Towards a New Social Science Research Agenda for Hydrogen Transitions: Social Practices, Energy Justice, and Place Attachment

Abstract

In recent years hydrogen has been repositioned as potentially playing an important role in the decarbonisation of global energy consumption, particularly the decarbonisation of heat. Reflecting a recognition that public support will be central to its success or failure, a body of research has emerged investigating public perceptions of hydrogen in a range of different contexts. The majority of this research has followed quantitative, positivist understandings of human behaviour and has attempted to pinpoint specific factors that determine hydrogen acceptance. This article proposes a different research agenda for hydrogen transitions that can inform hydrogen's introduction to domestic gas supplies as a fuel for homes. The article identifies and conceptualises three aspects of a hydrogen transitions research agenda: how hydrogen has the potential to impact gas-energised social practices of heating and cooking in the home; how it may shift lived experiences of fuel poverty and energy injustice; and how it may disrupt or enhance place attachments of the communities within which it will begin to be deployed. To illustrate the argument, the article presents findings from a research project exploring public perceptions of hydrogen blending in the United Kingdom. Drawing on these findings, it is shown how researching the potential impacts of emerging hydrogen transitions will require a broader and deeper engagement with theories of social practice, energy justice, and place attachment. The article concludes by summarising the implications of the argument for hydrogen researchers and identifying the challenges and opportunities of a new social science research agenda for hydrogen.

Keywords

Hydrogen, Transitions, Social Practices, Energy Justice, Place Attachment

1. Introduction

In recent years hydrogen has been repositioned as potentially playing an important role in the mitigation of climate change via the decarbonisation of global energy use [1], especially in cool and temperate climates, because burning it emits only water vapour and is thus free of carbon dioxide emissions. In particular, it is increasingly seen as a possible solution to the decarbonisation of domestic heat which, in the United Kingdom, comprised 98% of all residential emissions in 2016 [2]. In this scenario, hydrogen is beginning to be envisaged as gradually replacing natural gas (methane) as the fuel used in gas-fired appliances in homes, particularly space-heating boilers. In doing so, hydrogen is likely to move into one of the most intimate spaces in people's lives, engendering a broad array of transformations to social and economic structures wherever it is introduced.

The central argument of this article is that dominant social scientific research approaches to hydrogen are insufficient for understanding and analysing the changes associated with hydrogen's deployment in gas networks as a fuel for homes. Much of the now sizable literature which has developed over the past two decades has followed quantitative, positivist understandings of human behaviour. Drawing from social acceptance of renewable energy literatures and theories such as the theory of planned behaviour [3-6], most existing hydrogen perceptions scholars have adopted a conceptualisation of people or 'the public' as having pre-existing attitudes, values, and dispositions which subsequently shape the levels of acceptance or support they have for hydrogen. They have used survey-based methodologies with the aim of exploring specific factors that are hypothesised to impact upon acceptance, such as knowledge of hydrogen, environmental values, and trust in technology [7-12]. More recently, scholars have focused closely on hydrogen as a fuel for transport, reflecting the ways that hydrogen is beginning to be deployed alongside electric vehicles as a replacement for traditional carbon emitting transport options [13-17].

While the insights generated by this work are significant, in this article we propose that a different line of social scientific enquiry is necessary if we are to better understand the impacts of hydrogen as a fuel for homes. We suggest that this line of enquiry is necessary simply because bringing hydrogen into the home represents a change of the stakes involved: hydrogen will no longer be an unknown, peripheral technology that can be perceived and evaluated at a distance but will permeate homes, communities, economies, and everyday practices to an unprecedented degree. To make this argument we firstly conceptualise three ways in which hydrogen might impact people's lives by drawing upon recent research into the development of hydrogen technologies as well as wider work in energy research and social science. Firstly, we discuss how hydrogen has the potential to impact gas-energised practices of heating and cooking in the home; secondly, how it may change the lived experience of fuel poverty; and thirdly how it may disrupt the identities, landscapes, and economies of the communities within which hydrogen will begin to be deployed. Our analysis is necessarily tentative and partial, and is not intended to be definitive nor to exhaust the impacts that hydrogen might have. Instead, our aim is to conceptualise how the early stages of emerging hydrogen transitions will be lived and felt for many and to think through how this might unfold.

We then embark on an empirical analysis to ground and explore these themes, drawing from a project examining public perceptions of hydrogen blending in the United Kingdom. Hydrogen blending, defined as injecting hydrogen into the existing natural gas supply in small enough quantities to require no changes to domestic gas-fired appliances, is increasingly seen as an important stepping-stone towards a broader conversion of gas networks to carry hydrogen [18]. Part of the appeal of hydrogen blending is its supposed *non-disruptive* nature: it is seen by proponents as "a practical, non-disruptive and necessary step to lead to further CO2 savings with hydrogen in the future" [19:4]. In essence, our intention in this article is to explore the validity of this claim in light of the three issues that we identify.

2. Conceptualising the impacts of hydrogen

2.1. Hydrogen in the home

This section introduces what we see as the three primary impacts of the introduction of hydrogen as a fuel for homes. The first is its impact on gas-energised practices that take place within the home: cooking and heating. Gram-Hanssen and Darby provide a useful fourfold typology of the overlapping meaning(s) of home, whereby the home is conceptualised as providing security and control; as a site of activity; as a place for relationships and continuity; and as concerned with identity and values [20]. Here we are concerned with the combination of two of these; the notion of home as a place within which certain activities are undertaken, and as a place where continuity and permanence are socially reproduced. Combining these, our focus is on how cooking and heating practices achieve continuity and relative stability over time and how they may be disrupted or modified by hydrogen's introduction.

The impact that hydrogen might have on cooking and heating, whether in pure form or in a blend with natural gas, can be understood through social practice theory. Proponents of social practice theory broadly understand social practices as "embodied, materially mediated arrays of human activity centrally organised around shared practical understanding" [21:11]. Cooking and heating are two such practices that are ordered around different configurations of meanings, materialities, and competencies which are coordinated and brought together in time and space [22]. In material terms, cooking and heating are both carbon-intensive practices in that they usually (but not always) rely on the burning of natural gas on stoves and in boilers; natural gas, along with household technical infrastructures, constitutes the materiality of cooking and heating in homes. For our purposes, what is of interest is how a particular technical intervention aimed at decarbonising these practices – diluting or replacing natural gas with hydrogen – may or may not alter how they are performed by people. Drawing on the work of Lefebvre, Powells *et al* conceptualise such interventions in terms of *arrhythmia*, "disturbances to the pre-existing rhythms of performance of practices and the possibility of the emergence of new ones" [23:46]. What is at stake in such an approach is a consideration of whether hydrogen will alter practices of heating and cooking to a degree that people may find using it instead of natural gas (un)acceptable. A historical example of how this may occur is provided by the transition from 'town gas' to natural gas in the United Kingdom in the 1960s and 1970s. As Araposthathis *et al* have shown, the conversion of consumer appliances to burn natural gas precipitated a range of problems as established, habitual practices of heating, cooking, and doing laundry were disrupted by unfamiliar equipment, technical faults, and a new form of combustion. As they put it, "users could not get used to the new social practices" that emerged from the conversion [24:11].

This research highlights two possible causes of arrhythmia to practices of cooking and heating when hydrogen is added to domestic gas supplies. A first possible cause stems from the historical and cultural *meanings* of hydrogen itself. In the twentieth century hydrogen was utilised in two ways that have a lingering presence in the twenty first: in the development of thermonuclear weapons, which contained heavy hydrogen isotopes and were as a consequence colloquially termed H-bombs, and in hydrogen-filled airships, most prominently the German ship Hindenberg, which caught fire and was destroyed over New Jersey in 1937. Research has demonstrated that although hydrogen is most often perceived neutrally, perceptions of hydrogen as inherently explosive, dangerous, and associated with bombs do persist [7-8]. For instance, Sherry-Brennan *et al* used a free word association to gauge participants' initial reactions to hydrogen: 19.7% of responses were categorised as negative, with the words bomb, danger, explosive, and airship all mentioned [8]. However, these studies have not explored how these lingering cultural meanings might (re)shape the ways that social practices of cooking and heating are undertaken if hydrogen becomes a part of gas-energised social practices.

A second possible cause of arrhythmia relates to the *materialities* of hydrogen. Leaving aside the likely need to completely convert or replace current gas-fired appliances in homes if natural gas is swapped for hydrogen in gas supplies, scholars have highlighted how the physical and chemical properties of hydrogen could engender material changes to how practices of cooking and heating are undertaken. In pure form hydrogen is odourless, colourless, tasteless, and has considerable differences to natural gas in terms of ignition temperature, flame speed, and diffusion rate [see 18:304, 25-28]. If hydrogen is blended with natural gas these changes are lesser, but research suggests that there will still be material variations. For example, the "addition of hydrogen to natural gas would increase the flame speed, causing the flame to burn closer to the gas ring or oven burner" [27:27], and the visibility of the gas flame on cookers or boilers would decrease in proportion to the amount of hydrogen that is blended [27:33]. These challenges are considered relatively minor in the technical literature, but a social practices lens highlights that such variations may create moments of arrhythmia in practices of cooking or heating; temporary moments of hesitation and openness where a material change is confronted and which must then subsequently be investigated, negotiated, and absorbed into the practice, possibly with some degree of modification. Scholars working at the intersection of domestic energy use and social practice theory have shown how practices are influenced by forms of 'know-how' - habitual ways of interacting with energy that develop over time in specific domestic contexts [29]. They have stressed the senses of touch (for example, sensing heat), smell (in detecting gas leaks), sound (monitoring the sounds made by a boiler), and sight (judging whether or not appliances are working by examining the visibility and diameter of a gas flame) as important ways people manage and control their energy use on a day-to-day basis [30]. The use of hydrogen in the home will in other words constitute the entry of new *meanings* and *materialities* into everyday practices of cooking and heating, entries that may (re)shape the ingredients of those practices in ways that might, or might not, be deemed acceptable.

2.2. The costs of hydrogen

A second issue concerning the deployment of hydrogen for the home is how much it will cost, and how any costs are distributed, offset, subsidised, or otherwise governed. The scenarios analysed by the United Kingdom's Committee on Climate Change (CCC) provide an indicative example of the increased cost implications of emerging hydrogen transitions [31]. Their analysis states that the overall cost of producing hydrogen, including necessary Carbon Capture and Storage (CCS), "could add around 4bn/year to the costs of heat" [31:108]. In addition, the cost of installing hydrogen boilers and upgrading domestic piping could add a further £7bn/year, and the costs of converting the natural gas network to distribute hydrogen are uncertain but considerable [31:108]. In an earlier analysis, Dodds and Demoullin add that the labour costs and the costs of designing new hydrogen meters and leak detectors would add a further £300 and £160 per household respectively to the overall figure [26]. The CCC estimates that, overall, "[d]ecarbonising [the] heat that is currently provided by natural gas is likely to incur additional costs of around £28 bn/year" [31:107] This subsequently raises the question of the extent to which households will be required to pay more, either in energy bills or in taxation, to facilitate a conversion to hydrogen.

Much hydrogen perceptions literature recognises that cost is an issue, and has incorporated it into studies in two ways. Firstly, studies testing for the possible determinants of hydrogen acceptance have included income in their models as an independent variable. For example, in their study of public perceptions of hydrogen in the Netherlands, Achterberg *et al* note that those with higher levels of income were marginally less supportive of hydrogen technology [11]. Far more prominent however have been Willingness to Pay (WTP) approaches rooted in environmental economics, and which attempt to quantify the additional amount that people would be willing to pay for renewable energy technologies. The results and methodologies of these studies have varied. Some scholars have used Contingent Valuation Methods (CVM) to quantify willingness to pay. O'Garra *et al* found that there was a WTP for hydrogen buses in four European cities of between €0.29 and €0.35 per single bus fare, and that in some cities this was correlated with higher income [32]. More recent studies focusing on Korea have indicated a higher WTP of between $2 and $5 to support the broad introduction of hydrogen technology [33-4]. Other studies have focused on eliciting WTP for hydrogen in terms of acceptable percentage increases to current energy bills, with Maack and Skulason finding that an increase of between 10% and 20% was acceptable to their participants in Iceland [35]. There are exceptions to the trend [36], but the majority of this research demonstrates that a WTP more for hydrogen is present in different places and contexts.

However, Ricci *et al* have argued that there are problems with these approaches, particularly those focusing on CVM. Firstly, they noted these methods rest on the assumption that people "fully understand what [the benefits of hydrogen] would be, given that most of such benefits are public goods that people do not easily connect to their daily preoccupations and priorities" [7:5875]. The overall costs and benefits of hydrogen are, as we have suggested previously, still a matter of considerable uncertainty, and it is therefore unreasonable to expect people to translate any possible benefits into valid assertions of WTP. Secondly and relatedly, Ricci *et al* have also noted that the 'value-action gap' applies to hydrogen, namely that while support and WTP are moderately high there are limits to the extent to which people are willing to translate this support into tangible changes in their everyday lives, even assuming that the benefits of doing so are properly understood [37]. To this we would add that in current WTP hydrogen research, there is no engagement with wider research on energy deprivation and fuel poverty beyond the inclusion of income as an independent variable in statistical analyses. Income is evidently important in that it shapes the capacity of people to pay for energy, but focusing only on income as influencing WTP eschews a consideration of alternative social, political, and structural drivers, as well as households' experiences of energy use, energy bills, and deprivation [38].

An unexplored research avenue is therefore to connect the development of hydrogen technology and its analysis to notions of fuel poverty, and to concepts of energy vulnerabilities, energy precarities, and energy justice more broadly [38-40]. These approaches all have at their core a shift away from statistical methods towards analysing "how fuel poverty is experienced in everyday life" [41:2]. Concomitantly, they draw attention to the ways that energy policies, market fluctuations, and the development of new energy technologies unevenly and disproportionately impact upon different cross-sections of society in ways that are irreducible to statistical indicators. Middlemiss and Gillard, for example, suggest that macro indicators such as 'fuel poverty' have a limited ability to capture the dynamism of energy vulnerability and how it is shaped by structural and institutional factors beyond the influence of individual or collective households. Their analysis, based on qualitative research with fuel poor households, "paint[s] a broader picture of the experience of fuel poverty, which includes both new elements (social relations) and reframed understandings of older elements (the stability of household income)" [42:153]. Returning to hydrogen, our point here is that current WTP methods are useful for elucidating broad patterns of WTP, but could be strengthened by more fine-grained, qualitative work that explores the ways in which people think using hydrogen would complicate, or disrupt, their day-to-day experiences of energy use and economy, and connects this to wider structural forces. This is particularly important considering the uneven economic and social geographies of planned hydrogen trials and subsequent deployment in UK towns. It is to this that the third and final sub-section turns.

2.3. Place attachment and hydrogen infrastructure

The development and deployment of hydrogen will not be the same everywhere. Instead, locally contingent hydrogen transitions will take place in in different ways in different places. In the United Kingdom, a specific economic and social geography of hydrogen is emerging whereby particular places and regions are being positioned, or are positioning themselves, as at the vanguard of the hydrogen economy. There is not the scope here to fully unpack this geography, but it is partly emerging because of the growth and strengthening of alliances between different actors at multiple geographical scales, particularly gas distribution networks, local and regional government, and stakeholders in chemical and manufacturing industrial clusters [43]. These alliances see a possible hydrogen economy as fundamental to clean, green economic growth, and the North of England is emerging as a key meta-geographical focus, with interconnected hydrogen 'visions' currently in development [44-5]. Importantly, these visions are increasingly positioned as key to the reversal of the economic stagnation experienced by some of these areas in the aftermath of deindustrialisation. In parallel, the deployment of hydrogen will involve more infrastructural change than swapping natural gas for hydrogen in pipelines might imply. A case in point is the HyNet North West project, which envisions hydrogen production and blending plants, new pipelines, offshore carbon storage, onshore hydrogen storage facilities, and the construction of numerous hydrogen refuelling stations to support decarbonised road and rail transport. In turn, it envisages economic development for the North West of England, centred on historic industrial clusters and coordinated around the cities of Manchester, Liverpool, and Chester [45]. In these ways, hydrogen's development and deployment will be highly place-specific and involve significant infrastructural change.

This is crucial because renewable energy infrastructures are often a point of public contention and resistance. In relation to hydrogen, some research has focused on public perceptions of the actual or imagined construction of hydrogen refuelling stations in particular places. Much of this work has drawn on the NIMBY (Not In My Back Yard) idea, which "refers to situations in which people have a negative attitude towards a certain activity proposed for their own (local) residential area that they would support (or not object to) if it were situated somewhere else" [46:289]. For example, in their studies of public acceptance of hydrogen refuelling stations in the Netherlands, Huijts and colleagues hypothesise that "acceptability levels may [...] increase with distance – which means that there is a positive effect of distance on acceptability" [47:10369, see also 48]. They measure distance or proximity in terms of the "meters between one's house and the nearest fuel station" and subsequently employ structural equation modelling to argue that those living further away from a station are more likely to support it [47:10369]. While insightful, this work has thus far operated with a somewhat narrow sense of what constitutes space, place, and location. Local resistance or acceptance is thought of in terms of the physical, measurable proximity of one's residence to refuelling stations, which is then conflated with resistance to or acceptance of these infrastructures in particular *places*. What these studies cannot explain is why those who live closer to refuelling stations respond the way that they do, how they imagine and represent the distance between their homes and refuelling stations, and the specific ways that they feel (or do not feel) that their local areas may be affected by the construction of refuelling stations and associated infrastructures. They also eschew the specificity of place, and cannot account for the role of industry, history, and economic development in shaping the views of residents.

In an insightful critique, Devine-Wright has proposed an alternative theory whereby resistance to energy infrastructures should be conceptualised in terms of place attachment, identity, and belonging [49]. Drawing on theories of social representation, Devine-Wright proposes a theoretical framework whereby place change is understood as involving stages of initial awareness, interpretation, and evaluation, followed by different forms of acting on and coping with change [50]. A key inspiration for the role of place in this research is the work of Massey, who argues that place should be conceptualised as a perpetually evolving set of relations that is in a state of constant flux rather than the container within which those relations occur – place is not defined by the boundaries of a city, building or town [51]. This understanding of place has two distinct advantages: it firstly demonstrates that, although important, place is irreducible to demography and attempts to quantify spatial extent, and conversely cannot be defined without reference to historical and social relations, and secondly it allows for the possibility that place attachment can be felt and occur at multiple scales (street, neighbourhood, town, city, region) simultaneously and in different ways. In turn, it allows a way of conceptualising possible acceptance or resistance to hydrogen infrastructures that is sensitive to the shifting scales and sites of infrastructural change, and which pays particular attention to formative role of place histories, economies, and identities in shaping how people evaluate energy infrastructures.

In a 2010 article, Devine-Wright conceptualises threats to place and identity in terms of *disruption* [50]. He proposes that the phenomenon of disruption can explain how stronger feelings of place attachment can be associated with negative responses to particular infrastructure projects. But as he continues, "it would be misleading to presume that energy projects […] will *necessarily* disrupt place attachments" [50:272]. Instead, Devine-Wright suggests energy infrastructure could be seen as disrupting *or* enhancing place attachment and that feelings of place enhancement stemming from energy infrastructures can take various forms. For example, in the context of wind farms, Lombard and Ferreira have suggested that the rising values of the land on which wind turbines are located could be seen as a form of political-economic place enhancement [52], and Cowell *et al* have noted that the notion of 'community benefits' can be seen as an act of equation balancing, whereby the provision of concrete benefits can negate other disruptions caused by renewable energy projects [53]. The work of Devine-Wright and particularly the language of disruption therefore offers a way to think through how the deployment of hydrogen might unfold *in place*, and how hydrogen might be viewed by residents as impacting upon their local areas.

3. Research context and methods

In the previous section we have discussed and attempted to conceptualise three possible impacts that will be engendered by the introduction of hydrogen to the gas supply for homes. In what follows we present findings from a wider project examining public perceptions of hydrogen blending to empirically ground these themes and show how they might be explored.

The research upon which this paper is based was funded by *[detail deleted for anonymous review]*. Our aim was to conduct a study which would elicit perceptions of hydrogen and hydrogen blending from two samples of respondents that were broadly representative of [*anonymised trial areas*]. To do so we developed a mixed-methods approach which was designed to integrate spatial, quantitative, and qualitative analysis. Our synthesis of these modes of analysis was inspired by Ricci *et al*'s critique of quantitative methods in hydrogen perceptions research [7] and by our own reading of the insufficiency of extant literatures for thinking about the impacts of hydrogen in the home, as elaborated in the previous section. Ricci *et al* provide three criticisms of quantitative approaches in researching public understandings of hydrogen [7:5875]:

> "First, they are unable to cover complex and unfamiliar topics in-depth. Second, they are unable to deal with the socio-cultural contexts in which values, beliefs, perceptions and attitudes are rooted and the complex processes by which they are formed. […] Third, the necessity to have pre-structured questions leads to presenting respondents with issues that have already been 'framed' – by selecting what is relevant and what is not on a certain topic – leaving people no opportunity to frame the issues from their own perspectives."

They continue by stressing the value of qualitative approaches in eliciting and exploring public understandings of new technologies that are characterised by uncertainty and low public awareness. Yet, as they correctly note, qualitative methods have their own specific limitations, "such as the difficulty of being representative of wider populations when sampling for groups" [7:5876]. Overall, Ricci *et al*'s critique points towards the need for integrated mixed-methodologies for analysing hydrogen, particularly in the context of the ongoing shift towards using hydrogen as a fuel for homes.

We therefore developed a survey methodology which was designed to be deployed in two ways: online and through face-to-face surveys conducted in cafes. For the online survey, we used the online survey panel Prolific to obtain a sample (n=700) which was representative of [*anonymised trial areas*] in terms of age, gender, income, ethnicity and housing tenure.[1] To achieve this we used a quota based structured sampling frame to select 700 responses for analysis from an initial larger dataset of 1080 responses. The demographics of the possible trial areas was obtained from publicly available UK 2011 census data.

In addition to this dataset, we conducted face-to-face paper surveys with members of the public in nine towns across the North of England. These sites were chosen on the basis of their demographic, political, and socio-economic resemblance to [*anonymised trial areas*]. We included face-to-face surveys in the methodology to enable the collection of detailed qualitative data that would "allow for an in-depth exploration of the process by which views are formed and understanding is developed" [7:5876]. We chose to conduct these surveys in cafes because they have the virtue of being informal spaces that offer a relaxed and convivial atmosphere in which conversations can take place. To recruit, we approached potential participants outside cafes in the chosen locations, introducing ourselves, explaining the research, and asking if they would be willing to complete the survey and speak to us in the café over a drink and / or snack. The discussions with participants in cafes were designed to be stimulated by dialogue and deliberation, whereby participants worked through the possibilities and potential pitfalls of blended hydrogen with each other and with us. Furthermore, we deliberately allowed our conversations to be only loosely structured, following Ricci *et al*'s prerogative to allow people to frame, and raise, issues from their own perspectives with minimal prompting. This resulted in a smaller, separate dataset (n=102) that was not strictly representative of [*anonymised trial areas*] in a conventional sense but which was collected from towns similar to them. Conversations with participants were subsequently transcribed and coded for analysis following the principles of grounded theory [54]. Overall, this methodology ensured that we obtained two separate quantitative datasets, the smaller one accompanied by explanatory qualitative data, that in different ways represent the views of people and places like those in [*anonymised trial areas*]. The intention here was not to conflate the two datasets or treat them as one, nor was it to formally analyse their similarity or control for their differences. Rather, we aimed to explore both as different but related datasets.

3.1 Implications of research design

Although our wider survey design featured several more questions relating to hydrogen blending and hydrogen in general, here we restrict our discussion to those parts of the survey that are directly relevant to the three issues we have identified. The first relevant part of the survey provided participants with two pieces of information relating to the use of 20% blended hydrogen in the context of the United Kingdom:

> 1) "Since 1993, all appliances manufactured and sold in the UK have been tested to run on a mixture of 77% natural gas and 23% hydrogen. More recent studies have indicated that the addition of up to 20% hydrogen in the natural gas network is unlikely to present any extra risk or affect the day-to-day use of gas appliances, while reducing greenhouse gas emissions significantly."[2]

[1] The [anonymised trial] areas are not at the time of writing confirmed and may be changed, and for this reason we do not disclose them or their demographic compositions here, in agreement with our funders. However, for the purposes of our analysis, it is pertinent to divulge that our nine field sites are defined by below average personal incomes, relatively high levels of deprivation, and industrial histories and heritage.

[2] Following the 1990 (2009/142/EC) Gas Appliance Directive (GAD), all appliances manufactured and/or sold in the UK (and EU) since 1993 have been subject to and must pass a short-term test to run on a maximum of 23% hydrogen.

2) "Before natural gas became commonly used in the UK, the main gas used by UK homes and businesses was a manufactured mixture called town gas, which was composed of up to 50% hydrogen."

After each piece of information, participants were asked:

With that in mind, would you be more or less willing to accept up to 20% hydrogen in the gas provided to your home?

Participants were subsequently asked what impact they thought using 20% hydrogen in their homes would have on the environment, the economy, energy performance and efficiency, home appliance use, and safety. Following this, in the second relevant section of the survey participants were asked to score their support for hydrogen out of 10. Finally, we asked participants a question related to their willingness to pay for hydrogen, asking if they value hydrogen and whether they would be willing and/or able to pay more for it.

Before proceeding with the next section we first discuss the implications of two aspects of our research design. First, the information we provided to participants in the survey was necessarily selective and to some degree 'framed' the subsequent conversations, to use Ricci *et al*'s terminology [7]. Achterberg has shown that styles of information provision have a significant impact upon hydrogen acceptance [55], and there are certainly alternative pieces of information that could have been provided to participants, such as statements concerning uncertainties around the costs of hydrogen or the sustainability and emissions profile of hydrogen production techniques and supply chains. Ultimately, however, we chose our two statements because of our explicit aim to explore blended hydrogen in terms of how it might interact with home and domestic economy, both in our descriptive statistics and in subsequent discussions with paper survey participants.

Secondly, there is the question of who was excluded by this recruitment method. We collected paper survey data over a three-week period, Monday to Friday, from approximately 8am to 6pm. It is likely therefore that we excluded a large proportion of workers from our paper survey sample, and there is a separate segment of people who may also have been unwittingly excluded – those who do not like cafes, or being approached on the street, or genuinely unable to stop due to prior commitments or needing to be elsewhere. These issues aside, our paper surveys allowed us to integrate spatial, quantitative, and qualitative analysis in a way that, while not unproblematic, generated insights into the impacts that hydrogen blending for homes will have. In what follows we present the results from the online survey dataset and paper survey dataset side-by-side, and use the qualitative comments and explanations from the paper surveys to elaborate further on the results.

4. Analysis

In this section we explore our findings with reference to the three issues identified in the introduction and developed in Section 2. Firstly, we analyse our participants' responses to the prospect of using blended hydrogen in their home.

4.1. Home appliances and practices of heating and cooking

Participants were presented with the two pieces of information about hydrogen, stated in the previous section, in turn. Respondents were asked after being given each piece of information whether they would be more or less willing to use up to 20% hydrogen in the gas provided to their homes. Combining participants' responses together to create three categories – less willing, no change, and more willing – demonstrates that they were considerably more willing to use hydrogen after being given this information. In the online and paper surveys, 88% and 69.6% of participants respectively were more willing to use blended hydrogen after being informed that home appliances have been tested. In addition, 78.2% and 65.7% of online and paper survey respondents respectively indicated they would be more willing to use blended hydrogen after being informed that town gas included hydrogen and was previously used in the UK. Following this, participants were asked what impact they thought using blended hydrogen would have on the environment, the economy, energy performance and efficiency, home appliance use, and safety. Table 1 shows the results of these questions. Most notably, a majority of participants from both samples envisaged extremely positive benefits for the environment but, particularly in the online survey, envisaged that there would be no impact on home appliance use.

	Online Survey			**Paper Survey**		
	Negative	No Impact	Positive	Negative	No Impact	Positive
Impact on Safety	97	482	121	8	58	35
	13.9%	68.9%	17.3%	7.9%	57.4%	34.7%
Impact on Home Appliance Use	32	442	226	5	51	46
	4.6%	63.1%	32.3%	4.9%	50%	45.1%
Impact on Energy Performance	22	360	318	4	33	64
	3.1%	51.4%	45.4%	4%	32.7%	63.4%
Impact on the Economy	19	517	164	4	59	38
	2.7%	73.9%	23.4%	4%	58.4%	37.6%
Impact on the Environment	25	186	489	7	24	70
	3.6%	26.6%	69.9%	6.9%	23.8%	69.3%
Overall Impact	19	424	257	4	41	57
	2.7%	60.6%	36.7%	3.9%	40.2%	55.9%

Table 1: Participants' perceptions of the impacts of using 20% blended hydrogen. This question was asked as a five-point Likert scale, whereby 1=Very Negative, 2=Negative, 3=No Impact, 4=Positive, and 5=Very Positive.

In our discussions of this question, numerous paper survey participants observed that 'No Impact' was a good thing, largely because they perceived that little would change in their everyday practices of heating and cooking but there would be simultaneous positive impacts on the environment. For example, several participants made comments such as "hydrogen won't have any impact on climate change other than positive", "if adding hydrogen into our fuel increases energy but reduces the emissions then it's a positive change", and "no impact means positive in that it wouldn't change anything, but environmental and other benefits would be positive." In other words, these participants, armed with the information that using blended hydrogen would not require any modification to their home appliances, envisaged that their practices of cooking and heating would continue as normal.

However, a small subsection of participants did discuss ways in which they thought the hydrogen would disrupt or engender change to their practices of cooking and heating. Firstly, some participants did have an overarching perception of hydrogen as dangerous, flammable, and explosive – in many cases to a greater extent than natural gas. For instance, one participant commented that "hydrogen is much more flammable and explosive than natural gas so more dangerous and also more difficult to store." Some participants associated this with airships and, implicitly, the Hindenburg disaster, noting that "hydrogen in airships previously was extremely flammable" and that "hydrogen is a more powerful explosion in higher concentrations [like in] blimps". Another older participant knew that town gas was partly composed of hydrogen before our question about it, and told us that he remembered that using town gas made ovens more likely to explode. This participant continued by telling us that he viewed town gas and hydrogen so dimly that he would simply switch to an electric cooker rather than use blended hydrogen at all. But for most of our other participants, these meanings were not insurmountable, and were not envisaged as disturbing established practices of cooking and heating. Instead, participants emphasised that they trusted that "all safety aspects would be well investigated" before hydrogen was actually allowed to enter their homes. Put differently, a picture gradually emerged whereby some of our participants did associate hydrogen with explosions, but believed that seeing evidence of its safety would allow the smooth integration of blended hydrogen into their gas supplies.

Secondly, some of our participants did point us towards the sensory aspects of their everyday practices of cooking and heating. More specifically, they asked us questions about how blended hydrogen might change the ways they sense and perceive gas in the home. The majority of these questions related to the behaviour, smell, intensity, and visibility of flames, especially on gas hobs. One participant, for example, commented that "it might not be safe as its smell would be less", while a second participant commented that "hydrogen doesn't smell, you'd need to add a smell." Others talked about the possibility of the blue hue of the natural gas flame being diluted because of the hydrogen content. For many these questions were crucial: participants believed that regardless of whether or not their appliances were tested to run safely blended hydrogen, the key issue for them would be how their daily tasks of cooking and heating their homes might change as a result of the blended gas. As before, few of our participants believed that changes would be unacceptable, mostly because they told us that any changes to the smell, visibility, and intensity would surely be minimal because of the low content of hydrogen being blended. However, the fact that some of our participants recognised the possible impact of hydrogen on the sensory elements of their practices of cooking and heating does indicate that there is a need to explore and analyse exactly how this might happen. We will return to how this might be done in the conclusion.

4.2. Willingness to pay, experiences of fuel poverty, and distributional justice

To explore the issue of cost, we included a WTP question at the end of the survey which aimed to allow participants to indicate their willingness and/or ability to pay more for hydrogen. For this question, we did not use CVM or another method orientated towards quantifying WTP, following Ricci *et al*'s critique of these methods [7]. Instead, in keeping with our broader methodological approach, our aim was to generate descriptive statistics and allow paper survey participants to expand on their reasoning in subsequent discussions. Most relevantly, 67% of the paper survey sample and 63.4% of the online survey sample responded that they were not able to pay more for hydrogen. In other words, although only <10% of participants said they did not value hydrogen at all, around two thirds indicated that they would not be able to pay more for it even if they were willing to.

Our field sites were all chosen, in part, because their demographics are defined by below average personal incomes, relatively high levels of deprivation, and histories of industrial and economic stagnation. This was reflected by a large majority of paper survey participants, who explained their responses by discussing already high energy bills, low wages, and their subsequently inability or unwillingness to pay more for hydrogen. For example, participants commented that "I'd not be happy paying more simply because money is tight" and that they "would be willing to change but can't afford the extra cost." Discussions of low wages were often paired with a perception that the primary concern of energy companies is to extract profit from consumers and that attempts at regulation by government are woefully insufficient. One participant commented:

> "energy costs in the UK are currently too high, [and] every year they continue to rise beyond the rate of inflation. The top 6 suppliers have a monopoly on costs regardless of what Ofgem say. [Wholesale] costs are in freefall with price rises the norm."

For many, in other words, the double lock of low wages and high energy bills was the reason why they could not or would not pay more for hydrogen.

The ways that this double lock played out in the everyday lives of our participants can be understood in terms of distributional (in)justice, which refers to the uneven distribution of the benefits and costs of energy infrastructures across society and how these are shaped by structural forces [56]. In a field site near Stockton-on-Tees, for example, two participants disclosed that they were in receipt of Job Seekers Allowance and Personal Independence Payments, welfare benefits provided by the government to those out of work and unable to work due to disability respectively. These two participants talked in detail about their struggles with their energy bills in the context of what they considered “astronomical” direct debit payments to their gas supplier. In particular, our disabled participant told us that her disability was in her hand, and that she found it painful and time-consuming to write or type as a consequence. This was then exacerbated, she explained, when her energy supplier moved her automatically to an online account that she could not access, partly because of her disability but also because she presently cannot afford an internet connection at home. In doing so, she painted a picture of her home as a space that was completely unsuitable for managing her everyday life and talked in detail about frequent, exhausting trips to the bank and her inability to reach her energy supplier by phone. When we discussed hydrogen, she and other participants who disclosed struggling to pay their energy bills said they would not be able to pay more, but also believed that they were powerless to prevent any possible additional costs being passed to consumers.

Other participants displayed a sensitivity to the possible distributional injustice of the costs of hydrogen. Interestingly, many of our discussions focused on the inability of older, pension-age people to pay more than they currently do. For instance, one participant recognised that hydrogen would be beneficial for the environment, but then continued that

> “our fuel bills continue to rocket even though this winter we have had to make a conscious attempt to really cut back. I have always felt awful about the thought of the elderly sitting freezing in their homes but I understand their fear of being unable to pay their bills now.”

A second participant commented that “gas and electricity bills are already too high, [and] we hear most winters the elderly are dying as they can't afford to have heating on.” Such comments were typically, but not always, participants discussing the implications of hydrogen’s costs beyond their own, individual ability or willingness to pay for it and imagining how these costs might impact what they perceived as a particularly vulnerable segment of the population. One participant in Merseyside, however, disclosed that she felt unable to pay more for hydrogen because she had been adversely impacted by recent changes to the statutory age of retirement. She continued that she had expected to retire at 60, and had planned around the now redundant 60-year provision for her working life before learning that she would have to wait an additional six years to claim it.

Although these comments are indicative only, the discussions we had with participants around these themes emphasised the prevalence of structural social and economic factors (low wages, high energy bills, and changes to the national retirement age) and their disproportionate impacts across marginalised and vulnerable groups (disabled and older people). As these discussions developed, the points of particular importance to our participants became less and less concerned with a *willingness* to pay more for hydrogen, but rather the wider forces that in different ways shaped both their *(in)ability* to pay and their belief that being forced to pay more for hydrogen, whether in the form of taxation or increased energy bills, was both unavoidable and would exacerbate their ongoing struggles with the day-to-day impacts of fuel poverty. These findings suggest that social scientific analyses of the cost implications of hydrogen have to move beyond a simple WTP model and consider how hydrogen's deployment might disproportionately impact different cross-sections of society along social, economic, spatial, and structural axes.

4.3. Place attachment and local economic development

This final sub-section shifts the focus to place attachment and to place-specific disruptions/enhancements that might occur during hydrogen transitions. To explore this, we asked participants to rate their support for hydrogen on a subjective scale of 0 to 10, with 0 designating least support and 10 designating most support. Importantly, we asked this in three differently worded ways, asking 'out of 10': a) 'how much would you support the introduction of hydrogen as a fuel **for the UK** in the future?', b) 'how much would you support the introduction of hydrogen as a fuel for **your local area** in the future?', and c) 'how supportive would you be of a **20% blended hydrogen trial taking place in your local area**?' We did this to gauge any differences between participants' general support for hydrogen and more specific support for the trialling and use hydrogen in their own local areas, which we could then explore with paper survey participants.

	Support for Hydrogen as a Fuel for the UK		**Support for Hydrogen as a Fuel for your Local Area**		**Support for a 20% Blended Hydrogen Trial in your Local Area**	
	Online Survey	Paper Survey	Online Survey	Paper Survey	Online Survey	Paper Survey
Mean	6.96	7.08	6.91	7.09	7.09	7.15
Confidence Intervals (95%)	6.81-7.11	6.72-7.44	6.76-7.06	6.72-7.45	6.92-7.26	6.70-7.59
Median	7	7	7	7	7	7
Std. Dev.	1.98	1.82	2.05	1.84	2.28	2.23

Table 2: Participants' support for hydrogen as a fuel for the UK, for their local area, and for taking part in a 20% blended hydrogen trial

As shown in Table 2, our descriptive statistics indicate that support for hydrogen marginally increased when participants considered their willingness to take part in a trial. However, also notable in these results is that participants' scores were consistently higher in the paper survey than in the online survey. This is best explained not statistically but by the impact of acquiescence bias on paper survey participants. Talking to participants in cafes, over a coffee and snack, generates the conviviality for wide-ranging unstructured conversations about hydrogen, but simultaneously and as a consequence generates a small probability that participants will respond more positively when asked to score their support for the very thing that they have been discussing with the researcher. In contrast, the confidence intervals are larger in the paper sample due to the smaller sample size, indicating that regardless of any possible bias we must be more cautious about the higher scores across the paper survey sample. In addition, if we look more closely at the distribution of participants' scores a more complex picture emerges. Sentiment varied most widely when participants were asked to indicate their support for taking part in a hydrogen trial in their local area, as is reflected in the higher standard deviation figures for this question in Table 2. This suggests that levels of support can be affected by place attachments and that people might associate the possibility of an intervention such as hydrogen blending with disruptions or enhancements to place.

In our discussions with participants we touched upon different examples of how place disruption/enhancement influenced these scores. Safety, cost, and positive environmental impacts were all important in discussions about participants' more general support for hydrogen, but when participants turned to their own local areas and their support for trials more nuanced perspectives emerged. The best example of this is from the days we spent in a town near Stockton-on-Tees in the North East of England, which along with Middlesbrough and the wider Teesside conurbation has a history of heavy petrochemical industry and air pollution. Bush *et al* have suggested that air pollution in Teesside has become synonymous with poor health and social degeneracy, leading to an area "characterised by the double insecurity of economic decline and environmental pollution" [57:48]. Phillimore and Moffatt have argued that such a perception is both reinforced and challenged by residents of Teesside in complex ways [58]. More broadly, air quality and air pollution have been highlighted as significant rallying points for resistance to certain energy projects, particularly as related to fracking and biomass plants [59, 60]. Through Devine-Wright's lens of disruption/enhancement, energy infrastructures that emit smoke, noise, and other forms of environmental pollution can be conceptualised as disruptive to local landscapes and to place attachment, whereas projects that minimise (or reverse) pollution could be viewed as enhancing the identities and reputations of particular places.

These issues were foregrounded strongly be almost all of the paper survey participants we spoke with in this town. This took shape not as binary perceptions of hydrogen as polluting/disruptive or not polluting/enhancing, but in the form of numerous points that participants raised about how hydrogen was produced, whether it involved the burning of other fuels, and if so whether these fuels would emit particles detrimental to local air quality. Importantly, these questions were often positioned within a narrative of temporal amelioration; that now, in 2019, air pollution is finally beginning to recede in Teesside due to the closure of many of the chemical plants that were for decades at the heart of the region's industry. For these participants, therefore, their support for hydrogen was fundamentally dependent upon what the answer to a key question would be: would hydrogen production facilities bring air pollution back, or continue the process of reducing it? The broader point here is not about air pollution *per se*, but instead a confirmation that people's attachments to, or understandings of, the histories, economies, and broader characteristics of the places they live (whether conceived in terms of town, conurbation, region, or all/none of these) will shape their evaluation of hydrogen transitions in complex ways that are not reducible to the measurable or hypothesised factors that previous hydrogen perceptions work has considered.

In turn, however, one specific enhancement emerged from our conversations with participants concerning local and economic development. As noted in Section 2.3., hydrogen is often viewed by local government and industry as a possible pathway towards clean economic growth in areas with historic, but increasingly decaying, industrial strengths. This was strongly emphasised by participants in our field sites. To take two examples, one participant in a County Durham field site said he would support hydrogen if it created jobs or apprenticeships for young people in the area, who presently "have nothing". A second participant in a Merseyside field site narrated how her husband had been made redundant when the local coal mine was closed in the mid-1980s, and had been unemployed since. She asked us the same question: would hydrogen bring jobs and industry back to the local area, for him and for others? If so, she continued, she would be supportive of it. Often, such conversations were framed by grim, almost fatalistic discussions concerning the bleak employment prospects that were facing that particular place. In these ways, on the occasions where our conversations did turn to infrastructure and participants' local areas, our findings suggest that employment and the reversal of economic decline may take precedent in places with similar histories and identities to those we visited – those that will likely be the first to experience hydrogen transitions.

5. Conclusions

In this article we have suggested that the introduction of hydrogen into the gas supply of homes, whether in the form of pure hydrogen or a blend of hydrogen and natural gas, will engender a range of social and economic changes. We have argued that hydrogen has the potential to impact the stability of gas-energised practices of heating and cooking in the home, the lived experience of energy use and fuel poverty, and the identities, landscapes, and economies of the communities within which hydrogen will be introduced. In closing, we want to dwell on three broader implications of this article for what we think of as an agenda for social research and scholarship into hydrogen transitions.

A first implication is about concepts and theory. Thus far, hydrogen perceptions research has relied on predominantly psychological and attitudinal approaches to human behaviour that emphasise how certain inherent attributes – knowledge, environmental values, and gender, to give but three examples – interact to shape acceptance of or support for hydrogen. As we have shown, these approaches are useful but limited in approaching and conceptualising the social and economic changes that may occur as hydrogen enters domestic gas supplies. The potential impact of hydrogen on everyday experiences of energy deprivation is not reducible to or captured by attempts to quantify WTP, and changes to local landscapes, economies, and people's attachment to them cannot be satisfactorily measured by quantifying the distance between new hydrogen infrastructures and one's house. While we would not seek to be prescriptive in how this could or should be done, a starting point must be to bring hydrogen perceptions literatures into conversation with broader approaches in energy research and social science, whether to do with relational understandings of space and place, energy justice, or social practice theory.

A second implication concerns methodology. Throughout this article we have proposed that the quantitative and statistical methods that characterise current hydrogen perceptions research are, on their own, insufficient for understanding the impacts, problems, and opportunities that may emerge alongside the deployment of hydrogen in homes. Innovative mixed-methods approaches that integrate spatial, quantitative, and qualitative analyses have much to offer in deepening our understandings of hydrogen transitions. One possible research avenue would be to conduct research in, and with, households that will use or have used hydrogen to investigate how practices of cooking and heating change *in situ*, an avenue which could employ home-tours, diaries, and other methods aimed at capturing the mundanity of everyday energy use alongside more established methods such as surveys and interviews. Methods such as these have been utilised to investigate user interaction with other energy interventions [26, 61], and as hydrogen makes its way into people's homes these and similar studies represent a deep well of methodological techniques from which valuable insights could be hoisted.

Finally, this leads to a third implication – that of access and collaboration with industry. As we have previously noted, the development and deployment of hydrogen for homes is in many cases being led by national or regional gas distribution networks in collaboration with government actors and industrial partners. As a result, the first instances of deployment, such as blended hydrogen trials, can be enormously sensitive projects, particularly as it could be argued that as a consensus crystallises around the need to stop using natural gas for domestic and industrial heat, the stakes for hydrogen transitions are as high as the survival or demise of the global gas industry. A key challenge is therefore how researchers can work collaboratively within these networks to shape the emerging hydrogen agenda in ways that critically and ethically foreground their social, economic and justice implications and advocate inclusive approaches to analysing them. In this last respect we have no easy answers, but if nothing else we hope this article will stimulate new research into hydrogen that builds on, but simultaneously pushes in new directions, existing scholarship.

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