors and factors connected to each acceptance dimension (see Table 11).

Underpinning the potential for macro-scale transformation, *social* and *political factors* determine the conditions for technology development and diffusion. **Socio-political acceptance** centers on whether consumers perceive domestic hydrogen as a legitimate and just technology pathway for increasing social, economic, and environmental benefits. A favorable socio-political environment can be supported through commitment to a robust hydrogen strategy and clear targets. Following on from the UK Hydrogen Strategy, supported by the Heat and Buildings Strategy, and the British Energy Security Strategy, the government and key stakeholders should work towards facilitating adequate institutional and regulatory frameworks aligned to the net-zero and energy poverty agendas.

The potential for a socially acceptable transition to hydrogen homes will also be shaped by the level of **community acceptance**, which may depend on a wide range of *contextual factors* such as location, history, and heritage. Operating at the *meso*-level, community acceptance is needed at the outset to help facilitate local trials, infrastructural changes, and other physical measures for enacting a national hydrogen strategy. To reinforce both socio-political and community acceptance, the strategy should pledge long-term benefits to local communities where hydrogen is being deployed, especially in terms of employment opportunities and income security. Such deliverables should be clearly communicated to citizens during the planning process to ensure procedural justice and greater potential for restorative justice in historically deprived and degraded areas. At a later stage in the transition process, local communities and households must be willing to accept, or at least tolerate, the potential disruptive impacts associated with the conversion process. These disruptions will include infrastructural changes and operational activities at street level, as well as temporary disconnection from the gas grid and engineering activities within properties.

Finally, **market acceptance** for domestic hydrogen depends on the role of investors, industry and business actors, manufacturers, installers, and other intermediaries. Should these key actor-networks prove successful in driving low-carbon hydrogen production, while establishing an effective marketplace through robust supply chains and strategic investments; consumers must then be willing to invest in new appliances to actualize market acceptance. At the household level, market acceptance rests on whether consumers perceive domestic hydrogen as a 'like for like' replacement for natural gas [276], with willingness and ability to invest in or modify appliances, and to absorb related energy costs [43]. Together with the purchasing of hydrogen-fueled appliances, skilled technicians are needed to secure market confidence. Driven largely by *economic* and *socio-demographic factors*, market acceptance is critical for reinforcing socio-political support at the macro-economic level and financial investments at the *meso*-scale, alongside hydrogen adoption at the micro-level. All three scales hinge firmly on the cost-competitiveness of hydrogen. In the case that consumers should prove unwilling to invest in new appliances, the large-scale market introduction of hydrogen heating would likely require a more top-down, state-led approach, comparable to historical transitions to natural gas in the UK [277], Netherlands [278], Greece [279], and other countries.

Having defined each acceptance dimension and following the findings presented in Table 3, Table 11 extends the analysis with an overview of the main actors and factors shaping domestic hydrogen acceptance in the UK context. This addition reinforces the multi-dimensional and multi-scalar nature of social acceptance, and the diversity of key stakeholders and actors.

5.2. Attitudinal and behavioral dimensions of hydrogen acceptance

In presenting the main actors and driving factors linked to socio-political, community, and market acceptance, Table 11 reveals that three dimensions are insufficient for capturing the full breadth and unique configuration of social acceptance for hydrogen homes. This conclusion follows the turn from criticism to critical approaches, with domestic hydrogen studies attributing significant weight to the importance of attitudinal and behavioral acceptance factors (see Table 12). Notably, the behavioral dimension of the energy transition has often been overshadowed by a stronger focus on socio-political, community, and market aspects of renewable and low-carbon technologies.[19] While these dimensions remain critical to understanding social acceptance, technologies that are designed to permeate the domestic environment such as hydrogen boilers and hobs must be thoroughly understood in view of consumer attitudes and behaviors. As key determinants of individual acceptance [48,52,111,152], the inclusion of attitudinal and behavioral dimensions shifts the focus more directly to the micro-scale, wherein the market adoption of low-carbon household technologies is ultimately realized [55,281]. At the outset, constructing a valid framework calls for a distinction to be made between "beliefs or attitudes" and "actions or behaviors" [111].

Attitudinal acceptance depends on how public perceptions of domestic hydrogen are shaped by knowledge and awareness, which is influenced by *socio-psychological factors*. The emergence of attitudinal acceptance resounds with the establishment of cognitive legitimacy [282], enabling consumers to know and appreciate hydrogen-fueled appliances first-hand, which advances incorporation and conversion within the domestic environment [86,87].

Behavioral acceptance is determined by *socio-cultural factors*, resting on how consumers perceive the impacts of domestic hydrogen adoption on aspects of the "lived experience" of heating [283] and cooking [22], such as performance, functionality, comfort, safety, and disruption [23]. Firstly, households must be willing to tolerate the potential disruptive impacts and the overall installation burden associated with the conversion process itself.

[19] A case in point is the rise of public opposition, local resistance, political U-turns and planning constraints regarding the siting of onshore wind farms in the UK and other European countries such as Germany and Denmark [280].

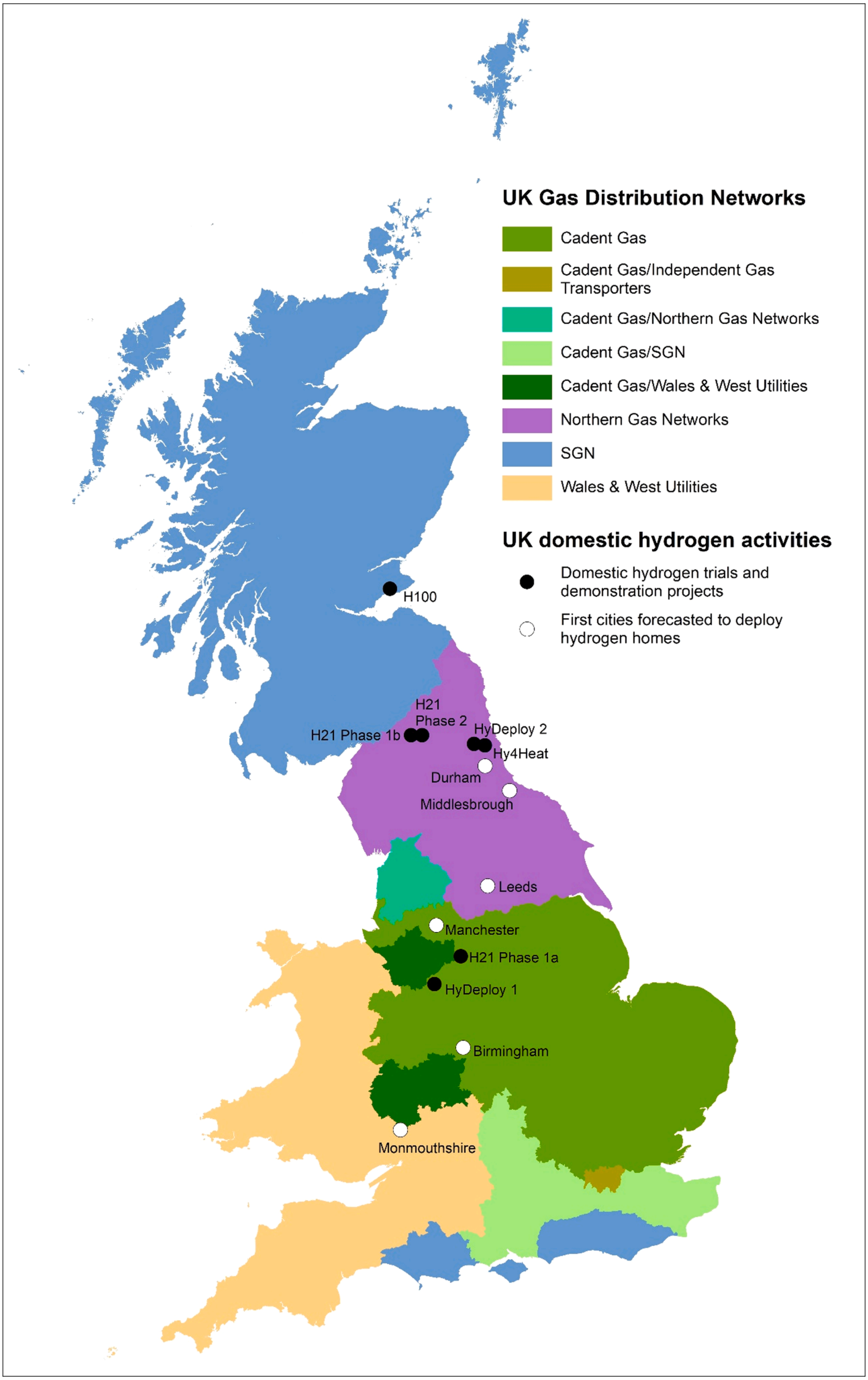

Fig. 8. UK domestic hydrogen activities by territories of Gas Distribution Networks.

Table 11
Actors and factors behind social acceptance of domestic hydrogen.

Acceptance dimension and significance to consumers	Actors	Factors
Socio-political		**Social and political**
Do consumers perceive domestic hydrogen as a legitimate and just technology pathway for increasing social, economic, and environmental benefits?	• Central government	• Public views on national priorities
	• Committee on Climate Change (CCC)	• Trust in the government's net-zero and energy poverty agenda
	• Department of Business, Energy & Industrial Strategy (BEIS)	• Impacts on energy/fuel poverty
	• Health and Safety Executive (HSE)	• Net economic impacts
	• Gas Distribution Networks (GDNs)	• Scope of industrial regeneration
	• Media	• Trust in evidence and information provided by political parties and other key stakeholders
	• General public	• Public perceptions of hydrogen production and distribution methods
		• Scope of community trials and demonstration projects
Community		**Contextual**
Do consumers perceive the local impacts of the switchover as tolerable or acceptable, with the transition securing long-term benefits for their local communities?	• Local government officials	• Trust in local government and supply chains
	• Local councils	• Perceptions of the safety and suitability of hydrogen storage
	• Supply chains	• Distribution of costs and benefits
		• Place attachment and historical heritage
		• Disruptions caused by the switchover at street level
		• Nature of communication processes
		• Level of community engagement
	Residents	• Socio-economic benefits linked to employment opportunities and community development
Market		**Economic**
Are consumers willing and able to invest in modifying or purchasing heating and/or cooking appliances; and to absorb potentially higher energy costs if gas bills increase?	• Hydrogen producers and distributors	• Costs of hydrogen production
	• Investors	• Cost of appliance upgrades
	• Gas companies	• Fuel/energy costs
	• Boiler manufacturers	• Impacts on property prices and rents
	• Gas engineers and technicians	• Financial impacts on households with home-based employees
	• Homeowners	• Incentive schemes and compensation packages
	• Tenants	• Maintenance and repair requirements
		• Alternative technology choices

Source: Authors' compilation based on [22,23,41,42,59,75].

Table 12
Attitudinal and behavioral factors of domestic hydrogen acceptance.

Attitudinal factors	Source(s)
• Safety perceptions	[22,23,41,42,75]
• Environmental values and awareness	[22,23,41,75]
• Knowledge and understanding of hydrogen as a fuel and technology	[41]
• Knowledge of hydrogen production methods	[75]
• Feelings associated with the word hydrogen	[41]
• Perceptions of climate change	[75]
• Perceptions of impacts of hydrogen appliances on heating/cooking performance and efficiency	[42]
• Perceived costs, benefits, and risks	[23]
• Role of information provision	[2,–23,41,42,59,75]
Behavioral factors	
• Impacts to the lived experience of heating and cooking (i.e. boiler and hob practices)	[23,59,75]
• Disruptions to daily routine and overall burden of installation	[23,59,75]
• Perceived impacts on home appliance use	[41,42]
• Maintenance and repairs	[59]

Source: Authors' compilation.

5.2.1. *Socio-political, cognitive, and socio-cultural legitimacy*

Social acceptance is strongly linked to the overall legitimacy of a given technology, which according to Aldrich and Fiol [282] has two distinct categories, namely socio-political and cognitive legitimacy. Socio-political legitimacy depends on the extent to which key stakeholders recognize the suitability of a new technology according to existing social norms and laws. In contrast, cognitive legitimacy operates on the consumer level, emerging as end-users become better informed and more knowledgeable about a new technology until it is incorporated and converted [88,89]. It follows that cognitive legitimacy is a precondition for facilitating socio-political legitimacy, since acceptance of a new technology by key stakeholders and the possibility for active participation and cultural adoption can only ensue following the spread of knowledge [282,284]. While socio-cultural norms influence public perceptions, socio-political legitimacy will be undermined when these perceptions are at odds with the perspectives of technical experts and policymakers [285].

To this line of thinking, a third dimension can be added, namely, 'socio-cultural legitimacy.' Behavioral acceptance – understood through the lens of social norms, intentions, habits, and actions [282] – calls for socio-cultural legitimacy, in the sense that hydrogen must align predictably to the established social practices of (natural) gas heating and cooking [42]. On one level, this means ensuring that the sensory experience of hydrogen provides a continuum to the lived experience of domestic energy in the UK context. In turn, technical solutions to hydrogen odorization and flame coloration [24,38] should minimize disruption to the socio-material nature of boiler and hob practices [22]. At an overall level, socio-cultural legitimacy rests on the extent to which hydrogen is viewed as a direct substitute for natural gas in terms of safety and performance of appliances [59,276], coupled to the critical benefits of energy efficiency, energy security, and decarbonization [28].

At the positive and active end of the social acceptance matrix, once cognitive legitimacy is firmly in place, the uptake of new socio-cultural values such as environmental citizenship [150,201] and energy-saving attitudes [286,287] may have a transformational impact on the diffusion of low-carbon domestic hydrogen. Accordingly, social acceptance rests on two additional questions concerning consumer attitudes and behaviors:

(1) **Attitudinal**: According to knowledge and awareness levels, do consumers perceive domestic hydrogen as a safe, reliable, efficient, and clean technology option, offering at least general equivalence to natural gas in terms of use and performance?

(2) **Behavioral**: Are consumers willing to tolerate potential disruptions to their domestic environment and daily routine during the switchover, and subsequent changes to the lived experience of heating and cooking?

5.3. Linking the five dimensions of domestic hydrogen acceptance

To facilitate a socially acceptable and efficient transition to domestic hydrogen, there should be a clear definition of what social acceptance means to different households and communities in the national context, accounting for the importance of geographical scale, household composition, housing tenure, and other key spatial and socio-demographic factors. As argued throughout this paper via the lens of social acceptance issues [54,110], the spatio-temporal patterns of renewable energy adoption [288] are shaped by a range of interacting scales, dimensions, and factors.

Synthesizing the theoretical, conceptual, and empirical findings, together with the results presented in Table 11 and Table 12, suggests that hydrogen acceptance is a co-evolving phenomenon rooted in the dynamic interplay of at least five distinct dimensions: socio-political, market, community, attitudinal, and behavioral acceptance (see Fig. 9). These dimensions should be regarded in one sense as distinctive building blocks for establishing social acceptance, but moreover as interacting layers that co-evolve over time within a heterogenous system. This co-evolution unfolds as consumers shift between positions of ignorance, resistance, indifference, ambivalence, tolerance, and acceptance, according to a wide range of socio-political, contextual, socio-psychological, socio-cultural, economic, and socio-demographic factors. This conceptualization unifies both criticism and critical approaches to the study of social acceptance, thereby closing the knowledge gap on the domestic hydrogen transition.

Attitudinal acceptance can be regarded as a foundation for encouraging households to adopt hydrogen, which is required to ensure that consumers accept the risks, benefits, and costs of the transition. If knowledge and awareness levels are lacking to an extreme, there is limited feasibility that consumers would take strides to actively support domestic hydrogen adoption. At present, the social acceptance of domestic hydrogen remains constrained by uncertainty about how its costs, benefits, and risks compare to other low-carbon heating technologies, such as heat pumps and district heating [23]. Previously, it has been shown that awareness is a precondition for the large-scale adoption of innovative, low-carbon technologies, which calls for easy access to reliable sources of information [151]. Domestic hydrogen is expected to follow suit in this regard. Thus, moving from tolerance/passive acceptance to active support, calls for sustained consumer engagement, which rests heavily on the efficacy of communication channels such as media representations and local councils. Furthermore, the potential scope of consumer engagement will be driven by the results of forthcoming trials and demonstration projects [289,290], as reflected by Cadent's "Green Print" for a low-carbon future: "the challenge of decarbonizing heat will require consumer engagement and consent on a scale we have not yet achieved in energy – and perhaps in any sector" [291].

In this sense, attitudinal acceptance underpins the scope for broader public support across the macro-level, serving to consolidate the level of consumer buy-in regarding the legitimacy of hydrogen, as a net-zero technology aligned to strengthening energy security and alleviating

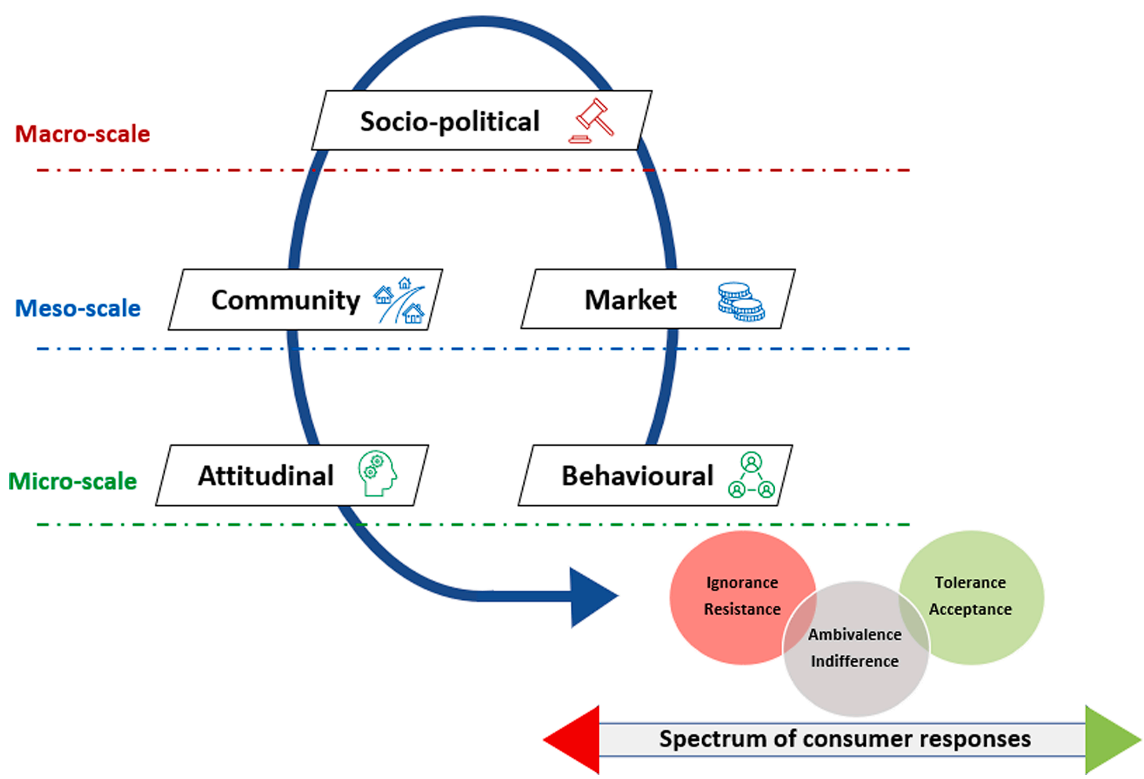

Fig. 9. The five dimensions of domestic hydrogen acceptance.

fuel poverty. At the *meso*-level, attitudinal acceptance can help consolidate community support by building trust and confidence, while also driving the potential for market acceptance by increasing consumer willingness to invest in hydrogen appliances and pay potentially higher energy bills. Finally, behavioral acceptance, if arrived to, helps realize the domestication of hydrogen heating and cooking, established on grounds on cognitive, socio-political, and socio-cultural legitimacy.

6. Conclusions

The consumer-facing side of the domestic hydrogen transition can only begin to be understood meaningfully through a critical, multi-dimensional approach to the study of social acceptance, which moves beyond the traditional dimensions of socio-political, community, and market acceptance. In drawing this conclusion, three key contributions have been made to the energy transitions literature, which can help facilitate clearer theoretical, conceptual, and empirical insights, as social acceptance research continues to evolve.

The first contribution is to provide a detailed analysis of the current state of research on the social acceptance of RETs. To the authors' knowledge, a clearly structured review of the literature is yet to be presented following the three waves of research identified by Batel [61]. Accordingly, future studies should take stock and move beyond criticism approaches by internalizing more critical perspectives. This can be achieved by examining social acceptance in multiple ways, several of which can be feasibly combined: through an energy justice lens; by accounting for spatio-temporal factors, socio-historical forces, and power relations; by applying a multi- and cross-scalar perspective; and above all, by recognizing the dynamic nature and richness of potential consumer attitudes and responses, as visualized in the social acceptance matrix. Accordingly, researchers should adopt a systematic and holistic approach that is conceptually and methodologically designed to explain the interdependency and interaction between relevant causal factors of social acceptance [111].

The second contribution is to unpack the main actors and key factors underpinning the social acceptance of domestic hydrogen in the UK context, situated according to their respective dimensions and scales. To date, information on domestic hydrogen trials and demonstration projects has not been presented in the academic literature, and moreover, these activities have not been matched coherently with corresponding evidence on hydrogen acceptance (i.e. results survey studies and focus groups). This synthesis provides a more concrete starting point for both stakeholder and spatial analysis. The research community should respond by analyzing key socio-political, socio-economic, socio-cultural, and geospatial parameters [45,292,293], supported by the application of ANT- [294,295], and SRT/SPT-based approaches [22,185].

Building from these core findings, this study presents a key conceptual contribution to the energy transitions literature, represented by the five dimensions of domestic hydrogen acceptance framework. Examining this configuration has revealed that hydrogen acceptance is more likely if the technology delivers net economic gains for the national economy, which trickle down to the population in a tangible way, for example, through employment opportunities, income security, and community development. Moreover, the emerging spatial dynamics of the UK hydrogen economy, characterized by industrial clusters and regional hubs, entail strong implications for energy justice and social acceptance. In turn, future hydrogen studies should unpack the impacts of place attachment and place identity on public perceptions, community support, and trust in key actors.

Ultimately, domestic hydrogen acceptance will rest on whether consumers view it as an economical, reliable, efficient, and fair technology, which will uphold safety standards and trust in the gas network, while living up to its net-zero promise. The transition to hydrogen homes must seek to deliver on all these fronts without exacerbating the propensity for fuel poverty or compromising the lived experience of heating or cooking. As the concept of hydrogen homes shifts towards becoming a tested and more familiar proposition for decarbonizing residential heating and cooking, scholars should internalize these findings to ensure social acceptance is considered critically: as a multi- and cross-scalar phenomenon; operating dynamically and unpredictably alongside a rich matrix of potential consumer responses. Such a commitment can direct the ongoing wave of social science research towards a more integrated understanding of how to support and accelerate a fair and efficient hydrogen transition in candidate cities and towns.

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:** Writing – review & editing.

Declaration of Competing Interest

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

Data availability statement.

Data sharing not applicable no new data generated.

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Further reading

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