Public perceptions of net zero technologies: social science research and evidence

Chief Scientist's Group report

September 2025

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Dr Robert Bradburne
Chief Scientist

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Executive summary

Background

The Climate Change Act 2008 established a goal for Britain to reach net zero carbon emissions by 2050. Achieving this will require huge technological and behavioural changes and the Climate Change Committee has acknowledged that, 'Public support is essential for the delivery of Net Zero' (Climate Change Committee 2024). There is a growing body of social and behavioural research on public perceptions of low carbon technologies, behavioural changes and attitudes towards net zero and climate change. This evidence can help decision-makers, regulators and operators of net zero technologies to understand how people think about net zero and the social and technological changes it will bring about.

As well as reducing demand and changing behaviours, many different technologies can play a part in lowering carbon emissions. These technologies rely on public acceptance for implementation and widespread adoption to realise the reduction in carbon emissions they promise. To reach the 2050 net zero target, average household emissions will need to reduce by 60%. Such large-scale changes rely on government policies being informed by meaningful public engagement (Committee on Climate Change 2019).

The Environment Agency will have a key role in net zero, for example by regulating low-carbon and carbon storage technologies through permitting and as the administrator of the Clean Heat Market Mechanism. The Environment Agency is also committed to consulting and engaging with the public. Therefore, it is important to understand current evidence about public perceptions of relevant technologies and to embed this knowledge within Environment Agency's work to support the pathway to net zero.

Methods

This project synthesised quantitative and qualitative research on public attitudes to net zero technologies, with the aim of informing the Environment Agency's role as a regulator of many of these technologies and protector of the environment and people.

The main method used in this project was a quick scoping review, which reviewed social and behavioural science research and policy documents on three case study technologies: lithium-ion batteries, heat networks and ocean alkalinity enhancement. For the case of ocean alkalinity enhancement, the quick scoping review was complemented by discourse analysis, which was applied to public discussions about a proposed trial of the technology.

Findings

Social science evidence shows that people are aware of and prepared to make changes to contribute to reducing carbon emissions. But it also shows that most expect impartial guidance, financial and policy support and consistent leadership from government. Some net zero technologies have attracted opposition from members of the public. This often

reflects deep-seated concerns about the potential impacts of new technologies and their installation on the environment, health and cost of living. As well as unbiased and scientifically accurate information about technologies' efficacy, safety and environmental impact, people need to be consulted and engaged about why and how decisions have been made, to feel that the processes involved have been just and that the risks and benefits have been distributed fairly.

Net zero represents enormous and sometimes costly changes in people's everyday lives, the places that are important to them and in national and local infrastructure. It is unsurprising that many people feel worried and anxious about what this will mean for them, even while they may also be hopeful about a lower-carbon future. Technologies like heat networks bring to the fore the disruption associated with decarbonisation. Social scientific analysis shows that such disruption is not simply about the inconvenience of local roads being dug up but also touches on the most personal and intimate spaces of people's lives – their homes and daily routines and the emotions and values associated with them as well as physical comfort and wellbeing.

Many net zero technologies are novel or unfamiliar to members of the public and so their impacts can seem uncertain. Relatedly, some people worry about having their autonomy curtailed by mandates to switch to low-carbon technologies. Informing people about the co-benefits of decarbonisation, such as improvements to air quality, can help communicate the positive impacts of net zero policies. Social and behavioural research also shows that seeing friends and family adopting new technologies can help them seem more familiar and appealing.

The evidence indicates the importance of trust in the acceptance or rejection of net zero technologies and policies. This includes trust in institutions delivering policies and regulation and those developing, installing and maintaining technologies. People expect to be informed and consulted about the net zero transition and the part they will and can play in it. They also want to be reassured that the risks, costs and benefits will be distributed fairly. Genuine public engagement, which is consultative and involves members of the public in a dialogue, is critically important in achieving this. Engaging with a broad range of people, including those who do not usually have their voices heard and who may be most vulnerable to the environmental and social impacts of decarbonisation, can also help ensure a just transition to net zero carbon emissions.

Introduction

The UK's goal of achieving net zero carbon emissions by 2050 has been described as a socio-technical challenge, as it will require significant behavioural changes and public support to be successful (Geels, Sovacool, and Iskandarova 2023; Wachsmuth et al. 2023). Data from government public attitude trackers show that there are high levels of concern about climate change (DESNZ 2023a). There is also evidence that individuals accept that they will need to make shifts in their behaviour and consumption, and that they expect the government and associated agencies to enable these transitions through changes and upgrades to infrastructure, as well as policies which support greener choices (Climate Assembly 2020). However, there is also substantial uncertainty amongst members of the public, reflecting a lack of familiarity with low-carbon technologies, concerns about costs to consumers and trepidation about the scale of the changes in everyday activities that may be required to reach the net zero goal.

Social scientists argue that it is vital for us to consider how members of the public think and feel about the net zero transition and their part in it (Khalid 2023; Verfuerth et al. 2023). This is also relevant to the Environment Agency's role in protecting the environment and people and regulating relevant industries. This project contributes to net zero objectives by communicating evidence:

- To understand popular perceptions and societal acceptance or rejection of likely net zero pathways, through case studies with specific relevance to the Environment Agency's work areas.
- To understand how public attitudes towards net zero technologies and their implementation could present risks, opportunities and uncertainties for the Environment Agency and for the broader effort towards net zero.
- To identify gaps in the evidence and opportunities for future research.

This report presents social scientific evidence about British people's perceptions of net zero technologies, focusing on three case study technologies that reflect different aspects of the net zero transition and how people may engage with it: lithium-ion batteries, heat networks and ocean alkalinity enhancement. Technologies that do not have at least minimal social acceptance face significant challenges in democratic settings. This, and the public's expectation about being consulted on major infrastructural and behavioural changes, mean it is important to study how people perceive net zero technologies, to understand whether and why they accept them and to appreciate the implications this may have for government and regulators looking to facilitate the pathway to net zero.

While it is common knowledge that individuals need to reduce their carbon footprint, there is much less awareness of the impact that specific actions have on reducing emissions. In fact, many people overestimate the impact of common actions and underestimate others (Steentjes et al. 2021). While policies oriented towards behavioural change can help incentivise actions that reduce carbon emissions, they need to be planned carefully so

they do not inadvertently penalise those who will struggle to make changes, such as those who rely on a car for work but who cannot afford to purchase an electric vehicle (Theminimulle et al. 2024; Middlemiss et al. 2024). Publics are willing to make changes, but think it is unfair if this is not matched by actions to reduce carbon emissions from governments and industries (Smith, Demski, and Pidgeon 2025; Verfuerth et al. 2023; Powell and James 2023).

Reaching net zero emissions can come with many co-benefits – for example, more active travel will reduce carbon emissions from transport, improve people's health (and therefore save money for health and social care), reduce consumer costs and potentially improve civic spaces, making them more accessible and enhancing community cohesion. Emphasising these co-benefits not only gives a sense of the full range of positive impacts that decarbonisation can have but also helps make the case for emissions reduction even for those who are less concerned about the effects of climate change. There is also evidence of a 'social circle' effect with net zero technologies and behavioural changes – when people see their peers, friends and family adopting low-carbon technologies and activities, they are more likely to do so themselves (Smith, Demski, and Pidgeon 2025). This suggests the importance of social norms on technology adoption and behaviour change, but also how these can be leveraged to support bottom-up changes to complement more top-down interventions.

The evidence shows that people want to feel some tangible benefit, or at least not a significant cost, if their local area is host to facilities that may have a detrimental effect on the local environment. The concept of just transition[1] describes the aim of ensuring that transitions like net zero do not adversely affect those who work in relevant industries. In practice, this means supporting workers in high-carbon industries to shift to low-carbon jobs, for example by retraining gas engineers to install and maintain heat pumps or supporting factory workers to find employment in a gigafactory or carbon capture facility in their local area rather than outsourcing all those new jobs.

The term procedural injustice describes instances where technologies have been implemented without sufficient or meaningful public engagement, or where procedures such as environmental impact assessments have not taken place. Many net zero technologies are celebrated for their contribution to global goals of emissions reduction, which can seem distant and even irrelevant to those who live in the places in which they are sited. Further, British people have quite strong expectations of autonomy and choice, including in infrastructure, which can shape their attitudes towards technologies (Smith, Demski, and Pidgeon 2025).

[1] See Glossary for definitions of key terms

Social scientists have pointed out that many of the changes associated with decarbonisation happen in the home, a space of great meaning and emotional salience, as well as a focal point of concern with the sudden rise in the cost of living in recent years (Demski, Steentjes, and Poortinga 2022; Office for National Statistics 2024). While this may seem obvious, it is often overlooked in policy discussions, which tend to conceptualise people in ways that overlook complexity and heterogeneity in public opinions, focusing more on the fact that people are 'for' or 'against' a technology and less on inquiring why they hold a particular position (Whitmarsh et al. 2025), or how profound change *feels* to people. Similarly, while behavioural change is emphasised in many net zero pathways and scenarios, this tends to be based in modelling rather than social scientific evidence and analysis, which could lead to policy recommendations that are informed by naïve or even biased views of how people think and act (Bickerstaff et al. 2024).[2]

While the public know about and are largely concerned about climate change, there is less knowledge of net zero policy and understanding of specific technologies that will be implemented to support decarbonisation. This is not surprising considering the complexity of net zero policy and the fact that many of these technologies are still under development or are not widespread in the UK. Greater understanding of net zero technologies and pathways could allay some people's concerns about technologies and their effects, as well as countering misinformation. However, simply providing people with more technical information is insufficient and conducting public engagement with the goal of persuading people to accept something can lead to mistrust (Ryder et al. 2023). Effective public engagement is inclusive, consultative and responsive to people's concerns, with a broad range of views and experiences represented, but also taken into consideration in whether and how technologies are implemented (Middlemiss et al. 2024; Climate Assembly 2020; Rohse et al. 2024). While some fear that such work might slow down decarbonisation, it can help prevent backlash that has even longer lasting consequences (Powell and James 2023).

Researchers have observed that many technologies are easier for people to accept in principle than when they directly affect them, for example because they are being installed close to their homes. Such local opposition reveals an important facet of how net zero technologies are received by members of the public, yet objectors are too often dismissed in public discussions using the pejorative label of NIMBY (Not In My Back Yard). Over a decade ago, Devine-Wright (2009: 426) proposed a different understanding: 'Local opposition is conceived as a form of place-protective action, which arises when new

[2] One exception to this is the Government Office for Science report, *Net Zero Society: Scenarios and Pathways* (2023).

developments disrupt pre-existing emotional attachments and threaten place-related identity processes'. Local opposition to net zero technologies may express concerns about irreversible changes that could alter or degrade the qualities of a place that make it meaningful and somewhere that people feel attached to. In simple terms, people are worried about the effects of new industries on their homes and the places that are important to them.

Labelling objectors as NIMBYs or blockers can reinforce social and political divisions and strengthen people's feelings of being left out of decision-making. Similarly, arguing that people with genuine concerns about technology installations should either be persuaded or ignored will likely only cultivate resentment and fuel polarisation. Contestation and even conflict are part of change and so should be carefully managed (Bickerstaff et al. 2024). Social science evidence shows that people are concerned that some aspects of net zero policy will result in a loss of autonomy and choice (Thomas et al. 2024). Instituting top-down interventions without meaningful public engagement risks fulfilling this expectation and fuelling anti-net zero arguments. Yet, while people do have concerns about the (unintended) consequences of net zero technologies, including on the environment, politicians tend to overestimate public opposition. For example, Climate Barometer have shown that 75% of the public would support an onshore wind farm being built in their local area, whereas Labour MPs think only 20% would support one (Climate Barometer 2024).

In a recent report (Bickerstaff et al. 2024), leading academics from across the social sciences have put the case for a stronger involvement in social scientific evidence and methods in planning for and reaching net zero. We have come to rely on fossil fuels to heat our homes, drive our businesses and fuel transportation and many of the things we use in our everyday lives produce carbon emissions, from concrete and plastic to eating meat or using the internet. Achieving the massive reduction in carbon emissions that is needed to reach net zero and prevent the worst effects of climate change will entail significant behavioural and societal changes. To realise these changes effectively, fairly and positively, we need to understand how and why people will be willing to engage in them, by drawing on the social scientific evidence base.

Methods

The technologies that this report focuses on were identified following advice from the project's advisory group, which included managers from the Chief Scientist's Group, Climate Change and Social Science teams. They were intended to capture technologies that are likely to come within the Environment Agency's regulatory purview, that are relatively novel (at least within the UK context) and which reflect some of the specific behavioural changes and social impacts associated with the net zero transition.

All sections are based on quick scoping reviews. Relevant literature from across the social sciences was identified through searching on Scopus. The following search terms and limitations were used, with the results also reported:

Lithium AND mining

Limited to: Subject area: Social sciences; Language: English

Yield: 133 results

Lithium AND battery

Limited to: Subject area: Social sciences; Language: English

Yield: 1612 results

(If further limited to: Country/territory: United Kingdom

Yield: 89 results)

Lithium AND gigafactory

Limited to: Subject area: Social sciences

Yield: 3 results

Heat AND networks OR district AND heating

Limited to: Subject area: Social sciences; Language: English;

Yield: 6756 results

(If further limited to: Year range: 2019-2024, Country/territory: United Kingdom

Yield: 464 results)

Ocean AND alkalinity AND enhancement

Yield: 77 results

Limited to: Subject area: Social sciences

Yield: 3 results

Ocean AND carbon AND dioxide AND removal

Limited to: Subject area: Social sciences

Yield: 19 results

Ocean AND negative AND emissions AND technology

Limited to: Subject area: Social sciences

Yield: 13 results

The yields of the search terms indicate the fact that lithium batteries and heat networks have been studied more extensively by social scientists than OAE. For those searches that yielded more results, further limits were applied in terms of country and year of publication to assist the process of identifying the most relevant literature to review. The relevance of the articles identified through the search was assessed first through the title, then the abstract. The articles were assessed as potentially relevant based on research topic, location and recency in time and on the use of social scientific methodologies. Snowballing was used to identify further relevant references from the bibliographies of these results. The report also draws on background academic and grey literature that was already familiar to the author.

The relevant articles were then saved to the EndNote referencing system and read by the author. Key findings and recommendations were highlighted in EndNote, then inputted into a literature review matrix in an Excel spreadsheet organised by themes. For example, for the worksheet on electric vehicles, there was the theme ‘social acceptance and opposition’, then codes that broke that down further such as ‘local opposition’, ‘environmental impacts’ and ‘working conditions’. All themes and codes were identified through the initial reading of the literature, so are tailored to that specific subset of literature.

The third section of the report, on ocean alkalinity enhancement, introduces a different method, presenting primary research that used discourse analysis to explore the public conversations surrounding the trial of a carbon dioxide removal technology in Cornwall. In discourse analysis, a researcher analyses the ways in which different actors represent something through speech and text to discern common themes, tropes and rhetorical devices. It can be a useful method for understanding perceptions of emerging technologies where there is little definitive knowledge about them on which to base opinions and to dig deeper into what controversies are expressing beyond the surface level.

For this discourse analysis, news articles and blogs on the ocean alkalinity enhancement trial in St Ives Bay were identified through an internet search. Each source was first assessed for relevance, then read closely to identify themes, tropes and key actors. While some social media posts were identified through this search, the analysis focuses on national and local media, blogs and industry magazines, as well as the websites of the relevant organisations. This is because the analysis is more focused on the

representations of the trial that are accessible to a general audience and which reflect the main voices in the debate, rather than more general commentators, though members of the public still feature in journalists' coverage. Each source was analysed, and key quotes and observations were inputted to a spreadsheet. Following a further layer of analysis, four overarching themes in the discourse were identified and are discussed in section 3: Ocean Alkalinity Enhancement.

1. Lithium-ion batteries

Introduction

Researchers and policymakers agree that lithium is an essential part of the net zero transition. The International Energy Agency (2022c) predicts that, if policies in line with the Paris Agreement goals are implemented, lithium demand will grow over 40 times by 2040 compared to today. This has led several countries to develop onshore lithium production, even while publics and NGOs have raised concerns about the as yet uncertain social and environmental impacts of lithium extraction.

The UK government advocates for onshoring production as a solution to energy insecurity, which has come into focus since the Covid-19 pandemic and Russia's invasion of Ukraine, and as a way of building higher sustainability standards into production (Riofrancos 2023). This implies confidence in the UK's environmental regulation and sustainability standards, though think tank Green Alliance argues that the industry will need policy interventions to thrive and warns that local opposition could present a barrier (Mckelvie and Bennett 2023). This section reviews existing social science and policy literature on production, manufacturing, use and end-of-life of lithium-ion batteries. It will focus on the UK context while drawing on literature from around the world, since there is currently a lack of social scientific research on these topics based in the UK.

Quick scoping review of social scientific research on lithium-ion batteries

Mining and production of lithium

The government is optimistic about the UK taking a leading role in lithium production. The Critical Minerals Strategy aims to maximise domestic production 'where viable for businesses and where it works for communities and our natural environment'. It also aims to develop mining skills and research and development and increase the recovery, reuse and recycling of lithium (BEIS 2023).

There are currently four companies developing lithium mining in England. British Lithium and Cornish Lithium are based in Cornwall, in areas that previously mined tin, copper and China clay. British Lithium plans to mine from hard rock, while Cornish Lithium will use both hard rock and direct lithium extraction (DLE) from geothermal brines. Northern Lithium and Weardale Lithium are both based in Weardale, County Durham, where silver and lead were previously mined. They both plan to use DLE from geothermal brines. DLE is claimed to have fewer environmental impacts. Weardale Lithium and Cornish Lithium are also exploring the potential for geothermal heat and energy generation as part of their extraction process. Cornish Lithium has received £24 million from the UK Infrastructure

Bank, while the other three have all received funding from the Automotive Transformation Fund. Most of the companies have carried out some form of public engagement and have information on their websites that appears to be intended for members of the public. Unfortunately, no literature was found which discusses social research on lithium mining in England at this early stage in its development.

Environmental and health impacts of lithium mining

Environmental impacts are an important factor in shaping public perceptions of technologies. Different production techniques have different (potential) environmental impacts associated with them (Vivoda et al. 2024), but public concerns about lithium mining tend to centre on water usage, water quality and air quality (Slattery et al. 2023; Lèbre et al. 2020; Noever Castelos 2023; Dunlap and Riquito 2023).

Concerns about negative environmental impacts are often hard to disentangle from ones about human health (Crespo-Cebada et al. 2020). There is uncertainty about the impacts of lithium mining on public health due to a lack of evidence (Agusdinata et al. 2018). However, the EC Chemicals Agency has recommended that 3 lithium compounds be considered as reproductive toxicants, though no decision has been made on whether to approve this (Noever Castelos 2023). In the UK, the HSE has recommended not classifying lithium as toxic, which is likely to lower costs and improve regulatory certainty for prospective lithium facilities in the UK (Dempsey et al. 2023)

Despite scientific uncertainty, social scientific research shows that lithium mining is *perceived* to be harmful to health by some members of the public in different countries (Rodrigues, Antão, and Rodrigues 2019). For example, in ‘Lithium Valley’, California, locals are concerned about the potential effects of lithium mining on air quality. This is particularly acute as the region already has degraded air quality and public health is characterised by severe respiratory issues (Slattery et al. 2023). Measures to monitor and mitigate (potential) impacts and reassure local communities, such as enclosing processing systems so that waste is not dispersed by wind, will be an important element in planning lithium extraction plants. As production develops, it will also be important to consider cumulative impacts.

Economic impacts of lithium mining

Lithium mining, like any developing industry, has the potential to create new jobs. This can benefit the local community and national economy and have indirect positive impacts such as improved transport and telecommunications infrastructure (Slattery et al. 2023). UK government strategies focus on the likely job creation of battery manufacturing rather than lithium production, but companies developing mines emphasise the potential for job creation. British Lithium, for example, predict their work will bring 300 jobs to Cornwall, employment for 3000 people through their indirect supply chain and an annual expenditure of £120 million within the county (British Lithium n.d.).

All the proposed sites for lithium mining in England have been mined for other products in the past. Mining heritage can feature strongly in personal and place identities, including in many parts of England. This can be positive, negative or a mixture of the two – depictions of mining as a heroic way of life often sit alongside accounts of personal risk and poor working conditions. While some people in former mining areas may welcome new forms of mining and associated job creation, some may be wary, especially if they seem predicated on the cycles of boom and bust that have historically been associated with extractive industries (Dunlap and Riquito 2023; Slattery et al. 2023).

Working within a lithium plant may be considered preferable to working in other forms of mining, though this may depend on the technique used. Goodale describes how brine evaporation presents relatively little physical danger compared to traditional enclosed mining and requires specialist skills (2024: 21). However, the Bolivian mine he studied did not offer employment opportunities for local peasant and Indigenous communities and the staff have to live on a secure site apart from their families (see also Weinberg 2023; Noever Castelos 2023; Turley et al. 2022).

Public support for and opposition to lithium mining

As we know from other technologies and industries, the perceptions and experiences of communities close to lithium mines will be key to their acceptance and successful operation. In several locations in South America, lithium mining has been associated with violations of human and Indigenous rights and with conflicts over land and water usage (Vivoda et al. 2024; Turley et al. 2022; Ciftci and Lemaire 2023; Weinberg 2023). In Portugal, researchers have found that local populations are often excluded from decision-making processes in relation to lithium mining (Silva and Sareen 2023). For a just transition, the benefits and costs of lithium extraction need to be distributed fairly. If this does not happen and local communities oppose the industry, then onshoring lithium production may become infeasible.

While there are geographical, environmental, economic, social and cultural differences between England and the other countries in which lithium is being produced, it is worth being aware of existing controversies, as products being manufactured and sold in the UK may be implicated in these supply chains (Grub and Wentworth 2023). People living near proposed lithium mines in England are also likely to have access to information about lithium mining through the news and social media, which may inform their perceptions of the industry and its impacts. Awareness of these issues can help us understand potential opposition to lithium mining and inform efforts to prevent negative impacts on local communities as mining develops in the UK.

During the early stages of lithium production in South America in the 1980s and 1990s, brine evaporation was relatively inconspicuous, so did not attract much public interest. But, according to researchers who have studied conflicts over lithium in Argentina and Chile, since the 2000s, ‘The mounting visibility of socio-environmental impacts from earlier projects [in particular, intensive water use] contributed to the communities’ scepticism

towards new expansions, exploration permits and project tenders in their regions' (Ciftci and Lemaire 2023: 13). Some opposition has been coordinated by transnational NGO networks (Riofrancos 2023: 36).

Within Europe, the Serbian government stopped a Rio Tinto lithium mine after widespread protests in 2022. In Portugal, the mapping of potential lithium extraction sites has provoked public opposition from environmental and cultural NGOs and local populations concerned about procedural injustice, the potential socio-environmental impacts of changing land use and the likelihood that new jobs would not go to locals (Dunlap and Riquito 2023). However, this opposition has not gained much traction, with civil society organisations largely supporting the Portuguese government's push towards decarbonisation while aiming to prevent excessive socio-environmental impact (Silva and Sareen 2023).

Local opposition often relates to perceptions of distributive or procedural injustice, the environmental impacts of specific technologies and complex processes of place identity, place attachment, and place disruption (Devine-Wright 2009; Devine-Wright 2022). For example, in Bolivia, hard rock mining carries negative connotations based on past experiences, and this has led some to approach lithium mining with scepticism or hostility, despite the government there promoting its importance for decarbonisation (Goodale 2024).[3] In California, Slattery et al. (2023) collected data from public meetings about the proposed development of a lithium mine and found that '…water consumption, public health impacts, local employment, and opportunities to participate are high-priority topics for community members'. The researchers therefore recommend that environmental and sustainability analyses address local communities' priorities such as water consumption, waste management, air quality and local employment. This can be achieved through public engagement, though this needs to be approached in a sensitive and open manner, rather than with instrumental aims that can make people suspicious (Ryder et al. 2023).

Governance and regulation of lithium mining

As several researchers point out, governance is pivotal in lithium mining, in relation to policy, market conditions and regulation (Noever Castelos 2023). Security of supply of critical minerals has become a dominant argument for onshoring lithium mining; this may be particularly relevant for the UK post-Brexit (Čavoški et al. 2023). Additionally, rising wages in South America have undermined the financial advantages of offshoring (Čavoški

[3] In South America, mining is also a politically contentious topic, that has been at the centre of debates about the effects of colonisation and exploitation of the natural world on both the environment and marginalised people.

et al. 2023).[4] British lithium mining companies and car manufacturers are likely to welcome policy support for onshoring, as it may represent incentives, security of supply and reputational benefits (Riofrancos 2023; Vivoda et al. 2024). Čavoški et al. (2023: 319) write,

> ‘[T]he ongoing renaissance of UK mining (such as the exploration work currently being carried out by a number of companies in Cornwall) will need to be underpinned by a supportive planning and permitting process that ensures prevention of environmental harm while also remaining mindful of the growing need for a domestic UK mining industry to achieve climate change goals. Outdated mining laws and cumbersome minerals rights regimes are a significant barrier to environmentally sustainable UK mining.

Lithium is prioritised in the government’s Critical Mineral Strategy (BEIS 2023), which argues that a stable supply is required because of ubiquitous technology use, the transition to low-carbon technologies and national security (see also Kester et al. 2020). It states that recent shocks to supply like the Covid-19 pandemic and Russia’s invasion of Ukraine, as well as China's current dominance of the lithium market, have led to insecure supplies, price volatility, opaque supply chains and a lack of accountability for ESG (environment, social, governance) standards. Like the UK Battery Strategy (DBT 2023), it promotes the UK as an international leader of responsible mining and emphasises the importance of accelerating a circular economy approach to critical minerals.

Manufacturing of lithium-ion batteries

Policy literature on battery manufacturing is focused on establishing a robust market in the UK and determining effective instruments to support this. Organisations working in this field share an assumption that establishing the UK as a leading manufacturer of lithium-ion batteries is important for both the economy and reaching net zero. While lithium batteries will have various uses in future scenarios, this assumption reflects the significance of car manufacturing in the UK economy, as well as the prevalence of car ownership. The UK Battery Strategy states, ‘The Government’s 2030 vision is for the UK to have a globally competitive battery supply chain that supports economic prosperity and the net zero transition. The UK will be a world leader in sustainable design, manufacture, and use, underpinned by a thriving battery innovation ecosystem’ (DBT 2023: 7).

[4] Notably, value generation is very uneven in the lifecycle of lithium, with only 2% of the supply chain value coming from the mining and refining processes, compared to 54% in the final stage of electric vehicle manufacturing (Sanchez-Lopez 2023)

The Faraday Institution predicts that the UK will need 10 gigafactories by 2040 to meet the UK's need for batteries across a range of applications, from EVs to grid storage, and argues that the government should seize this critical moment, or risk losing the opportunity to become a market leader and jeopardising the future of the car industry and the jobs it supports (Faraday Institution 2022). Similarly, Green Alliance states that the UK has the greatest projected capacity for lithium refining in Europe (Mckelvie and Bennett 2023), but argues that we 'need a broad reaching strategy, covering the entire supply chain, from extracting raw materials to recycling' and that private investors need certainty and policy stability for market confidence (Mckelvie and Bennett 2023: 3).

In China, the government has prioritised the development of an EV market. It contributed 200 billion RMB (nearly US$6.5 billion) in monetary support to the EV industry between 2008 and 2020 and has reduced the costs of new electric cars for consumers and increased charging facilities through subsidies and tax exemptions (Han, Liu, and Jiang 2024). This early start has enabled China to dominate the market (Gong and Hansen 2023) – 2022 figures show that the country accounts for 60% of new EV sales globally and that its lithium battery manufacturing capacity is 77% (Wu 2024). Concern about China's dominance has prompted the USA and EU to implement policies and laws to expand their domestic capacity, such as the USA's Inflation Reduction Act. Yet, despite these moves to support onshoring, Chinese firms are establishing gigafactories in Europe, while American firm Tesla has built gigafactories in China and Europe (Asaba et al. 2022; Cooke 2020; Han, Liu, and Jiang 2024).

Both the Faraday Institution and Green Alliance suggest that the UK could distinguish itself from other producers through its environmental credentials, as it has decarbonised its grid rapidly. The Faraday Institution (2022: 20) estimates that British-made EV batteries would be '12% greener than the European average', though this assumes that recycling would take place in the UK, which is not currently the case (Mckelvie and Bennett 2023). The current high cost of electricity in the UK, compared to the EU average, could also work against establishing British lithium manufacturing. British firms will also need to be careful about ensuring the robustness of any claims to sustainability, so as not to undermine public and consumer trust.

The UK government has predicted that successful execution of their Battery Strategy will create 100,000 jobs in battery manufacturing and supply by 2040 (DBT 2023: 6). The creation of new jobs is likely to be broadly welcomed, though for a just transition, any jobs created by the lithium-ion battery industry would need to offer equivalent or better conditions than those already available. While it is difficult to assess how future gigafactories might compare with current workplaces, some critics have drawn attention to reports about workplace injuries, racial discrimination and potential negative health and environmental impacts from pollution associated with Tesla and Samsung battery plants (Cooke 2020; Wu 2024). Some gigafactories in Europe have also been criticised for employing small numbers of locals (Garbis et al. 2024; Wu 2024).

A few gigafactories have been met with local resistance despite political and media support, like Tesla's first European gigafactory, in Grünheide, Germany, where locals were concerned about negative environmental impacts. A planned battery plant by Chinese market leader CATL in Hungary has also attracted controversy. The CATL gigafactory, which will be the largest in Europe when it opens in 2025, has been unanimously supported by local and national government, but sparked opposition amongst locals and opposition parties. Protestors were concerned about negative environmental impacts including water usage, changes to a natural area and the energy intensity of battery production in a country that relies on natural gas for power (Wu 2024). According to Wu, opposition arguments reflect public mistrust of the Hungarian government, but also suspicion about Chinese and other East Asian companies and investors in the area, partly due to the negative reputation of the Samsung SDI battery factory in the town of Göd, which has increased carbon emissions in the area and received numerous labour protection fines (Wu 2024).

The use of lithium-ion batteries: electric vehicles and battery energy storage systems

Electric vehicles and battery energy storage systems (BESS) are expected to represent the major uses of lithium in the UK. Electric cars exemplify the kinds of behavioural changes on which achieving net zero relies and most of the literature focuses on the reasons why people do, and do not, buy and use electric cars. However, adoption of electric vehicles relies not only on individual choices but also infrastructure, economic incentives and policy levers. The social science literature on BESS centres on public perceptions of the technology and general and local acceptance but also raises questions about whether publics in the UK will accept novel and decentralised energy systems.

Battery electric vehicles

Sales of battery electric vehicles (BEVs) are rising (SMMT 2024). In the latest National Travel Attitudes Survey (wave 9, 2023), of those who said they were planning on buying a new car, 49% said they would buy an ultra-low emission vehicle as their next vehicle. 41% of those with the lowest income (less than £15,000) said they would buy an ultra-low emission vehicle (DfT 2023).

The success or failure of electric cars, and thus their potential for contributing to the net zero target, relies on consumers shifting away from internal combustion cars towards BEVs. Policies to support their adoption therefore need to be informed by research about consumer perceptions and preferences. A survey of UK motorists published in 2018 categorised barriers to adoption of EVs into two main groups: economic uncertainty and socio-technical factors (Berkeley, Jarvis, and Jones 2018). They found that economic uncertainty was found to be significantly associated with age and geography, whilst socio-technical issues were (weakly) related to gender. Socio-technical issues include how BEVs are perceived in a material and practical sense. For example, the current popularity

of SUV-style cars may influence perceptions of BEVs' suitability in terms of size, appearance and safety.

People with strong environmental values, who might be expected to be early adopters, can be sceptical about BEVs' green credentials, especially in relation to sources of electricity and battery disposal (Berkeley, Jarvis, and Jones 2018) and evidence of an association between adopting BEVs and concern about the environment is mixed (McBain, Axsen, and Wilson 2023). One study found that purchasing BEVs is more strongly associated with a desire to make a good impression on others and positive perceptions about practicality and upkeep than environmental values (McBain, Axsen, and Wilson 2023). A German experimental study found that, amongst people working in the car industry who did not have strong environmental values, messages emphasising the potential cost savings of owning a BEV were more effective than those promoting BEVs as a sustainable option (Decrinis et al. 2023). While this evidence is limited, it does show that appealing to environmental values is not the only, or necessarily the most effective, way to promote uptake of BEVs.

Given their cost, financial support for those thinking of purchasing BEVs is likely to be welcomed (Jordan 2023). Policies aimed at driving uptake of BEVs need to be carefully designed so they do not have unintended consequences for people on low incomes, for example by penalising ownership of internal combustion engine cars amongst those who rely on a car to get to work but cannot afford a BEV (Theminimulle et al. 2024). If BEVs remain out of reach for people with low incomes, people in areas with insufficient public transport and people with limited mobility, this could limit their lives, access to services and social and economic participation.

One of the most widely discussed barriers to BEV adoption is 'range anxiety', or concern about running out of charge before reaching a charging point. Although, some scholars point out that the discourse of range anxiety can accentuate barriers to BEV adoption and distract from other barriers like cost (Noel et al. 2019). Most BEVs now have ranges that are well matched to general expectations of range. However, range anxiety can still have a detrimental effect on the experience of driving a BEV, for example with people not using heaters in their cars to preserve battery life, avoiding longer or unfamiliar journeys, or even having an EV as a second car and retaining an internal combustion engine car as their primary vehicle, which contradicts the intended role of BEVs in the net zero transition (Berkeley, Jarvis, and Jones 2018).

Strategies to alleviate range anxiety could include improving charging infrastructure and parking, investing in research and development of batteries with faster charging, public awareness campaigns, and giving people opportunities to test-drive BEVs (Berkeley, Jarvis, and Jones 2018; McBain, Axsen, and Wilson 2023). The issue of range anxiety reflects the fact that many people have high expectations and high dependence on cars in their everyday lives, so BEVs will most likely need to meet or exceed expectations of internal combustion engine cars to be widely accepted (Kester et al. 2020).

As Bonsu (2021) points out, policies that specifically support people on lower incomes to own BEVs would not only address the cost barrier but also help mitigate the fact that lower-income communities tend to be more exposed to air pollution. A survey of over 400 internal combustion engine car drivers in London found that respondents were more in favour of incentives to purchase a BEV such as grants or tax relief compared to disincentives such as the ultra-low emissions zone (ULEZ), though in practice it may be that a mixture of incentives and disincentives works best to achieve the desired outcome (Jordan 2023). According to City Hall, the ULEZ has led to declines in NOx and CO_2 emissions, thereby improving air quality (Mayor of London 2023). Communicating such benefits beyond climate mitigation could help support adoption of BEVs.

Battery energy storage systems

Social scientific research on public perceptions and acceptance of BESS is limited but diverse, reflecting the different applications and scales at which batteries could be deployed. The public's knowledge of BESS is low (Ambrosio-Albalá et al. 2020) and exposure to further information is desired by research participants (Brennan and van Rensburg 2023). As with other novel technologies, people's familiarity with similar technologies, from disposable alkaline batteries to the rechargeable lithium-ion batteries used in mobile phones and BEVs, is likely to inform their understandings and perceptions of grid-scale batteries.

Research on energy storage technologies conducted in the UK found that the main perceived benefit was that BESS would reduce carbon emissions and enable more renewable energy. More negative or ambivalent views reflected concerns about health and safety, particularly related to fire and toxicity, siting and feasibility of the technology (Thomas, Demski, and Pidgeon 2019). Participants also discussed measures to mitigate these risks like safety certification and recycling, which the authors suggest 'point[s] the way to regulatory pre-conditions on which future acceptability may rest' (Thomas, Demski, and Pidgeon 2019: 9). The UK Battery Strategy survey shows that safety is also a concern for professional stakeholders, both in relation to fire risk and disposal of batteries, with respondents identifying a need for further regulation for both, as well as more consistent policy and greater training and guidance for those processing batteries (DBT 2023: 63).

While evidence is limited, studies of public perceptions of BESS found positive attitudes in Germany, Canada (Baur et al. 2022) and the UK, where the public 'has strong expectations about the technology, its benefits and its management' (Ambrosio-Albalá et al. 2020: 1) and associate BESS with technological progress (Thomas, Demski, and Pidgeon 2019). Some British research participants expressed concerns about the cost of BESS (Ambrosio-Albalá, Upham, and Bale 2019; Brennan and van Rensburg 2023). German people were also concerned about 'the environmental impact of the technology (production and disposal, unsustainable raw materials, impairment of flora and fauna)' and 'concerns about costs related [to] the use of the technology (disposal costs, decline in land and property values, high taxes)' (Baur et al. 2022: 7). Research shows that general acceptance of BESS may not always translate into local acceptance. This may reflect

concerns about a loss of living space or fire and explosion risks (Baur et al. 2022), or negative perceptions of a facility's impact on health, environment, property prices and the appearance of the landscape (Brennan and van Rensburg 2023).

One issue that emerges in the literature on BESS is the specific question of community battery storage. Ambrosio-Albalá et al. (2019: 145) found that, in the UK, '…people could not imagine the case where a community would share a battery bank or pay to use a portion of the battery' and believed it would only work if households had a direct benefit such as monetary compensation. An Australian study, by contrast, found that citizens felt that having a local, decentralised energy storage system would result in greater engagement and agency amongst local communities. Others, including particularly Aboriginal participants, expressed a desire for financial benefits from such schemes to remain local. The authors consequently conclude that planners should consider funding, ownership and governance of such technologies alongside technical questions when they are being implemented (Ransan-Cooper et al. 2022: 5). Thomas et al. (2019) found that British research participants felt that domestic and community battery systems could facilitate self-sufficiency and reduce dependence on energy companies, which they perceived as untrustworthy. Some participants thought that 'maintaining a centralised energy system equated to maintaining an undesirable status quo that denied users a say in how it is governed, with potentially deleterious impacts on consumers and the environment' (Thomas, Demski, and Pidgeon 2019: 8).

End-of-life of lithium-ion batteries

Globally, 95% of all lithium-ion batteries – which currently mostly originate in consumer electronics – are sent to landfill (Skeete et al. 2020: 3). If landfilled, this critical and valuable resource is lost, while 'If recovered and recycled, that volume of lithium and cobalt would be enough to make 220,000 battery electric cars' (Evans, Plumpton, and Peake 2021: 15). Green Alliance therefore argue that establishing lithium recycling in the UK would reduce costs, lower the greenhouse gas emissions of new products and support UK businesses, and state that the Environment Act provides a basis for increased recovery and reprocessing of critical resources.

Some researchers forecast that, by 2025, there could be a 'dynamic stockpile' of over 100,000 redundant lithium-ion batteries in the UK, as the first of the current generation of BEVs become obsolete (Skeete et al. 2020). Recycling lithium-ion batteries is challenging due to the lack of standardisation in battery design and chemistry, limited recycling infrastructure and the potential for exposure to hazards including fire, explosion and toxic emissions during processing, which poses risks to human health and the environment (Ahuja, Dawson, and Lee 2020). Currently, e-waste is often informally recovered in hazardous working conditions and with low recovery of critical minerals, underlining the importance of ensuring that recycling is carried out responsibly (Skeete et al. 2020).

The UK Battery Strategy survey found that stakeholders were concerned about what happens at the end of lithium-ion batteries' lifespans. They identified that scaling up recycling facilities could make British companies more competitive. Relatedly, stakeholders noted the importance of battery health monitoring in enabling recycling and improving knowledge about battery life cycles. Respondents were critical of waste regulations, which they felt were outdated and unsuitable to current and future battery technologies (DBT 2023: 62-63).

As well as recycling and reuse, changing models of ownership would reduce the need for critical minerals, facilitate a circular economy and help reduce energy demand (Čavoški et al. 2023; Bonsu 2021). Ahuja et al. (2020) propose a 'servitisation' model, in which BEV batteries are owned by the manufacturer while the consumer retains ownership of the car itself. They argue that this would both increase recycling and reduce the cost barrier for BEV adoption. Putting the onus on manufacturers to manage battery end-of-life would, they say, provide an incentive to maintain and extend the life of batteries.

Some researchers argue that, since recycling of lithium-ion batteries is currently insufficient to be profitable, a circular economy approach will need to be stimulated by regulatory intervention (Ahuja, Dawson, and Lee 2020). Čavoški et al. (2023: 321) point to the EU Batteries Regulation, which sets specific recovery targets for critical minerals, which escalate over time and will, they argue, focus efforts on the recovery of the highest value and most critical materials in Europe.

The UK government seems optimistic about creating a circular economy of lithium-ion batteries and argues that doing so would reduce the environmental impacts of battery manufacturing and dependence on others for critical minerals (BEIS 2023). Reusing and recycling lithium would also, according to the UK Battery Strategy, increase opportunities for repurposing and the government anticipates that BESS will be the most significant second life use for EV batteries (DBT 2023: 52). The government characterises current UK capacity for recycling EV batteries as emerging, though it acknowledges the advantages that increased recycling and a circular economy will bring. It therefore states that, 'The Government is conducting further work on regulatory levers to incentivise reuse, repurposing, and domestic recycling infrastructure for all battery chemistry types, including lithium-based technologies' (DBT 2023: 53; Mckelvie and Bennett 2023). It will also be important to futureproof these industries so that they can accommodate changes in battery composition and technology over time (Skeete et al. 2020).

Discussion and gaps in research

Even though lithium batteries are familiar technologies, their future development is, like many other technologies, characterised by uncertainty. There is scientific uncertainty about the environmental and health impacts of lithium mining and manufacturing. Social research shows that people are concerned about the possible, if uncertain, environmental and health impacts of this industry. While businesses and the government are optimistic

about lithium mining and manufacturing in the UK, they face competition from China and other countries and regions which are also onshoring lithium production and manufacturing. While the lithium battery industry may produce good jobs, it is uncertain how they will compare with other green jobs, whether they will benefit local people and what working conditions will be like. Further, while enormous resources are going into lithium batteries, future batteries may use new materials and chemical processes – given the UK's research and innovation capacity, this could be an opportunity, but it will need to be planned for (Faraday Institution 2022).

BEVs show the importance of behavioural change and consumer choice in decarbonisation, but also how messaging about such changes needs to be carefully planned and tailored. Communities near lithium mines and gigafactories and people purchasing new cars need to be convinced of the overall benefits of lithium batteries. The evidence highlights several important issues in this vein. Firstly, policies need to take account of the different resources and constraints that people have – people with lower incomes may need financial support to acquire a BEV rather than an internal combustion engine car, just as people with physical disabilities should not be penalised for driving rather than using inaccessible forms of public transport. Secondly, appealing to environmental values is not necessarily the most effective way to promote net zero technologies like BEVs – emphasising co-benefits like improved air quality may reach more people and inform targeted messaging that reaches people on issues they care about. Research from the Grantham Institute and PCAN found that co-benefits resonate with members of the public in the UK and that their perception of the importance of the co-benefit increases with their exposure to that issue (Jennings and Paterson 2023).

Another aspect that emerges from the literature on adoption of BEVs is the high expectations and dependence many people have on cars. This can reflect inadequate or high-cost public transport and the needs of people with limited mobility or who rely on cars or vans to travel to or carry out their work. But it may also reflect a culture in which owning a car is seen as a rite of passage into adulthood, a sign of freedom, or part of an aspirational identity. So, while sharing and servitisation models of car ownership may appeal to some based on reduced cost, improved air quality and reduced carbon emissions, they might challenge some people's identities and aspirations and therefore meet some resistance.

The evidence also suggests that people expect businesses and government to act on climate alongside members of the public and that there is public appetite for regulation, even when there may also be mistrust in specific institutions or individuals. A key lesson from the social scientific literature on lithium batteries is that publics expect to be informed, consulted and enabled to participate in decision-making about the development and adoption of technologies. The purpose of such engagement work should not be to persuade people to comply with top-down measures, but to build systems that work for most people, maximise benefits for people and the environment and represent value for money for producers, funders and consumers.

Gaps in research

Beyond the fact that most research relates to other countries, there are several other gaps in the literature. Most evidence is focused on the present and near future, or on specific points in the lifecycle of lithium batteries, so it is difficult to get a sense of the bigger picture. One researcher points out that most research tends to consider the environmental impacts of lithium extraction from a global perspective, by looking at greenhouse gas emissions, rather than the local impacts of mining (Slattery et al. 2023). Even though most research and policy focuses on lithium's part in decarbonising energy and transport, there is very little discussion of lithium's long-term sustainability, including whether climate change and drought will affect future production (Bustos-Gallardo, Bridge, and Prieto 2021). Finally, there is little consideration of what the cumulative environmental or social impacts of the lithium industry may be, including its potential carbon emissions, in the UK or elsewhere.

2. Heat networks

Introduction

Space heating is responsible for around a third of terrestrial carbon emissions in the UK (Becker et al. 2023). Home heating represents 14% of this, a proportion that has only fallen slightly since 1990 (Shepheard et al. 2024), but there is low awareness of this amongst the British public (BEIS 2020a). 85% of British homes use mains gas for home heating; those which are off the gas grid tend to use oil or electric heating (Shepheard et al. 2024). Decarbonising heating is vital for reaching net zero (Shepheard et al. 2024; Climate Change Committee 2020). But, as Becker et al. (2023: 2) point out, 'unlike the decarbonization of electricity supply which has started to occur largely without most citizens noticing, changes to the heating system will have to involve users'.

Around 2% of UK heating comes from heat networks, but the Climate Change Committee (CCC) estimates that this could expand to 18% by 2050 (DESNZ 2023b). The CCC's Balanced Net Zero Pathway reflects four priorities over the coming decade, including improving energy efficiency, scaling up installation of heat pumps and expanding heat networks (using low carbon and waste heat) (Climate Change Committee 2020: 109). This section reflects these priorities by focusing on heat networks which use different heat sources but all employ heat pumps. The Environment Agency is responsible for permitting ground-source heat pumps in relation to the abstraction or polluting of groundwater, while Ofgem has recently been appointed as the regulator of heat networks. The EA has also been appointed scheme administrator for the Clean Heat Market Mechanism, which is intended to facilitate the switch from fossil fuel boilers to heat pumps.

Heat networks are not a novel technology and have been widely adopted in several countries, particularly in the Nordic region. This was largely precipitated by the energy crisis of the 1970s and a consequent move towards energy independence, while the UK instead focused on using domestic sources of coal and natural gas (Millar, Burnside, and Yu 2019). A tenth of heating in Europe comes from heat networks (Thornton et al. 2017). In the UK,

> Historically, district heating systems serving the domestic sector have been instigated by local authorities, connecting council and community buildings. These buildings are seen as long-term, stable anchors underpinning the capital investment required during initial network development. Examples include Sheffield, Nottingham, Westminster (Pimlico), Southampton, Birmingham and Woking. Some authorities, such as Aberdeen, built up heat networks to alleviate fuel poverty. Heat networks grew substantially during the council house building boom between the 1950s and 1970s. However, many of the systems were decommissioned in favour of individual heating of buildings by natural gas. (Thornton et al. 2017: 8)

In a comprehensive sustainability analysis, Balode et al. (2021: 19-20) report that, in comparison to individual heating technologies, heat networks led in technological efficiency, economic viability, consumer safety and comfort. Expanding heat networks and decarbonising their heat sources is now a government priority. A report for the former government Department of Business, Energy and Industrial Strategy (BEIS) is clear about the positive role that the government has seen for heat networks in recent years: 'The UK government is committed to delivering a self-sustaining heat networks market, which is attractive to investment, where costs continue to be driven down, consumers are properly protected and benefit from reliable and affordable heating, and one which supports the decarbonisation of heat' (BEIS 2020b).

This section will briefly review social scientific literature on heat networks and domestic heating in the UK and, where relevant, other northern European countries. It will highlight some of the social and cultural factors that influence people's perceptions and adoption of heat networks that have emerged from social scientific research, as well as referring to historical research on previous transitions, such as the adoption of central heating in the UK in the mid-20th century. It will then provide an overview of current policy and government-commissioned social research around heat networks in the UK. Longstanding concerns about the monopolistic aspects of heat networks and the different experiences of consumers on heat networks compared to those with individual gas boilers point to the significance of behavioural change and public perceptions to the successful rollout of further heat networks. Finally, five case studies of heat networks using heat pumps are outlined to give a sense of the scale and range of current and emerging projects.

Quick scoping review of social scientific research on heat networks

Developing heat networks in the UK

Heat networks rely on a steady baseline of demand ('anchor loads') to secure investment, which is why many tend to be in cities and blocks of flats including social housing (Smith 2019; Turnell et al. 2023). In the UK, local authorities are often closely involved in the development of heat networks (case studies 1, 3 and 4), and heat networks are one important way in which they can lower their area's carbon emissions as well as making use of local sources of waste heat (Turnell et al. 2023). Across the world, heat networks are often publicly owned, especially by municipalities (BEIS 2020b).

One of the benefits of heat networks is that they are suitable for a wide range of heat sources and the source can be changed during the network's lifespan. They can also be suitable for heating buildings that would be less appropriate for an individual heat pump, such as blocks of flats and some older buildings. The example case studies in this report all utilise heat pumps, with a range of heat sources including freshwater, geothermal mine water and waste heat. Historically, most of the UK's heat networks have relied at least in

part on natural gas as their heat source (BEIS 2020b). Countries with established heat networks including Denmark and Norway are moving towards decarbonised fourth generation (4G) heat networks (Askeland, Rygg, and Sperling 2020). These aim to operate at lower temperatures, incorporate low carbon heat sources and manage supply and demand, though they depend on upgrades to infrastructure, insulation, radiators and controls to optimise performance (Millar, Burnside, and Yu 2019). Beyond this, some developers, including in the UK, are looking to 5G heat networks, with low temperature or ambient loops that reduce heat loss and have the capability to cool as well as heat (Turnell et al. 2023).

As a heat source, water has the advantage of having greater volumetric energy density and more constant and predictable temperatures than air; water-source heat pumps are also quieter than air-source heat pumps (Millar, Burnside, and Yu 2019). Geothermal heat is reliable and has a constant temperature (Millar, Burnside, and Yu 2019; Bailey, L, and Watson 2013). Mine water could provide a sustainable, low-enthalpy heat source for heat networks and several schemes have been in operation in the UK since the 1990s, including the Dawdon site in County Durham which will now supply Seaham Garden Village's heat network (case study 3) (Brabham et al. 2020). The Mining Remediation Authority (previously, the Coal Authority) claims that mine water could 'provide all of the future space heating and cooling requirements for the coalfield communities'; a quarter of UK homes and businesses are in coalfields and 90% of the largest urban areas are over or adjacent to abandoned coal mines (The Coal Authority 2020: 6).

Smith (2019: 4) points out that waste heat (see case study 4) has zero additional carbon, but that the industrial processes that create it may emit substantial amounts of carbon, and this will need to be accounted for when designing and upgrading heat networks. Another factor to consider in decarbonising heat networks is the source of electricity that their heat pumps use. In Drammen, Norway (case study 5), the city's heat network extracts heat from the fjord, uses ammonia as a refrigerant and is powered by cheap hydroelectricity (see also Askeland, Rygg, and Sperling 2020). In other countries with less access to cheap and predictable renewable energy, powering heat pumps may present challenges (Smith 2019).

Behavioural change

Previous heating and energy transitions have depended on various factors, including changes in technology, government and industry support and social attitudes. For example, the rapid switch to coal-fired central heating in British homes in the early 1960s has been described as a result of the advent of small-bore systems that suited terraced and semi-detached houses and were cheaper and more convenient; the efforts of the British Coal Utilisation Research Association (BCURA); and a growing expectation of improved housing standards including whole-house heating (Hanmer and Abram 2017).

In contrast to the clear improvement in comfort, cost and convenience of switching from single coal fires to central heating, low-carbon heating technologies like heat networks and heat pumps bring a similar experience but with disruption and, in the case of individual heat pumps, high upfront costs (Hanmer and Abram 2017; McCarthy 2023). This, along with the fact that most people express satisfaction with their gas central heating – despite also experiencing problems with draughts, damp and condensation (Becker et al. 2023) – presents a challenge for those facilitating the transition to low-carbon heating.

The government's current approach to decarbonising domestic heating systems largely relies on voluntary adoption of technologies like heat pumps by individual householders, supported by financial incentives but limited information about the installation process or the difference in how heat pumps operate compared to a gas boiler.[5] A study of stakeholders in German municipalities found that, 'heat pumps and district heating were perceived as modern and eco-friendly but also as complex and expensive' (Krikser, Ehlers, and Profeta 2024: 9), but that these negative perceptions decreased amongst those who had greater experience with them. The approach to heat networks, which are by their nature more communal, is different, but still relies on local authorities and companies taking the risk of adopting or supporting a much less familiar – and in some cases, unpopular (BEIS 2020a) – technology.

Path dependency is 'a neutral term that describes systemic processes that serve to maintain the status quo' (Braunger 2023: 4). Lock-ins occur when new pathways are blocked by infrastructural, behavioural, discursive and institutional path dependencies and carbon lock-in refers to persistent use of fossil fuel systems despite their known negative climate impacts. Resistance to decarbonisation of heating systems can be due to path dependencies that reinforce established routines and discourage disruption or the learning of new skills and processes. Path dependencies can also emerge for new and low-carbon technologies – for example, more than 90% of heat pumps in Norway, the country with the highest number of heat pumps per capita in Europe, are air-source heat pumps, despite the fact that ground-source heat pumps tend to be more effective in cold climates due to the higher initial cost, lack of public awareness and fewer trained installers of ground-source heat pumps (Sadeghi, Ijaz, and Singh 2022).

[5] There are various schemes providing information about heat pumps, such as the Energy Saving Trust, though many consumers may still require a certain amount of background knowledge and ability to navigate technical information. People often understandably want information about novel technologies before adopting them, though this may recede once they are normalised – after all, most people do not have in-depth technical knowledge about how gas boilers work.

Path dependencies may be reinforced by incumbents with an interest in the natural gas sector. For example, Lowes et al. (2020) have identified a coalition of actors including gas boiler manufacturers, gas distribution networks and lobbyists who have created a discourse of 'green gas' as an alternative to electrification (see also Harvey and Cooke 2023). In this discourse, the use of lower carbon gas represents continuity and minimal disruption, despite the uncertainties around technologies like hydrogen and carbon capture utilisation and storage on which this vision of the future relies. While they recognise that electrification does present technical and financial challenges, Lowes et al. (Lowes, Woodman, and Speirs 2020) criticise this green gas discourse as a 'discourse of delay' that is not genuinely aimed at reducing carbon emissions. The Future Homes and Buildings Standard, due to be introduced in 2025, does not consider hydrogen boilers 'zero-carbon ready'.

While 20th century energy and heating transitions were led by government (McCarthy 2023; Hanmer and Abram 2017), current strategy for decarbonising heating relies heavily on consumer choice, yet academics predict that, 'A transformation of this scale is unlikely to succeed without concerted action and significant government involvement' (Becker et al. 2023: 16). This would include financial support for consumers, training for installers, raising consumer awareness of heat networks and other low-carbon technologies, and regulation of heat networks (Millar, Burnside, and Yu 2019; Becker et al. 2023). Braunger (2023) also argues for more attention to phase-out of old technologies alongside the phase-in of less familiar technologies. These measures would help break the path dependencies that reinforce the use of individual gas boilers. Similarly, government-commissioned research has found that British people think government leadership is necessary to facilitate the heating transition, though would strongly prefer this to include engagement with citizens so that local contexts and public views are incorporated (BEIS 2020a). This study also found that workshop participants speculated that people might try and avoid complying with policies that required them to switch to low-carbon heating, such as by buying up and hoarding gas boilers or buying parts for them from overseas in order to delay switching for as long as possible (BEIS 2020a: 39).

Heating and meanings of home

Some social scientists have criticised policy approaches which assume that technology adoption is a straightforward function of informed and rational choices, for underestimating the socio-cultural factors that influence decisions (McCarthy 2023; Bickerstaff, Hinton, and Bulkeley 2016; Andersen, Christensen, et al. 2022). In order to fully understand people's approaches to home heating, it is important not only to consider their perceptions of specific technologies, but the significance and salience of home as a place of comfort, sanctuary and intimate caring relationships (Ambrose et al. 2023; McCarthy 2023). It will also be important for policymakers to take account of the potential environmental impacts of heat networks and heat pumps, both negative and positive, as these are likely to influence public perceptions and acceptance of heat networks and their heat sources.

Heat networks have been adopted in countries in which communal heating and building-level cooperation is more widespread compared to the UK (BEIS 2020b). Therefore, ‘Ceding the customer-supplier relationship, and even heat billing, to the building level would be a cultural shift for many UK residents’ (BEIS 2020b: 28). While British people express an awareness that reducing carbon emissions requires societal change, a sense amongst some that heat networks are inferior to other heating systems (BEIS 2020a: 27), which may be partly due to unfamiliarity, reflects some resistance to making this cultural shift.

In a study of people’s experiences with heating transitions, Ambrose et al. found that participants focused on ‘the rhythms, routines, relations and practical intricacies of daily life and how they have evolved over time’ (Ambrose et al. 2023: 4) and rarely referred to the broader political and economic events shaping them. This underlines the inward, domestic focus of people when they think about home, which can shape how they approach fundamental changes to their homes such as new heating systems. Similarly, the disruptions of heating transitions are typically framed in material and financial terms within policy discourses, but such changes also affect relationships, caring responsibilities and norms and aspirations of home and hospitality and are consequently also ‘culturally and psychologically disruptive’ (Thomas et al. 2024).

Understanding the social and cultural salience of home heating can help explain why some people are reluctant to relinquish traditional forms of heating, such as attachments to wood as a source of fuel or seeing fireplaces as a domestic focal point. These attachments may also relate to the geography and history of particular places, as well as expectations of different kinds of housing (BEIS 2020a). Thermal comfort relates not only to achieving a particular temperature, but also the different practices, routines and relationships that inhere within a building. Conventions of comfort change over time and place, as the shift to central heating in the 1960s demonstrates. Now, expectations of thermal comfort may extend to convenience and ease of use of heating systems (McCarthy 2023).

Human geographers have advocated for more attention to place in social research. Place-based approaches emphasise the value of considering physical location as more than just a value-free backdrop to social and economic activities. Place identity refers to the sense that people have about a place and can often relate to physical and socio-economic characteristics, such as whether a place has mining heritage or is considered naturally beautiful. These identities of the place are then thought to be reflected in the identities of people associated with that place. Place attachment refers to the process of feeling attached to a place and the outcomes of that process.

The example of a proposed – but later terminated – mine water heat network in Caerau, Wales, demonstrates the importance of place in how people think about heating, which may be all the more salient for heat networks: ‘Because Caerau had experienced the negatives that come with being a mining community (pollution, health problems) and subsequent mining closure (unemployment), everyone felt that the scheme would be

constructive in bringing the community some benefit from the mines' (Shirani 2020: 26). Writing about the same proposed scheme, Brabham et al. (2020: 7) describe the community engagement undertaken by the scientists alongside their exploration project, a primary objective of which was to reassure locals that they were not undertaking exploration for shale gas, given the vocal opposition to fracking in the UK. Such concerns about the environmental impacts of installations like heat networks may well be an important factor in their public acceptance across the UK.

Recent research commissioned by the EA investigated temperature changes resulting from ground-source heat pumps. It found that such thermal plumes, and therefore the geochemical and microbiological impacts associated with them, are likely to be limited, though any impacts they did have would be greater with larger installations (Environment Agency 2024c). The EA is responsible for permitting ground-source heat pumps, though closed loop systems are exempt if they are fully sealed and do not abstract or discharge water to the environment, or if they were installed before October 2023 (Environment Agency 2024a). The EA has a regulatory position statement (RPS) that it will not usually take enforcement action for systems installed after October 2023 as long as the system meets certain conditions and does not cause environmental pollution or a hazard to human health (Environment Agency 2024b).

While many heat pumps currently use F-gases (many of which have high global warming potential) as refrigerants, this is changing and the International Energy Agency (IEA 2022a) estimates that, even with current refrigerants, heat pumps emit at least 20% less carbon than gas boilers. They also state that switching from gas boilers to heat pumps will improve air quality and reduce hazards associated with combustion. The fact that heat networks which employ heat pumps largely have neutral or positive impacts on the environment will likely add to their acceptance by the public, though of course individuals will weigh this against any negative experiences of disruption or unexpected costs. This demonstrates the importance of access to accurate, reliable information from trusted sources, which is also reflected in government research with heat networks users, outlined below.

Control, choice and justice

Perceptions of the heating transition may be coloured by previous negative experiences and prior injustices, such as abrupt deindustrialisation or top-down interventions in social housing (Ambrose et al. 2023; Shirani 2020). 13% of English households experienced fuel poverty in 2023 (DESNZ 2024a) and many people encounter heat-related problems due to inefficient systems and poor insulation, which Becker et al. (2023) suggest offers an opportunity to improve people's perception of the heating transition through the co-benefits of thermal comfort, health, energy efficiency and consequent financial savings. There is a clear link between deprivation and negative experiences of home heating in the UK, which has been brought into focus by the sharp rise in energy prices following Russia's invasion of Ukraine, with effects on heating practices such as reverting to heating single rooms to

save money. Beyond the current focus on heating, some are looking ahead to the effects of global heating, anticipating increased future demand for cooling in the UK. Given the common experience of financial pressures, especially in relation to heating and energy costs, many research participants are clear that reductions in cost will be necessary for people to be convinced to join a heat network (Shirani 2020).

Research on heat networks has repeatedly found that one of the key concerns that people have is about the lack of control and choice associated with these systems, which again relates to affordability (Thomas et al. 2024; Ambrose et al. 2023; McCarthy 2023; Krikser, Ehlers, and Profeta 2024; Thornton et al. 2017; Hodges, Goaman, and Smith 2018). Other countries take different approaches to pricing, with some regulating prices, some offering recourse to the Competition Authority and others capping prices. For example in Norway, for consumers subject to mandatory connection, prices are pegged to the nearest market comparator – in this case, electricity, which is very cheap due to abundant hydropower (BEIS 2020b).

As Ambrose et al. (2023: 35) note, heating and energy provision are typically affected by major political changes and successful transitions depend on trust in those implementing these changes (see also McCarthy 2023; BEIS 2020a). Based on recent research on British people's perceptions of heat decarbonisation, Thomas et al. report that top-down interventions could be seen as impeding 'autonomy and choice, a core value in public deliberations over energy systems change'. They continue:

> Furthermore, many participants expressed discomfort at the expectation that heat decarbonization may require them to make decisions relating to uncertain, costly and potentially disruptive changes to their homes. … Concerns over choice often manifested not only in scepticism towards heat networks as fostering local authority monopolies but also in cynicism towards policy instability with frequent reference to multiple changes in the UK government between 2016 and 2023. (2024: 5)

Many social researchers and campaigners have pointed out that the low-carbon transition may exacerbate inequalities among vulnerable groups including older people, those on low incomes and people with disabilities, so making low-carbon heating affordable is important not only so that customers can access and pay for basic services, but also to ensure a just transition (McCarthy 2023).

The valorisation of choice and control amongst research participants can reflect a range of perceptions and experiences, from economic and social vulnerability and associated feelings of powerlessness, to nostalgia for traditional practices, to a sense of injustice about where the burdens of decarbonisation fall (see also BEIS 2020a). So, a preference for control is not only a simple desire for achieving a particular temperature or price (Andersen, Christensen, et al. 2022). A further dimension to this is an insistence amongst some members of the public that new infrastructure like heat networks should benefit local communities, who have experienced the disruption of their implementation, and future generations, for example through training and employment opportunities (Shirani 2020).

Heat networks illustrate the fact that usually people do not and often cannot adopt new technologies without institutional support and infrastructural change. While people from diverse backgrounds may feel strong motivations to reduce their carbon footprints, the ability to be an early adopter of low-carbon technologies is typically a result of having certain financial and other resources. People with fewer resources may, by contrast, be subject to top-down interventions with good intentions but which can leave them feeling like ‘guinea pigs’ who have little say in the way a scheme is designed and who may have to suffer snagging issues associated with being the first generation of users (Shirani 2020).

In a context of financial precariousness and widespread concern about climate change, many people feel a tension between wanting to ‘do the right thing’ and giving up practices of cultural significance and personal meaning (Ambrose et al. 2023). Similarly, some feel social pressure and moral judgement about making greener choices and therefore experience fatigue and exasperation about expectations to take on the financial, material and social disruption of retrofitting (Thomas et al. 2024). Recognising this mismatch between publics’ pro-environmental aspirations and their everyday constraints is important for policymakers and operators. As Andersen et al. point out in a study with Danish district heating professionals, perceptions of end users are important: ‘Not only do they influence how technologies and policies are designed, they are also likely to affect how energy professionals interact with residents, which, in turn, can also affect how energy transitions occur’ (2022: 2).

Social research on heat network consumers and operators

BEIS commissioned Kantar Public to carry out a postal survey of heat network users in England and Wales in 2016. The survey aimed to build on previous qualitative data to achieve a statistically robust picture of consumer experiences and thereby inform future consumer protection policy alongside the rollout of the government’s Heat Networks Investment Project (HNIP – see Annex 1). The survey (Thornton et al. 2017) found heat network users were more likely than the national population of England and Wales to live in flats, smaller and newer homes, social housing or larger urban homes. The other main difference is that 44% of heat network users were retired, compared to 14% in the wider population.

Main findings from the survey include:

- Heat network users are just as satisfied with their heating system as those not on heat networks.
- Lack of control over heating seems to drive some wasteful cooling and heating behaviours amongst users of heat networks. Higher levels of over-heating and lower levels of under-heating was found amongst those on heat networks. Most heat network users are also billed in a way that does not incentivise energy saving.

- Most heat network users report being no more or less satisfied with the level of control over their heating system, except for those who are struggling financially, who were more likely to be dissatisfied with their level of control.
- Service interruptions were more frequently experienced by those on heat networks, but these were more likely to have been resolved within 24 hours. However, heat network users were also more likely to experience outages lasting a week or more than those not on heat networks.
- Mean price reported by survey respondents was similar, whether or not they were on a heat network. However, the median price indicated that heat network users paid around £100 less than non-heat network users.
- The heat network sector seems to have relatively poor transparency. Heat network users are less likely than non-heat network users to have received information about their heating system, including maintenance arrangements.
- Nearly a third of heat network users had complained or had reason to complain about their system, compared to around a quarter of non-heat network users.

The Centre for Sustainable Energy (Hodges, Goaman, and Smith 2018) conducted a subsequent qualitative study with users and providers of heat networks in England and Wales. The aim was to inform development of a future market framework for heat networks. This research was aimed at exploring areas of dissatisfaction and complaints, so likely reflects a more negative than average experience.

Main findings from interviews and focus groups with heat network users include:

- Consumers had problems achieving the right temperature for heating and hot water, with some experiencing over-heating and others experiencing excessively hot or inconsistent water temperatures, the latter of which was also associated with water wastage.
- Most reported not experiencing unplanned or short outages. Those who did report ongoing problems with unplanned outages largely lived in newer homes (built after 2010) – this is inconsistent with the survey data, which found outages were commoner in older properties.
- Views on metering were mixed. Most unmetered users preferred paying a flat rate, though some thought it could lead to wasteful heating behaviour.
- Users generally believe the inability to switch providers when on a heat network is unfair and that this disincentivises providers from securing the lowest prices for users.
- Users preferred regular billing. Those who had received unexpected high bills tended to think their heating situation was unfair. Similarly, those who had had negative interactions with their heat supplier perceived their billing to be unfair, while those who had had positive interactions tended to be more positive and trusting of their supplier and to think their bills were fair.
- Some expressed dissatisfaction with the information provided to them at the time they bought their homes and some in newer private-led heat network schemes expressed strong mistrust of the information they were given before moving into

their homes. However, those who reported that the system was explained to them at the point of sale were satisfied with their supplier and willing to accept slightly higher prices.

Main findings from interviews with heat network providers include:

- Public- and private-led providers both report using competitive procurement and short-term contracts to achieve best value and quality of service.
- Public sector providers reported that they had undertaken major works to improve the housing stock and/or heat network but had not passed on these costs to consumers.
- Metering services are often subcontracted. A range of arrangements exist, with many making efforts to retrofit non-metered systems.
- Providers report complaints from users about not receiving sufficient information about their heating system before moving in and attribute responsibility for this to developers, landlords, private sellers and conveyancers.
- Providers in public and private schemes supported greater regulation to balance against the natural monopoly of heat networks and protect consumers. They identified a need for greater transparency around billing, greater efficiency, demonstrable value for money and to improve complaints resolution.

Kantar Public also conducted qualitative research with consumers of heat networks on behalf of the Competition and Markets Authority (CMA) in 2018 (Fu and Abbassian 2018). The study used a journey mapping technique which explored participants' home move journeys and the information they received about their heating system. Key findings include:

- Most interviewees had low awareness of heat networks before moving into their home. Those with some awareness had mixed perceptions, with some believing them to be efficient and environmentally friendly while others thought them inefficient and wasteful.
- The heating system was not a high priority when people moved home, due to other considerations like budget and high demand for housing. Only those with very negative experiences said they would avoid a property with a heat network when moving in the future.
- Information about heating was not typically provided at the property search stage. Generally, people learnt about their heating system upon moving in. Often, more information came when there were problems and disruptions to service and tended to come from their supplier, building managers, neighbours and online sources of information.

Interviewees also thought that more information should be supplied to those moving into properties with heat networks, including expected costs and tariffs, billing and disruptions. The researchers suggest that having more information may help counterbalance the sense of having constrained choices by heat network users (Fu and Abbassian 2018: 3), which

seems to echo some of the findings in the qualitative study with heat network users (Hodges, Goaman, and Smith 2018). Fu and Abbassian also found that interviewees did not engage fully with the information that was provided, which reflects people's experience of the constraints of the housing market:

> One of the key reasons for [not engaging fully with the information about heat networks] was that utilities were not considered important in the context of a competitive housing market, where choice was already often severely constrained. Further, respondents tended to assume that heating will meet a basic standard and will operate as other energy utilities do (for example, with similar reliability, consumer protection and ability to switch), so were even less likely to pay attention to the minimal information received. (Fu and Abbassian 2018: 25)

Policy approaches to heat networks

Denmark is often cited as a leader in heat networks, with over 60% of households connected to a heat network (Danish Energy Agency 2017). Its first combined heat and power (CHP) plant, which supplied heat to a hospital, was established in 1903 and district heating systems using waste heat from local electricity production were developed in the 1920s and 1930s. Heat networks using CHP were rapidly expanded in response to the 1970s oil crisis, which brought the country's dependency on imported fuel and consequent energy insecurity into focus. In the 1980s, Denmark developed heat network zoning, in which local authorities produced municipal heating plans identifying areas where heat networks could be developed. Danish law prevents heating supply companies from making a profit.

Denmark aims to stop using fossil fuels by 2050 and there have been discussions about ensuring that its use of biomass, which plays a significant role in the system, is sustainable. Alongside this, there are plans to use heat pumps, powered by wind, solar and waste heat, combined with improved efficiencies and lower temperature heat network systems. Denmark banned installation of fossil fuel boilers in new-builds in 2013 and installation of oil boilers in buildings within areas served by a heat network or natural gas from 2016. Norway, which has the highest proportion of heat pumps per capita, banned fossil fuel boilers in 2020 (Woollard 2023). Ireland effectively banned fossil fuel boilers in new homes through its 2019 Nearly Zero Energy Building (NZEB) regulations and in 2023, only 5% of newbuilds had them installed. Residents in Ireland can access a €6,500 grant to replace their boiler with a heat pump (the equivalent grant in the UK is maximum £7500), with further financial support available for those in fuel poverty and a One Shop Stop service to support and finance retrofitting (Department of Housing 2024).

The UK government has developed a range of policies and incentives to support the expansion of heat networks, which, as noted, is a key objective in planning for net zero. There are a range of funding mechanisms available for the improvement, planning and

development of heat networks in the UK, as well as various legal and regulatory measures (see Annex 1). Many of the case studies outlined below have taken up these mechanisms.

Case studies: Heat networks using heat pumps

Case study 1: Swaffham Prior Community Heat Network

Technology type: Air- and ground-source heat pumps

Location type: Rural village (off gas grid)

Cost: £12m

Funding: £40k HNDU[6]; £3.27m HNIP; match funding and loan from local council, to be repaid via household bills over 60 years.

Estimated carbon saved: 1,052 tCO2e annual average over first 15 years (Triple Point 2023; DESNZ 2023b)

Status: Operational since 2022

Website: https://www.cambridgeshire.gov.uk/residents/climate-change-energy-and-environment/climate-change-action/low-carbon-energy/community-heating/swaffham-prior-heat-network/about-swaffham-priors-heat-network

Swaffham Prior is a village of 300 homes in rural Cambridgeshire. There is no natural gas supply in the village, so most residents have relied on oil boilers. Across Cambridgeshire, around a third of households are off the gas grid (Bourgeois 2018). In 2021, the government launched a consultation on phasing out fossil fuel heating in places with no gas supply and stated that they would support a 'heat pump first' approach from 2026 (BEIS 2022). This zero-carbon system is the first rural village heat network in the UK and produces 4.4 GWh per annum.

The heat network is powered by a hybrid system of air-source and ground-source heat pumps, with electric boilers as an emergency back-up. The ground-source pumps are used in the winter and air-source in the summer. Because of the power of the network, even listed buildings can be heated sufficiently, which would be challenging with an individual air-source heat pump. The hybrid system also boosts the resilience of the

[6] See Annex 1 for further information.

network. The energy company and heat network assets are the property of Cambridgeshire County Council, who are also responsible for operation and management, customer service and billing. The heat network is registered with Heat Trust.

The project was initiated by Swaffham Prior Community Land Trust, which wanted to address fuel poverty in the village. In 2018, they commissioned consultancy Bioregional to assess the viability of a village heat network and potential low-carbon sources of energy. Working with Cambridgeshire County Council, the trust identified a plot of land owned by the council, which became the site of the network's energy centre. Funding from the government's HNDU supported the development of the project. They appointed Avieco as project manager, Bouygues (now Equans) to implement it and provide ongoing maintenance and LineUndrawn to manage community engagement. There is limited information available about community engagement, but Emma Fletcher, chair of Swaffham Prior Community Land Trust, has observed that there was some local frustration at the disruption caused by the laying of pipework and some mistrust about the network. She has written, 'it is difficult to encourage people to take what they consider a leap of faith, to understand that oil boilers will not be here forever and that every home must be adapted as part of the global effort to address climate change' (Fletcher 2023).

The mixture of properties in the village, including many older and several listed buildings, and the lack of reliable data about oil supply and demand made it challenging to determine demand. The design of the system was therefore informed by a demand survey, in which 5 archetypal property types based on existing homes in the village were fitted with meters. The price of heat has been fixed to be less than what consumers would pay for oil for the first five years and will then switch to be comparable to electricity prices. Connecting to the network is free of charge. There are also grants available for villagers on low incomes to improve their home insulation. At least 60 households are on the network and more are expected to join as their oil boilers reach the end of their lives.

Case study 2: Bradford Energy Network

Technology type: Air-source heat pumps, gas boilers

Location type: Urban

Cost: £55m[7] ("Bradford's cultural connection: a model for low-carbon district heating" 2024)

[7] FairHeat report the cost as £70m.

Funding: £20m Green Heat Network Fund, private investment from 1Energy/Asper Investment Management JV

Estimated carbon saved: 8,000 tCO_2e per year

Status: Under construction, opening 2025/2026

Website: https://bradford.energy/

Bradford Energy Network (BEN) is a joint venture between 1Energy Group and Asper Investment Management and is intended to deliver low-carbon heating and hot water to residential buildings and 34 non-domestic buildings including heritage buildings. It will be the largest ASHP installation in the UK so far and aims to produce 60GWh in the first phase ("Bradford's cultural connection: a model for low-carbon district heating" 2024).

The city of Bradford, which has a population of 537,000, plans to be net zero by 2038. Working with heat network specialist FairHeat, the system has been designed to use low carbon energy sources, balanced against cost and the requirements of conventional radiator systems within the existing building stock. Three quarters of the heat will come from the heat pumps, with the remainder from gas boilers, which will compensate for low external temperatures and act as a back-up. BEN will use carbon offsets and source green[8] grid electricity, which they claim will make the network zero carbon ("Bradford's cultural connection: a model for low-carbon district heating" 2024). As with any heat network, there will be potential to change the energy mix over time, which will improve flexibility but also potentially reduce the carbon emissions of the heat sources.

FairHeat are also carrying out surveys of potential customers' buildings and current heating systems to support their system design and to support customers with Public Sector Decarbonisation Scheme grant applications. One example of this is the HM Courts and Tribunals Service, which was supported by 1Energy and FairHeat to successfully apply for £3.5k grant funding from the Public Sector Decarbonisation Scheme (Fairheat 2024). It has been reported that the process of connecting customers to the network will create five full time and five part time jobs, though presumably these may be temporary jobs and it is not clear if any measures are in place to specifically support local employment (Young 2023).

[8] The article's author does not specify exactly what they mean by 'green' electricity.

Case study 3: Seaham Garden Village

Technology type: Geothermal (mine water) heat pump

Location type: New-build, garden village

Cost: Unknown

Funding: £4.3m HNIP, £3.8m HNDU

Estimated carbon saved: 1200 tCO_2e in 1st year, aiming for 3000 tCO_2e in 25th year of operation (Evans 2020)

Status: Under construction, village planned to be completed in 2030

Website: https://www2.groundstability.com/seaham/

The Mine Remediation Authority (formerly, the Coal Authority) (Mining Remediation Authority n.d.) report that one quarter of UK properties sit on coalfields and that, if mine water were used as a geothermal source of heating, it could theoretically provide sustainable, renewable zero-carbon heating for that whole population. Seaham Garden Village is being built adjacent to the Coal Authority's Dawdon mine water treatment scheme. It will have 1500 homes, half of which will be affordable, along with a primary school, shops, health and wellbeing hub and innovation centre. All of these will be connected to the UK's first large-scale minewater heat network. This is intended to be a commercially viable demonstrator project that will show how sustainable energy heat networks can be duplicated across the UK coalfields.

The heat network is being developed by the Mine Remediation Authority, Durham County Council and Tolent Construction; Nordic Heat are supporting them with the procurement and supply chain process (Thomas 2020). The mine water at Dawdon is warmed by geothermal processes to 18-20°C, which is unaffected by seasonal variations in climate. The heat will be abstracted from the mine water by water heat pumps and supported by thermal stores, electric boilers and roof and ground solar PV. It is thought that the scheme could also provide opportunities for the development of aquaculture and vertical farming. Installation of the heat network is planned concurrently with other infrastructure such as roads to minimise costs and installation time.

The North East and Tees Valley represent the UK's first designated 'heat network cluster' (Invest North East England 2022). In 2020, the region was selected as part of the then government's High Potential Opportunities Programme (HPO), which promoted a variety of British projects to foreign investors (Department for International Trade 2020; Triple Point n.d.). Durham County Council aims to be net zero by 2050, but to have already reduced carbon emissions by 60% by 2030. Heat, which represents 38.5% of the county's current

emissions, is one of their target areas for intervention. For the council, this is an opportunity to make economic use of the former mines, provide clean energy for new homes, alleviate fuel poverty, encourage new employment opportunities, create social value and reduce carbon emissions. Expected social value outcomes include the promotion of local skills and employment, growth of responsible regional businesses, healthier, safer and more resilient communities, protecting and improving the environment and promoting social innovation (Durham County Council 2020).

Case study 4: Bunhill Heat and Power Network Phase 2

Technology type: Heat pump, waste heat from London Underground

Location type: Urban

Cost: £23m (approx.)

Funding: £16.3m from Islington Council (Islington Council 2020), €14,074,931from EU CELSIUS[9] project (European Commission 2019)

Carbon saved: 500 tCO_2e per year (European Commission n.d.; Colloide n.d.)

Status: Operational since 2019, extension of existing network

Website: https://www.islington.gov.uk/environment-and-energy/energy/bunhill-heat-network

Bunhill Heat and Power Network was established in 2012 and provides heat and power to 850 homes and 2 leisure centres in the London borough of Islington. In 2019, its owners Islington Council expanded the network. Bunhill phase 2 uses a ventilation shaft from the Underground to recover waste heat. A large ammonia heat pump extracts this heat, which is then circulated through the heat network, supplying a further 500 homes and a primary school with heat and hot water. There is capacity for a new 1000-flat development to connect in future. It can also be used to cool the Tube tunnels.

While the original energy centre, a gas combined heat and power (CHP) plant, does not use renewable energy, it is more efficient than a standard power station. Its £3.8m cost was funded through grants from the Greater London Authority and the Homes and

[9] The EU's CELSIUS project aimed to support European cities to develop energy efficient, secure, affordable and low carbon district heating and cooling solutions, with a focus on maximising the use of waste or secondary heat.

Community Agency. It has also helped to reduce fuel poverty, as it offers residents – many of whom live in social housing – at least 10% reduction in their energy bills. Bunhill Phase 2 was a collaboration between Islington Council, Transport for London and the Mayor of London. It was funded by the council and a grant from the European Union (Ramboll n.d.). The heat network provides 9,000 MWh per year (European Commission n.d.).

For the phase 2 expansion, the council carried out community consultation and made a short video featuring local children to inform residents and promote the scheme (Energy Rev n.d.). The fact that this was an extension of an existing scheme probably helped win support from locals, as well as external funding. The use of waste heat also aligns with Islington Council's 2030 net zero target. The Mayor of London has also committed to ensuring London has net zero carbon emissions by 2030 and City Hall sees heat networks as an important part of achieving this goal while also making heating more affordable for residents. Using heat pumps and waste heat also contribute to policy goals to improve air quality in London.

Case study 5: Drammen Fjernvarme District Heating, Norway

Technology type: Water-source heat pump

Location type: Urban

Cost: Unknown

Funding: Unknown

Estimated carbon saved: 15,000 tCO_2e per year (BEIS 2018)

Status: Operational since 2011

Website: https://www.neatpumps.com/case-studies/drammen-district-heating-heatpumps/

The Norwegian city of Drammen, with a population of 63,000, is home to the world's largest heat network. Glasgow-based company Star Renewable Energy developed the heat pump that extracts heat from fjord water to serve this network when it was extended in 2011 (Star Renewable Energy n.d.). The original heat network was extended as it was no longer able to meet the needs of the city's growing population; it was also an opportunity to switch to a renewable energy source. The heat pump uses ammonia rather than hydrofluorocarbons as a coolant and is run through electricity derived from hydropower, so has virtually zero carbon emissions. Using ammonia means the system will not contribute to ozone depletion and enables a temperature of 90°C, so the system can heat older buildings without the need to retrofit. The system is owned by Drammen

Fjernwarme, which is 50% owned by the municipal energy company and 50% by a commercial energy company and produces 67 GWh per year (WWF Scotland 2016).

Norway aims to be a low emissions country by 2050 and to reduce emissions by at least 50% by 2030, including through carbon taxes. Bans on the installation of fossil fuel-based heating systems and oil-fired heating, which was previously widespread, came into effect in 2016 and 2020 respectively. 92% of Norway's electricity comes from hydropower (IEA 2022b). Norway is thought to be the country with the highest number of heat pumps per capita in Europe (Sadeghi, Ijaz, and Singh 2022). In 2001, the Ministry of Climate and Environment founded Enova, which is responsible for supporting energy efficiency and alternative sources of energy and has promoted adoption of heat pumps with information campaigns and subsidies (Sadeghi, Ijaz, and Singh 2022). Norwegian municipalities are entitled to require new buildings to be connected to a heat network when a district heating license has been issued, though the requirements can be modified to suit local conditions. Heat network companies are obliged to provide municipalities with relevant information to ensure the process is effective and appropriate (Energy Facts Norway 2024). In Drammen, every new-build over 1000m^2 is legally required to have a water-based heating system and to be connected to the district heating system and the heating price is controlled to be lower than alternative fuels (WWF Scotland 2016).

According to Star Renewable Energy, the heat pump they developed, called the Neatpump, can be used to extract heat from seawater, air or any industrial waste stream, so has potential to be applied in many different locations. They have been exploring opportunities to work on heat networks with UK housing associations and councils and in cities across Europe and claim that 'the Thames River could generate 1.25GW of capacity, enough to heat 500,000 homes' (Anderson 2015).

Discussion

While energy policy is often treated as a matter of using quantitative data to model and project consumption patterns, the empirical evidence of people's experiences and perceptions of heat networks demonstrates that heating is both a routine matter that can be governed by rational choices about cost and something that has great personal meaning. A warm home symbolises comfort, contentedness and wellbeing. It also represents relationships and values – of loving family relationships, hospitality and cosiness. With the recent rise in the cost of living, a warm home also indicates financial stability.

Heat networks, especially when they are being retrofitted, involve disruption. Implementing them can be physically and materially disruptive for those on the network and those who use the streets where pipes are being laid. But infrastructure changes like this also disrupt values, norms and everyday routines, as well as people's sense of place and their visions of the future. This gets to the heart of the fundamental change that net zero represents, which can incite feelings of anxiety, uncertainty and fear. This is not to suggest that people

have only negative emotional responses to net zero – uncertainty can be experienced alongside optimism and relief that there may be solutions to mitigate climate change – but more to emphasise the fact that net zero and the behavioural and infrastructural changes associated with it are experienced by people and so will have emotional valence.

Heat networks are by their nature a top-down intervention, though ideally, they will be as energy- and cost-efficient as possible, both by design and in the way they are used by consumers. Any top-down intervention, like heat network zoning or phasing out gas boiler sales, will raise questions in publics' minds about autonomy and procedural justice, though these can be managed through public engagement which allows developers to be transparent about the benefits and costs and to take on board people's concerns and suggestions for improving the service being provided. In some of the cases discussed here, this has also been managed through pricing which ensures consumers on heat networks are not paying more than if they were with an individual provider. The fact that heat networks' heat source can be changed and their energy efficiency improved makes them an attractive option within the net zero pathway. While they may remove some autonomy from end users, they make low carbon heating more affordable and could therefore reduce fuel poverty as well as carbon emissions – this was the explicit intention with case study 1, for example.

It is perhaps no coincidence that heat networks are most extensive in countries with stronger cultural values of collectivism and greater experience of living in buildings with shared spaces and services like Denmark's cooperative housing system, *andelsboligforening*. The UK has strong cultural values of individualism, which are closely bound up with ideas of home as a private sanctuary away from public life and this can factor into people's perceptions of heat networks. Nonetheless, as case study 1 shows, heat networks need not only be suited to urban apartment blocks or social housing but can also serve small villages with diverse architectures and heating needs. Some campaigning organisations have called for using the energy transition to effect greater decentralisation of heating in the UK. While this relies on resources and determination to institute, it may appeal to people's values of autonomy, so smaller community-owned and managed heat networks might have broad appeal. This would be an important area for future research.

3. Ocean alkalinity enhancement

Introduction

There is increasing awareness and acceptance that storage and removal of greenhouse gases is necessary alongside emissions reduction to reach net zero by 2050 (Climate Change Committee 2020; IPCC 2023). If global warming exceeds 1.5°C, emissions could be reduced by scaled-up deployment of greenhouse gas removal technologies, though it should be remembered that the adverse impacts of climate change would increase with a greater magnitude of overshoot (IPCC 2023: 23)

Ocean alkalinity enhancement (OAE) is an emerging carbon dioxide removal (CDR)[10] technology that aims to use geochemical mechanisms to capture CO_2 from the atmosphere and store it in the water column. It is thought to have potential for long-term removal (Cooley et al. 2023: 44; WRc 2024) and medium to high potential CO_2 removal (Cooley et al. 2023: 47) As well as mitigating climate change, some proponents of OAE argue that this technique will reverse acidification (Kitidis et al. 2024).

OAE and other CDRs have been viewed with scepticism by members of the public and campaigners because of a fear that carbon sequestration technologies could deter decarbonisation, as well as concerns that technologies could be implemented with insufficient public consultation and scientific verification of their efficacy and safety (Satterfield, Nawaz, and Boettcher 2023). Further research and modelling are needed to verify the quantity and durability of OAE's potential for CO_2 removal, primarily to ensure effectiveness and safety, but this would also bring credibility to carbon accounting based on this technique. However, public scepticism and mistrust of operators and regulators could delay or stop such testing.

Perceptions of emerging technologies like OAE tend to be influenced by the (perceived) attributes of the technologies themselves, the position and experience of those perceiving them, governance of the technology and the physical and/or social environment which will receive the technology (Cooley et al. 2023; Satterfield, Nawaz, and Boettcher 2023). People also draw upon their knowledge and experience of more familiar technologies when assessing novel ones (Satterfield, Nawaz, and Boettcher 2023). When people make such comparisons, it is worth noting not only the characteristics they

[10] Several different terms are used to describe this group of greenhouse gas removal technologies, but carbon dioxide removal (CDR), which obviously focuses specifically on carbon dioxide, will be used in this report since it is common in this field.

perceive, but also which technologies they view as comparable. For example, CDRs have been shown to spark comparisons with shale gas exploration, with potential 'ripple effects', in which the negative perceptions of risk and trust that have cohered around fracking amongst UK publics could bleed into perceptions of CDRs, despite the differences between them (Cox, Pidgeon, and Spence 2022).

OAE is a relatively unpopular technology, including when compared with other marine CDRs (Nawaz, Peterson St-Laurent, and Satterfield 2023; Merk, Andersen, and Tvinnereim 2023; Bertram and Merk 2020). The most salient factors in public perceptions of OAE are perceptions of climate change risk, perceptions of and relationships to the sea, trust in the technique's effectiveness and governance and a general preference for natural solutions to climate change. Satterfield et al. (Satterfield, Nawaz, and Boettcher 2023: 3) have identified some additional factors in negative perceptions of OAE, including the dispersal of materials (which tends to be viewed less favourably than storage techniques), the use of materials derived through mining, analogies with waste disposal and concerns about the energy consumption and fair distribution of risks and benefits.

Planetary Technologies' OAE trial in St Ives Bay

This section centres on a case study of the Planetary Technologies OAE trial in St Ives Bay, Cornwall. The analysis will focus on the public discourse that surrounded this case – how it was discussed and represented by the different actors involved. This case provides an opportunity to take a place-based approach to understanding public perceptions of a net zero technology (Waller, Cox, and Bellamy 2024: 9)The scientific and societal uncertainties around OAE also present an opportunity for horizon-scanning, which may help government and regulators anticipate public reactions to OAE and other carbon removal technologies (Cox et al. 2021).

Planetary Technologies (previously, Planetary Hydrogen) is a Canadian firm founded in 2019. It has been funded by Shopify, the XPRIZE Carbon Removal Milestone Award and received £250,000 from the UK government through its Direct Air Capture and Greenhouse Gas Removal Innovation Programme (DESNZ 2024b). Planetary's proposed trial involves adding magnesium hydroxide to the wastewater pipe at the South West Water waste water treatment works in Hayle, which is on the bay to the east of St Ives town, to bring about the geochemical reaction that leads to carbon being drawn down into the sea (Environment Agency 2024d).

In Phase 1 of the project in 2021, Planetary Technologies identified Hayle as the ideal pilot site and assessed the rates of magnesium hydroxide application and associated permitting requirements, concluding that a new permit would not be required (Planetary Hydrogen 2022: 9). The pilot study, Phase 2, took place in September 2022 (Kitidis et al. 2024) and aimed to verify CDR resulting from the addition of magnesium hydroxide and to produce a monitoring, reporting and verification plan (Planetary Technologies n.d.).

Public attention to the pilot was initiated by an article in The Times in February 2023. Senara Wilson Hodges, a long-time environmental activist who had recently become a St Ives town councillor, was concerned about this new, larger trial and organised a protest at Gwithian Towans beach in April 2023 (Rack 2024). She raised the issue at a town council meeting the same month and found that others were also concerned. Planetary Technologies had also held public information sessions in March in Hayle, Truro and online and one article reports that residents in Hayle have been much more supportive of the project than those in St Ives (Rack 2024). The proposed Phase 2 trial received media coverage in the Guardian, ITV News and several local outlets.

As the new trial would have increased the amount of magnesium hydroxide being used compared to the pilot, Planetary Technologies had to secure a Local Enforcement Position for South West Water's permit from the Environment Agency. In the autumn of 2023, the EA commissioned the Water Research Centre (WRc) to complete an audit of Planetary's proposal. As BBC News and others reported, the WRc found the overall likely impact of the trial to be low risk and that the technique had potential for significant net carbon removal, but also made recommendations for refining their process and monitoring (WRc 2024).

In February 2024, Planetary decided to postpone the Phase 2 trial for 6-12 months and have said they are working to identify alternative sources of magnesium hydroxide that are fully traceable and have a low carbon footprint (Planetary Technologies 2024), which is one of the WRc's key recommendations. A second protest took place at Gwithians Beach in April 2024. In July 2024, researchers from Plymouth Marine Laboratory, its commercial subsidiary PML Applications Ltd. and Planetary Technologies published an article claiming that the St Ives Bay pilot trial confirms the viability of OAE (Kitidis et al. 2024). It was reported in April 2025 that no further trials would take place in Cornwall due to commercial infeasibility (BBC News 2025).

Method: Discourse analysis

Hall defined a discourse as 'a group of statements which provide a language for talking about – i.e. a way of representing – a particular kind of knowledge about a topic' (Hall 2018: 86). As they help shape understandings of emerging technologies, discourses also affect how they are governed, in turn influencing how they come to be developed, implemented and regulated (Boettcher 2020; Cox et al. 2021; Hajer 1993; Williams and Sovacool 2019). Discourse analysis aims to determine a discourse's meaning and how that meaning is constructed through rhetorical devices in relation to the social context in which the discourse takes place. The St Ives Bay OAE trial has been controversial and, because the proposed trial has been postponed indefinitely, its environmental and social impacts are yet to be determined. Consequently, much of the evidence about it exists at the discursive level, so discourse analysis is an appropriate method at this formative point in its history.

Following an internet search for articles and blogs on the St Ives Bay trial, each source was read closely to identify themes, tropes and key actors. Sources include national and local news websites, blogs and industry magazines. This analysis focuses on textual analysis, but notes were also made about the visuals that accompanied texts. Social media was excluded from the analysis as it was focused on representations that would be accessible to a general audience. Following further analysis, the initial themes were consolidated into four overarching themes, which are explored in depth. Relevant academic literature was identified through a search of Scopus and by following additional relevant references cited in that literature. Further background reading included the WRc report on the trial, the websites of Planetary Technologies, Seal Research Trust and Save Our Bays, published reports by Planetary Technologies and Plymouth Marine Laboratory and the Environment Agency's 'Planetary Ocean Alkalinity Enhancement Trial Information Page'.

In the early stages of development, experts tend to dominate how technologies are framed and understood, including by policymakers (Nawaz and Lezaun 2024). Yet, by deploying established framings and proposing new ones, campaigners can shift the discourses around technologies, in positive or negative ways. In the case of OAE, readily available associations like the 'geoengineering' label can be a potent shorthand for opponents, given its negative connotations of large-scale intervention in natural processes and of potential for undermining climate mitigation efforts (Corner et al. 2013). As with any framing, the technical accuracy is only partly relevant, because all discourses also convey feelings, values and ideals. Indeed, in a situation of low public awareness, as with OAE, the way technologies are framed and the associations that adhere to them may become especially influential in how they are ultimately perceived (Nawaz, Peterson St-Laurent, and Satterfield 2023).

Discourse analysis of the Planetary Technologies OAE trial

Key actors

Boettcher (2020) carried out discourse analysis on debates about a proposed code of conduct for climate engineering research. Boettcher identifies four 'speaker positions' within that discourse: principled gatekeeper (e.g. NGOs), responsible information provider (e.g. scientists), strategic controller (e.g. government, regulators) and self-benefit maximiser (e.g. industry). While the first three categories are positive governance roles, the last one is negative. In the St Ives Bay OAE trial discourse, Planetary Technologies and South West Water seem to be perceived with scepticism and mistrust by opponents to the trial and therefore appear to fit the 'self-benefit maximiser' position according to critics of the trial. Local campaigners' calls for more research and references to the WRc's assessment of the trial imply that they have more neutral or positive attitudes towards scientists and regulators, including the Environment Agency.

While it can be reductive to view cases like this as a binary contest between supporters and opponents, the discourse is constructed in this way. Nonetheless, three further categories of actors can be identified, including agents, the affected and arbiters. While most actors fit into one of the five categories identified, journalists represent a range of positions.

Categories of key actors:

- Proponent – e.g. Planetary Technologies; South West Water; supportive journalists/media outlets
- Agent – e.g. magnesium hydroxide/brucite; Hayle wastewater pipe; funders and investors
- Critic – e.g. Local: Seal Research Trust[11]; Keep Our Sea Chemical Free; Cornwall Carbon Scrutiny Group; the local community. Regional/national/international: Surfers Against Sewage; ETC Group; Hands Off Mother Earth! Alliance; critical journalists/media outlets
- Affected – e.g. St Ives Bay; local wildlife, including seals; the sea; carbon; 'future generations'/local children; fishing and tourism industries
- Arbiter – e.g. Environment Agency; Water Research Centre; scientists; 'balanced' journalists/media outlets

Non-human actors are included in this list, as proponents and critics of the trial mobilise a selection of human and non-human actors in support of the case they are making. For example, seals, whose positive symbolic value has long been utilised by environmental campaigners, feature quite strongly in this case, as does carbon, which is perceived as a problem to be reduced and removed, while magnesium hydroxide appears in the discourse variously as a 'chemical' that is being 'dumped', as a 'laxative' or 'antacid' and as a 'natural alkaline'.

Themes

The social science evidence suggests that securing societal acceptance for OAE may be a challenge across different national contexts. The St Ives Bay trial can help us understand this by illustrating opposition in a specific place. Nuclear power, genetically modified organisms and shale gas exploration, which like OAE have all aroused public concerns about unintended consequences, are often cited as examples of how whole classes of technology can be rejected by publics based on early failures or severe risk perceptions

[11] The full name of the group is Cornwall Seal Group Research Trust, but they routinely refer to themselves as the Seal Research Trust (SRT).

(Satterfield, Nawaz, and Boettcher 2023). However, these examples also demonstrate how technologies may be accepted in one context and rejected in another, as well as how attitudes can shift over time and in response to events (Jasanoff 1995).

Four main themes, each of which have points of overlap, emerge from the discourse surrounding the St Ives Bay OAE trial: 'dumping chemicals', which featured in several headlines and indicates concern about OAE's use of obscure chemical processes; 'secret test', which relates to the Phase 1 pilot trial and lack of accompanying public engagement; 'unintended consequences', which centres on locals' concerns about OAE as an unproven and experimental technology that could have deleterious effects on the local ecosystem; and 'the natural beauty of St Ives Bay', which reflects the place-based considerations of this case.

'Dumping chemicals'

The theme of 'dumping chemicals' relates to ideas of dirt and pollution, public suspicion of unfamiliar chemicals and conflicting ideas about waste management – all of which overlap to some extent with the other themes. This theme, and the related depiction of St Ives Bay as a 'dumping ground' (Save Our Bays n.d.), relates to people's perceptions of waste, which the literature suggests is, or will become, salient in relation to OAE. The social science evidence (Cooley et al. 2023; Satterfield, Nawaz, and Boettcher 2023) points to public concerns about 'dumping' waste into the sea and the fact that the material being dumped is associated with mining, an industry already commonly identified with dirt and pollution (Andersen, Merk, et al. 2022). This may be particularly acute for those who are concerned about climate change. In the case of Cornwall, the dumping chemicals theme might also reflect local ambivalence about the area's mining heritage.

Anthropologist Mary Douglas discussed dirt as matter out of place and explained that 'Eliminating it is not a negative movement, but a positive effort to organise the environment' (Douglas 1966: 2). Douglas argued that that which is considered clean or dirty symbolises broader values about right and wrong, order and disorder, life and death respectively (Douglas 1966). In the St Ives Bay trial, there is a further layer to public concerns about dirt and pollution, indicated by journalists' descriptions of magnesium hydroxide as a 'laxative'. This attention-grabbing trope establishes an association between OAE, excrement and uncontrollability. This is implicitly reinforced by the involvement of South West Water, at a time of public scrutiny about the performance of water companies.

Magnesium hydroxide and brucite (magnesium hydroxide's mineral form) are depicted and perceived differently by the different actors in terms of sourcing, chemical composition and the quantities in which they are, or will be, used. For example, the CEO of Planetary Technologies describes them as 'naturally occurring alkaline minerals' and a 'natural antacid' (Bencsik 2023), while critics have discussed the 'dumping' of 'tonnes of laxatives' (Vergnault 2024) and magnesium hydroxide being 'pumped into the sea as a slurry' (St. Ives Local 2024). There have also been allegations about sourcing associated with asbestos and nuclear waste, which have been refuted by Planetary Technologies (Weeks

2023).[12] These negative perceptions reflect broader popular concerns about exposure to unfamiliar chemicals and pollution and indicate mistrust in industries.

Ideas about outsiders play a subtle but noteworthy part in coverage of the St Ives Bay trial. Across the media and activist coverage, the fact that Planetary Technologies is a Canadian company is frequently mentioned. Several sources also note that the magnesium hydroxide is being sourced from China, via the USA. While both Canada and the USA are G7 countries with which the UK has close relationships, this invocation of people on distant continents could contribute to a sense, expressed by some protestors, that OAE is being imposed on them by 'outsiders'. This may be particularly salient somewhere like St Ives, where there have been tensions around issues like second-home ownership (Gold 2024). The mention of 'Chinese' chemicals could also spark negative associations with China as somewhere with heavy industry and poor air quality and as a manufacturer of 'cheap' goods (Dou and Li 2024). Interestingly, Planetary has carried out another OAE trial in Nova Scotia, where it is headquartered, and did not experience significant public opposition, which Mike Kelland attributes to the company being headquartered in Nova Scotia and because they learned from their experience in Cornwall and engaged the public early and quickly (Rack 2024).

'Secret test'

Securing social acceptance is more likely when publics have been informed about emerging technologies and had their views listened to (Satterfield, Nawaz, and Boettcher 2023). One of the main critiques of the initial OAE trial in St Ives Bay is that it was not publicly announced. In the media coverage and in critics' narratives, this manifests in the theme of a 'secret test' (St. Ives Local 2024; Weeks 2023). This could connote alarming images of 'mad scientists' and unethical experimentation. This theme, which overlaps to some extent with the 'unintended consequences' theme discussed below, points to two important elements of public concern: the 'secret' part indicates a crisis of trust, a critique of the ethics of experimentation, a failure in public engagement (procedural injustice) and broader concerns about governance; the 'test' part relates to ideals of science, research and evidence and the contending standards that different actors expect for an emerging technology like OAE. These expectations may be even higher when an individual expects to be personally affected by a technology.

Trust, in technologies themselves and in the institutions that govern and regulate them, is crucial for social acceptance (Bertram and Merk 2020; Satterfield, Nawaz, and Boettcher

[12] WRc report that the brucite used in the pilot was sourced in China. They note that traceability is difficult and that more robust testing for contamination, with a particular focus on asbestos, is necessary.

2023). The ‘trust asymmetry principle’ states that trust is easier to lose than to gain. Members of the public tend to be concerned about the motivations of scientists and companies developing CDRs (Corner et al. 2013; Andersen, Merk, et al. 2022) and the ‘secret test’ theme reflects a suspicion of Planetary’s and South West Water’s intentions. This mistrust likely reflects the lack of public consultation in the initial trial, which may have been exacerbated by the unfamiliarity of Planetary Technologies and poor reputation of South West Water.

Where trust in institutions is high, people may be more willing to accept unpopular technologies like OAE because their fears are allayed by an expectation of effective regulation and monitoring (Cooley et al. 2023). However, trust is not straightforwardly linked with acceptance and can be pragmatic (Nawaz, Peterson St-Laurent, and Satterfield 2023). The media coverage of the trial generally depicts the Environment Agency as an independent, expert body and as having decision-making power, with several articles having lines such as ‘The EA is yet to decide whether a full scale trial will go ahead’ (BBC News 2024). The fact that the Environment Agency was not notified about the pilot trial may have made protestors more sympathetic to arbiters like the Environment Agency, since they are in a similar position, but also more mistrustful of Planetary Technologies and South West Water, if they suspect they had ‘something to hide’.

It is commonly understood that people’s responses to technologies are driven by perceptions and that giving people more information does not always lead to acceptance (Cooley et al. 2023). However, it is still helpful to gauge levels of understanding and awareness of novel technologies amongst publics, not least when there may also be issues of mistrust in those developing and implementing the technologies (Merk, Andersen, and Tvinnereim 2023). Social scientific research on OAE has found that members of the public have low awareness of the technology but would like more information and more research (Andersen, Merk, et al. 2022). In research with Norwegian respondents, Andersen et al. (2022) found that people struggled to understand carbon removal and this led them to focus on the short-term negative impacts rather than climate mitigation.

OAE is in its infancy, so it is difficult to characterise the potential benefits, as well as risks, associated with this technology. Public uncertainty mirrors scientific uncertainty about its effects on ecosystems and human health. Laboratory and field experiments and modelling can indicate the potential effects of OAE, but are limited when it comes to identifying impacts in specific contexts (Nawaz et al. 2023). Providing more information about the technology and how it works, including through specific trials and experiments, may help people to form stabler opinions. Further, more information is something that people want, though this is less about the technicalities of marine CDRs and more about their likely impacts on ecosystems, local communities and economies and on the climate (Andersen, Merk, et al. 2022: 8), which is reflected in the discourse surrounding the St Ives Bay trial. However, this presents something of a catch-22 situation, since those impacts will be best characterised following trials and experiments.

Some of the most prominent critics in St Ives claim that they support the idea of using new technologies to respond to the climate crisis in principle, but would like further, more controlled, testing of OAE to take place. For example:

> The Seal Research Trust has called for a closed water test of magnesium hydroxide in St Ives Bay to get a definitive understanding of its impact, before open sea trials take place.
>
> Charity founder Sue Sayer MBE said: "The conclusion [of the WRc report] that there is a low risk to marine organisms from magnesium hydroxide in this trial is worrying, as no testing has been done on St Ives Bay seawater and species such as brown crabs and lobsters, let alone the long term testing on 'multiple appropriate marine species' recommended by the EA.
>
> "Of even greater concern to us is the WRc's assessment, that the formation of calcium carbonate sediment is a medium risk, as this will cover sea bed species and be ingested by seabed feeders such as seals." (BBC News 2024).

This call to carry out further testing in more controlled conditions reflects protesters' sense of what constitutes 'good' science, in terms of rigour and ethics. There has been a move towards explicit discussions about how to make CDR research and innovation responsible (Boettcher 2020). Social scientists have called for public perceptions and the potential social impacts of OAE to be integrated into such efforts (Nawaz, Peterson St-Laurent, and Satterfield 2023).

'Unintended consequences'

Over a decade ago, Corner et al. (Corner et al. 2013: 493) found that British research participants discussed geoengineering technologies including CDRs as moral lessons that expressed their concerns about the potential unintended and irreversible consequences of 'messing with nature'. CDRs have come to be distinguished from more radical geoengineering technologies like solar radiation management since the 2015 Paris Agreement (Waller, Cox, and Bellamy 2024: 11) but members of the public associate geoengineering with largescale manipulation of the environment and as a strategy to continue fossil fuel production and use (Low, Baum, and Sovacool 2022). Shedding the geoengineering label will therefore probably improve perceptions of OAE. Planetary Technologies have themselves claimed that 'Our approach sits between natural and engineered carbon removal solutions. It boosts a natural carbon removal process: if left alone, the oceans would balance out excess carbon in exactly the same way, but it would take several hundred thousand years. By increasing the ocean's ability to absorb and store carbon, we're trying to give it a helping hand' (Planetary Technologies 2023).

Concern about 'unintended consequences', particularly for the bay's ecosystem, is readily apparent in the comments of opponents to the St Ives Bay trial, for example, in an article in the Guardian that covered the Keep Our Sea Chemical Free April 2023 protest at Gwithin Towans beach:

> The firm's [i.e. Planetary Technology's] scientists say the chemical deployment could reduce the acidity of the ocean and remove CO_2 from the water, thereby drawing harmful CO_2 out of the atmosphere to replace it.
>
> But protesters fear the chemistry may negatively affect the bay of St Ives' precious marine ecosystem, which includes a grey seal population, and are demanding greater scientific scrutiny.
>
> Senara Wilson Hodges, the protest organiser and a St Ives town councillor, said: "We are all terrified of the climate crisis but you can't use that fear to say: 'You've got to go ahead with this project.' We're worried about what will happen to the local environment if they scale this up and how it will react with the heavy metals from mining waste that's in the bay."
>
> Kath Lawrence attended the rally with her partner and their two children. She said: "We spend every spare moment here and often see the seals and dolphins. We're here today for our children's futures. We want them to be able to enjoy the bay for years to come.
>
> "We don't know what the outcome will be if they dump these chemicals into the sea. I'm sure there are more natural ways of solving the climate crisis." (Weeks 2023)

Concern about unintended consequences, sometimes manifested in the 'slippery slope' metaphor, is established in narratives around controversial technologies from genetic modification and genome editing to shale gas and nuclear energy, so this critique could have the added rhetorical power of being associated with already unpopular technologies (see also Cox, Pidgeon, and Spence 2022). Responding to such an ambiguous and potentially far-reaching critique is very challenging for proponents of technologies that become controversial like this.

One assumption embedded in the unintended consequences theme is that OAE is irreversible. If technologies are perceived as having irreversible consequences or leading to irreversible losses, this can make them appear intolerably risky (Cooley et al. 2023: 54). In a subsequent academic article reporting the results of the pilot, the authors state that, there was 'no apparent "memory" of the MH [magnesium hydroxide] addition' (Kitidis et al. 2024: 4), suggesting that administering magnesium hydroxide to the site should not have irreversible consequences. The WRc report states that, 'Magnesium hydroxide (MH) is of low acute toxicity to aquatic organisms. It also does not persist in the environment nor bioaccumulate in aquatic organisms' (WRc 2024: 34). Though, as they make clear, this low risk of ecotoxicity relies upon uncontaminated supplies of magnesium hydroxide (WRc 2024: 36).

Numerous studies have established that people show a preference for technologies that appear not to be 'messing with nature' (Corner et al. 2013; Nawaz and Lezaun 2024). Naturalness is commonly associated with purity, permanence and balance, while

unnaturalness is associated with immorality and danger (Bertram and Merk 2020). However, what people perceive to be natural varies across space and time. OAE illustrates this well, as some proponents claim it is just accelerating natural processes, while some critics dismiss it as geoengineering. Scholars have pointed out that, if it proves to be effective at mitigating climate change and reversing ocean acidification, OAE could come to be perceived as restoring nature (Cox et al. 2021; Low, Baum, and Sovacool 2022). Yet, if proponents claim OAE is natural but this is not accepted by the public, this could exacerbate negative perceptions and reduce trust (Satterfield, Nawaz, and Boettcher 2023).

The unintended consequences theme contains an argument about what is often termed ‘moral hazard’. While it has been applied in the geoengineering debate somewhat inconsistently (Tsipiras and Grant 2022), moral hazard generally refers to the idea that CDRs may distract from or even prevent emissions reduction, because people come to think they are less necessary or urgent if carbon can be captured and stored. While the local protestors seem to be most concerned about the uncertain effects of OAE on the local ecosystem, some of the broader discourse about the trial relates to moral hazard (Low, Baum, and Sovacool 2022).

The moral hazard argument relates to public perceptions of the intentions of proponents of OAE, which may manifest in suspicion about their motives and claims for what they are doing (and this relates to the ‘secret test’ theme). This is exemplified by an article in Geoengineering Monitor, which criticises Planetary Technologies for having ‘commercial interests’ in OAE and claims that producing magnesium hydroxide from brucite ‘may use more carbon dioxide than is captured [through OAE]’ (Geoengineering Monitor 2023). The latter claim has been refuted by Planetary Technologies and they have an article on their website that explicitly discusses moral hazard (Kelland 2023). However, in their article reporting the results of the St Ives Bay pilot, Kitidis et al. (2024) acknowledge that, at that small scale, the embedded and operational emissions did exceed the avoided emissions, but suggest this would shift with scale-up, depending on the approach taken.

Researchers (Nawaz, Peterson St-Laurent, and Satterfield 2023) have found that a renewed sense of urgency about preventing climate change is leading some publics to be more receptive to CDRs including OAE (see also Corner et al. 2013: 941), though it may still be less popular than other techniques. In the excerpt from the Guardian above, Senara Wilson Hodges is quoted saying, “We are all terrified of the climate crisis but you can’t use that fear to say: ‘You’ve got to go ahead with this project.’ Planetary’s CEO Mike Kelland is quoted in the same article saying, “‘Reducing all emissions is job number one and nothing we do will make a difference if we don’t achieve that … But we also need to act carefully and incrementally with ocean-based carbon removal. At some point, we are all going to run out of time”’ (Weeks 2023).

‘The natural beauty of St Ives Bay’

Policy discussions about CDRs tend to refer to the global or planetary scale – for example, in relation to global emissions targets – which can exacerbate a sense that local contexts are not being sufficiently accounted for, as well as a perception that technologies like OAE are being inflicted upon locals by outsiders. The representation of St Ives and the surrounding bay is critical in this case and locals will have more authority in this part of the discourse than outsiders. Notably, many of the photographs that illustrate media reporting of the case depict St Ives town, St Ives Head and Porthmeor Beach, rather than Hayle, where the magnesium hydroxide would be administered. Visually, therefore, St Ives town and its surrounding beaches, which are likely to be familiar to many readers outside of Cornwall, stand in for St Ives Bay as a whole.

St Ives Bay is typically described in positive terms by all. Proponents of OAE emphasise that the bay has the perfect conditions for their trial, while for local opponents, it is a place of natural beauty, and their economy and people’s wellbeing rely on that natural beauty being preserved. Yet, this is not a pure distinction – Mike Kelland has written about his links with the area on the Planetary website:

> While my family lives in Canada, we have deep family roots in Cornwall. My parents immigrated to Canada from Cornwall just before I was born and we have close family members who still live there. I built sandcastles as a kid at Praa Sands, Perranporth and Gwithian, and my cousin taught me how to surf the waters of those same beaches. I’ve hiked the entirety of the South West Coastal Path around the Cornish coast. Cornwall has always felt like home.
>
> Unfortunately, that home is in grave danger. No matter how much work we do to protect our coasts, climate change is already posing a threat to Cornwall’s community, and to the natural beauty of St Ives Bay. I am proud to be able to bring Planetary to Cornwall as part of a global effort to protect that beauty. (Planetary Technologies n.d.)

In this passage, Kelland makes claims of belonging to Cornwall through family and experience. He then mobilises this claim to make a case for the trial, explicitly drawing on the theme of St Ives Bay’s natural beauty. Whether this strategy is convincing to locals will probably depend on how concerned they are about OAE, how much trust they have in Planetary Technologies and how flexible their beliefs about local belonging are. Some locals may be reassured by Kelland’s links to the area, while some may feel his claims to belonging are inadequate because he is not ‘born and bred’ Cornish.

The St Ives Bay OAE trial illustrates the importance of looking at local acceptance as well as more general acceptance of emerging technologies. Some scholars conceptualise this in terms of place – the location of any technology or infrastructure is closely related to public perceptions, social impacts and governance (Cooley et al. 2023: 43). Acceptance and opposition are closely linked to place histories, identities and attachments (Devine-

Wright 2009), including how residents think of an area, for example as an ‘industrial’ or ‘natural’ place (Whitmarsh, Xenias, and Jones 2019). People living in (post-)industrial areas may be more willing to accept new industrial facilities not only because of potential economic benefits, but also because such facilities fit with local identities and values and because people have a sense that the risks of industrialisation are familiar and manageable. At the same time, when people have a strong sense of a place as ‘natural’ and ‘beautiful’, and when livelihoods depend on this, such as through fishing and tourism, the benefits of something like OAE may be less clear to them. Further, as the Guardian excerpt in the previous section shows, some protestors are concerned about the interaction between legacy mining waste interacting with magnesium hydroxide, suggesting a sceptical or critical attitude towards mining even in an area with strong mining heritage.

Research has found that people find interventions in the sea more troubling that terrestrial ones (Andersen, Merk, et al. 2022; Nawaz, Peterson St-Laurent, and Satterfield 2023) and this is true for those living both in coastal areas and inland (Satterfield, Nawaz, and Boettcher 2023). Most people view the sea as fluid, dynamic, unpredictable and sensitive to impacts and may therefore be sceptical about institutions’ ability to regulate and monitor interventions in marine environments (Nawaz, Peterson St-Laurent, and Satterfield 2023; Satterfield, Nawaz, and Boettcher 2023). Those who see oceans as adaptable tend to be more comfortable with OAE, while those who see the sea as fragile are more likely to find it discomforting (Cooley et al. 2023; Nawaz, Peterson St-Laurent, and Satterfield 2023; Satterfield, Nawaz, and Boettcher 2023).

These findings from existing research are reflected in both the ‘unintended consequences’ and ‘natural beauty of St Ives Bay’ themes. Opponents’ concerns about the uncertain consequences of OAE on wildlife gives a sense that they perceive the sea and the ecosystem which it supports to be fragile and vulnerable and their calls for more controlled experiments echo the research evidence about public perceptions of interventions in the sea being difficult to control. In this case, opponents seem to be most concerned about OAE’s effects on the local ecosystem. This may in part reflect the fact that Sue Sayer, representing the Seal Research Trust, has been a prominent voice in the campaign, but it is not entirely surprising given the established perception of St Ives as a place of natural beauty, on which its tourism industry depends. Again, the involvement of South West Water and its poor reputation for environmental protection is likely to be relevant here, as well as broader public concerns about water quality that are currently prominent in the media.

Opponents’ discourse about local impacts shifts between the bay itself, the seals, future generations (of humans), other marine species (and implicitly the local fishing industry, some of whose members have supported protests) and the seabed. Proponents have tried to appeal to locals’ connections to the sea by emphasising the potential that OAE has for remediating ocean acidification and Mike Kelland has repeatedly referred to OAE as being akin to ‘giving the ocean an antacid’. This shifts the focus away from magnesium

hydroxide's laxative properties and implies that administering it is a benign, healing action to help the ailing sea.

Nawaz et al. (2023: 8867) have cautioned that, 'As OAE research expands, it will be imperative that we enrich our understanding of its local consequences, if we are to ensure that risks and benefits are not distributed in ways that compound existing vulnerabilities and entrench environmental injustice'. The four themes in the St Ives Bay trial discourse converge in relation to such questions of fairness, justice and equity. All four themes express a perception that the trial has been imposed on local people, other species and the place in which they live, by outsiders whom they have little reason to trust. Opponents feel that the trial has been covered up, which makes them suspicious of its intentions and indicates a sense of procedural injustice. The unfamiliarity of OAE, combined with scientific uncertainties about its effectiveness and safety, which can only be addressed through more experimentation, mean that its benefits and risks, and how and where those will be distributed, are unclear. For locals, St Ives is a place of natural beauty which needs protecting. This indicates a sense of vulnerability, which may reflect local concerns such as the decline in traditional industries like fishing and the impacts of tourism, but also anxieties about the effects of climate change and the urgent need to mitigate it, in ways that do not exacerbate existing social inequalities and environmental vulnerabilities.

Discussion

While Planetary Technologies and South West Water were not required to publicise their pilot test, their choice to carry it out without notifying the public led to suspicions about their motives and the trial's potential impacts. It also meant that they were unable to learn what concerns and questions people had or to consider how to address them early in the process. Planetary were at a disadvantage while locals felt that they had been subject to procedural injustice. As the social scientific evidence shows, Planetary were likely to face challenges with local acceptance due to widespread negative perceptions of OAE and other CDRs and because industry actors tend to be viewed with more suspicion than other more trusted messengers. The ability of marine CDRs to sequester carbon will only really be known by conducting large-scale in situ trials and so companies will need to engage with publics more effectively if they are going to be able move towards scale-up (Rohse et al. 2024). Questions about the effects and benefits of OAE and whether these are distributed fairly and equitably are a likely site of future contention.

Currently, the fact that OAE is likely to be financed through carbon markets does not feature strongly in the discourse around it, but this is likely to be an area of future contention. This aspect of the business model could be perceived through existing suspicion about Planetary's intentions and concern about OAE being a global project that is being imposed on local areas without enough consideration for place identities and attachments. Proponents of OAE and arbiters will need to anticipate public scepticism and even opposition to carbon markets in the future deployment and scaling-up of CDRs including OAE (Nawaz et al. 2023; Cooley et al. 2023).

In this case, critics have emphasised concerns about the unintended, unanticipated and even irreversible impacts that OAE might have on the local ecosystem. This partly reflects the specificities of St Ives as a place of natural beauty with fishing heritage and a reliance on tourism. More broadly, if net zero technologies like OAE come to be associated with negative environmental impacts, or even just the perception of these, this could contribute to a perception that climate goals and environmental protection are contradictory. Without meaningful public engagement around technologies like OAE, perceptions that the negative impacts of climate change mitigation accrue to local communities could take hold, delaying and even preventing net zero pathways from being implemented.

An in-depth article in Hakai magazine reports an interesting factor in the case, which was absent from other coverage, that the community in Hayle, where the trial was due to take place, was more accepting of the proposal than those in St Ives. The article reports that Hayle's mayor at the time, Anne-Marie Rance, who has a background in geoscience and is supportive of CDRs, does agree that Planetary's initial public engagement efforts were 'widely perceived as evasive and condescending', but 'felt compelled to defend the trial against its diehard opponents, driven by a sense that the stakes reach far beyond this corner of Cornwall'. This indicates the importance of the framing of local and global impacts – and the assumption that these would be different or even in conflict – in this case.

It is important to pay attention to the rhetoric, frames, tropes and storylines that are deployed in discourses, but also those that are excluded. For example, if OAE had been framed as primarily a means to alleviate ocean acidification, rather than carbon sequestration, it might have been more positively received by the community in St Ives Bay, not least because this could have been viewed as a more locally focused aim than carbon removal. However, the WRc audit of the St Ives Bay pilot notes that, 'There is potential for mitigation of ocean acidification impacts near injection sites, however, ocean pH is largely restored to pre-OAE value once alkalinity-enhanced seawater has equilibrated with atmospheric CO2' (WRc 2024: 48), so the claims about de-acidification are still quite speculative.

Like public perceptions, discourses are not static and may shift over time. The evidence suggests that some members of the public are becoming more receptive to CDRs as the urgency of climate change increases. If public perceptions shifted towards seeing OAE as a natural process, or 'giving nature a helping hand', this could lead to greater acceptance. However, some critics may be suspicious about claims to naturalness, especially from commercial companies. Further, some Cornish people have opposed proposals for seaweed farms, which are generally thought of as a nature-based solution to climate change, across several sites in the county. The reasons given in one BBC article (Butler, 2024) include a belief that the area's natural beauty will be ruined and that the aim of the companies involved is profit rather than mitigating climate change. This shows that what counts as natural and acceptable may not be entirely predictable or consistent. It also suggests that resistance to any form of CDR may be particularly pronounced in this region. However, there is a potential source of common ground here, in that both proponents and

critics conceptualise carbon dioxide as a problem that needs to be resolved. The question of how is obviously more contentious, but if the different parties were able to come together over this basic problem and the need for an urgent resolution, a mutually acceptable way forward might be reached.

While the case has been presented in the media as a binary contest, the key actors have been careful to present measured arguments, avoid personal attacks and engage with other perspectives. Since the initial protests, staff from Planetary have organised several public engagement events and held meetings with critics. This suggests some potential for the proponents and critics to find areas of agreement if they continue to work together constructively.

One of the key points of contention in this case is what constitutes good science. Yet, this is also a site of potential agreement, if handled sensitively. Despite their differences, all the parties seem to value science and to want more evidence about OAE's effects, even if for slightly different reasons. This case illustrates that, as well as scientific facts and findings from experiments, we need evidence about how people think and feel about technologies to be able to build consensus about whether and how they should be deployed.

Discussion: Net zero and people

The social science evidence and some of the current public discussions about net zero reveal an emerging tension between the goals of climate change mitigation and the potential impacts that specific emissions reduction measures could have on the environment. The impacts of net zero technologies on the environment and wildlife are varied and while reducing carbon emissions will generally have many positive effects, this is not straightforward. It is therefore important to be clear about the negative and positive impacts that net zero might have on the environment and society and to involve publics in discussions about how to manage this and, where necessary, determine trade-offs between benefits and risks. A lack of transparency about this issue may exacerbate distrust and scepticism in these technologies and even the broader net zero goal.

Another point of tension in current debate around net zero, which can also be found in the social science literature, is between the urgency of mitigating climate change and the careful planning that needs to go into doing so successfully. For some, the urgency of arresting climate change trumps any other possible concerns, even when, for example, an alternative technology is unproven or may produce more carbon than expected. As social scientists and other analysts have argued, while technologies can certainly play a vital role in reducing carbon emissions, we still need to reduce demand to maximise emissions reduction (Climate Assembly 2020; Climate Change Committee 2020; Jenkins and Hopkins 2018). Some protestors have sounded a note of caution about relying on technology to allow us to live the same high-carbon lives as usual, given that climate change cannot be mitigated through technology alone, but will also require societal change (Garbis et al. 2024; Thierauf 2024).

Net zero is a future-oriented goal and so some social scientists have made the important point that policies for net zero and the changes required to achieve it entail imaginaries of the future. As Thierauf writes in relation to gigafactories, 'It matters how the future is collectively imagined, anticipated, predicted, expected, and prepared for in the present because such practices do something, they increase the chances of materialising some futures over others. They become the foundations on which strategic alliances are formed, policies developed, investments made, infrastructures built, etc.' (Thierauf 2024: 3).

Net zero pathways rely on visions of the future, scenarios that are made of different combinations of actions, behaviours, technologies and policies. Some of these futures provoke anxiety and the spectre of unwelcome change for members of the public. Understanding the fears that transition can provoke is an important part of planning for a low-carbon future. As well as understanding the pathways to net zero and the changes entailed, it is worth remembering that, along the way, technologies and projects will fail, be abandoned or delayed until a future date. This is, in one sense, a normal part of technological development, but it can also be unsettling for people who have a stake in the technology, especially if it adds to a sense of being left behind or a guinea pig in others' experiments, with an associated lack of agency.

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Glossary

- **Distributive justice**: refers to whether resources and opportunities have been fairly distributed across a society or community.
- **Environmental justice:** the just treatment and meaningful involvement of all people, including those from marginalised and underserved communities, in decision-making and other regulatory activities that affect human health and the environment. It aims to protect people from disproportionate and adverse human health and environmental effects and hazards, including those related to climate change, the cumulative impacts of environmental and other burdens, and the legacy of racism or other structural or systemic barriers.[8]
- **Geoengineering:** this term refers to a range of technologies, some existing and others that are still in development, but which all aim to alter or control the Earth's climate, usually with the goal of preventing further anthropogenic climate change (Corner et al., 2013). Historically, the term has been applied to carbon dioxide removal technologies and solar radiation management (SRM), but since the Paris Agreement, CDRs have tended to be distinguished from SRM and disconnected from the geoengineering label (Waller et al., 2024, p. 11).
- **Just transition:** refers to a transition to a clean and green economy or industry which incorporates elements of social and environmental justice, employment rights and protections for workers, fairness in energy access and use and procedural and distributive justice.[9]
- **Moral hazard:** originally defined in relation to insurance, this describes a situation in which insurance creates a perverse incentive for actors to engage in risky behaviour. It has been applied in slightly different ways within the geoengineering debate
- but refers to a 'concern that knowledge of geoengineering in the public consciousness will undermine climate change' (Tsipiras & Grant, 2022, p. 28) and therefore deter or delay efforts to reduce emissions.
- **Procedural justice**: refers to fairness in the allocation of resources, but more specifically to the processes and procedures associated with that allocation – so, for example, procedural justice has occurred when environmental regulations are enforced fairly, transparently and consistently and are not open to bias.

Annex 1: Funding and policies supporting development of heat networks

Funding mechanisms

- BHIVE – DESNZ extended the original BEIS Heat Investment Vehicle, which established a Dynamic Purchasing System (DPS) for heat networks, to spring 2025. It is intended to support public sector heat network owners and developers in England and Wales to procure equity and asset finance for their projects from a range of potential funders.
- HNDU – the Heat Networks Delivery Unit supports early development of heat networks by funding local authorities in England and Wales for activities such as heat mapping, feasibility studies and detailed project development.
- GHNF – the Green Heat Network Fund launched in 2022. It is a core element of the HNTP and is aimed at facilitating the development of low-carbon heat networks across the UK. It supports commercialisation and construction of new low- and zero-carbon heat networks and retrofitting and expansion of existing heat networks through a 3-year capital grant fund. It is led by an external partner, Triple Point Heat Networks Investment Management.
- HNIP – the Heat Network Investment Project was a £320m fund supporting commercialisation and construction for heat networks in England and Wales. It aimed to support the establishment of a market for heat networks and thereby stimulate increased external investment.
- HNES – the Heat Network Efficiency Scheme funds applicants from the public, private and third sector in England and Wales, supporting improvements to poorly performing heat networks to improve their services. Capital and revenue grants totalling £80 million are available in recurrent funding rounds between 2023 and 2028. This scheme is focused on optimising user experience rather than decarbonisation. It is open to all systems regardless of their heat source and it does not place any obligations on operators to employ or switch to low-carbon heat sources, though of course any improvements in efficiency can reduce emissions somewhat.
- HNTP – the Heat Network Transformation Programme supports scale up of low-carbon heat networks, enabling heat network zoning in local areas. £338 million is available between financial years 2022/23 and 2024/25.

Key legislation and policies

- Clean Heat Market Mechanism (CHMM)[13]

This policy, developed by the Conservative government, was implemented in April 2025. It aims to increase uptake of heat pumps from the supply side by mandating that boiler manufacturers' domestic sales include minimum 4% heat pumps in the policy's first year, 6% in the second year, increasing year on year by amounts to be determined. Small companies and those with sales below 20,000 gas boiler or 1000 oil boilers will be exempt. The government identified the EA as an appropriate scheme administrator for the CHMM and the EA has agreed to take on this role, so will be responsible for overall delivery, ensuring compliance and carrying out enforcement actions where appropriate.

- Future Homes and Buildings Standards[14]

Due to be introduced in 2025, this policy aims to reduce carbon emissions from the residential building sector by 75-80%. It focuses on building materials, glazing standards and low-carbon heating in new buildings. It includes a phasing out of fossil fuel boilers, originally due to come into effect in 2025, but now extended to 2035. The standards aim to ensure new buildings are 'zero-carbon ready' and specifies that this does not include hybrid or 'hydrogen-ready' gas boilers. The performance requirements for these standards are based on 'notional buildings with an efficient air source heat pump or a 4th generation heat network that uses air source heat pumps', underlining the assumption that heat pumps and heat networks will be the main ways in which buildings are heated in the future.

- Heat and Buildings Strategy[15]

This strategy, published in 2021, outlines a plan for achieving greater energy efficiency and developing a market-based approach to low-carbon heating, as well as testing the viability of hydrogen heating. It set out the ambition for phasing out gas boilers from 2035 and put the case for building the market for heat pumps and heat networks. The advantages of heat networks, according to this strategy, are the fact that they can use a variety of heat sources and that they can reduce peak energy loads through thermal energy storage. The strategy commits to continuing to provide financial support through the HNDU, HNIP, GHNF and HNES (see above). It also states that new regulations will be

[13] Clean heat market mechanism - GOV.UK (www.gov.uk)

[14] The Future Homes and Buildings Standards: 2023 consultation - GOV.UK (www.gov.uk)

[15] Heat and Buildings Strategy (publishing.service.gov.uk)

introduced and that the Heat Networks Market Framework will introduce maximum carbon emissions limits in the 2030s.

- Heat Network Market Framework[16]

The Heat Network Market Framework is a policy statement from the 2022 Energy Bill. The Bill aims to address the lack of regulation of heat networks, with new consumer protections, carbon emissions limits and technical standards. Ofgem was appointed as the heat network regulator in Great Britain in the Energy Act 2023.

- Heat Network (Metering and Billing) Regulations[17]

These regulations originally came into force in 2014 and were updated in 2015 and 2020; they aim to improve energy efficiency and reduce carbon emissions from heating. They place obligations on heat suppliers to install meters where it is cost-effective. Where meters are in place, heat suppliers must ensure they accurately record consumption and remain in constant operation, as well as billing customers based on their actual consumption at least annually.

- Heat Networks Regulation and Zoning[18]

The Energy Security Bill introduced a regulatory framework for heat networks and powers to enable heat network zoning in England, with the aim of regulating prices and enabling the sector to decarbonise their heat sources. The previous government argued that heat networks 'are a proven, cost-effective way of providing reliable, efficient, low carbon heat at a fair price to consumers, while supporting local regeneration'[19] and can make use of both large-scale renewable and waste heat sources. This regulation is a response to the Competition and Markets Authority's recommendation that the government regulate the sector following the social research outlined above. It aims to secure fairer pricing and a more reliable service for consumers as well as to extend powers for heat network developers to develop networks more quickly such as excavating roads. It gives Ofgem, as the regulator, enforcement powers if heat networks are not performing at required

[16] Heat networks: building a market framework - GOV.UK (www.gov.uk)

[17] Regulations: heat networks (metering and billing) - GOV.UK (www.gov.uk)

[18] Energy Security Bill factsheet: Heat networks regulation and zoning (updated 20 March 2023) - GOV.UK (www.gov.uk)

[19] Energy Security Bill factsheet: Heat networks regulation and zoning (updated 20 March 2023) - GOV.UK (www.gov.uk)

standards. The Bill also appoints the Energy Ombudsman and the Alternative Dispute Resolution Body and Citizens' Advice as the consumer advocacy body.

Heat network zoning is intended to help scale up heat networks by requiring certain buildings (not usually domestic properties that are not already connected to a heat network) within a designated zone to connect to a heat network. This should also provide great market certainty for heat network suppliers. Zoning aims to identify areas that are particularly suitable for heat networks due to factors such as high building density and availability of low-carbon heat sources. It involves central government, local authorities, industry and local stakeholders coming together. This policy is intended to save 13.1 million tonnes of CO2e over carbon budgets 4 to 6 (2023 to 2037).[20]

[20] Energy Security Bill factsheet: Heat networks regulation and zoning (updated 20 March 2023) - GOV.UK (www.gov.uk)

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