The role of policy in creating opportunities for alternative futures in heat decarbonization

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Abstract

This paper analyses key decision-making processes relating to alternative pathways for heat decarbonisation in the UK. Decarbonising heating is a key element of reaching the UK's target of net zero emissions by 2050. Currently space and water heating in the UK is heavily reliant on fossil fuels with approximately 85% of households using natural gas for heating (BEIS, 2018). With the extent of the changes needed to reach net zero and the long equipment and infrastructure lifecycles involved, key decisions to set up pathways to decarbonising heat across the UK are needed within the next 5 years (CCC, 2016). BEIS (2018) is, at a national level, currently developing policy plans to make these decisions by 2024. However, there are significant policy challenges in planning and making decisions for the complexity of intertwined changes in heating technology, user behaviour, business models (and regulation) of installation and characteristics of buildings that will be involved in changes to infrastructure systems that reach across regions and nations as well as into people's homes and day to day living.

As part of the Operationalising Socio-Technical Energy Transitions (O-STET) research project, this paper analyses actors' perceptions of UK developments for heating decarbonisation, focussing on understanding key decision points. This research draws on analysis of key policy documents, interviews with diverse actors across the sector (11) and a workshop with key policy actors to investigate structuring of policy decisions. This study highlights the different framings that actors hold of the challenges and opportunities around heat decarbonisation challenge and how they construct key decision-points. There is some evidence that a dominant framing, of a one-time national decision centred on the future of the gas grid and choosing between hydrogen and electric futures for heating at a national level, has potential to break down. A key factor challenging this framing is the increasing concern with user needs and acceptance. This shifting of focus within policy circles highlights both the need for socio-technical understanding and the difficulties of collecting and working with evidence that extends beyond techno-economic understanding.

To address these challenges, this study applies and explores the benefits of the socio-technical concept of branching points in understanding ways in which decisions are and can be structured in addressing heating decarbonisation. Foxon et al. (2013) define branching points "as key decision points at which choices made by actors, in response to internal or external stresses or triggers, determine whether and in what ways the pathway is followed." A branching point approach highlights that the ways in which technology decisions are structured and navigated for decarbonisation is *politically mediated* (Rosenbloom et al., 2018). This branching point analysis of decisions in UK heat decarbonisation highlights the usefulness of this concept for reviewing and structuring decision-making processes. In the stakeholder workshop, the branching point concept was combined with a framework from Cherp et al., (2018) to form the basis of co-development process for structuring decisions (combining techno-economic, sociotechnical and political perspectives) that was trialled – this approach shows promise for supporting complex decision processes for energy system decarbonisation and the research continues to develop this process further.

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Introduction

Decarbonising heating in the UK is an important element for meet emissions targets. 17% of current emissions (2016) are attributed to space heating (and cooling). Existing heating systems within the UK are dominated by the use of natural gas by a boiler (usually within an individual dwelling) that provides both space and water heating. Approximately 85% of households use natural gas for heating (BEIS, 2018). This approach is used across a wide variety of housing stock and across urban and rural settings. A further challenge to developing alternative heating is the heavy interaction with people's homes and domestic practices and the UK has relatively poor energy efficiency performance of housing (compared with other European countries) (Guertler et al., 2015). The high-temperature heating systems conventional in the UK can provide comfort alongside poor insulation performance however, low carbon alternatives often use lower-temperatures and will require upgrades in building performance. Technologies and practices for heating need to be transformed over the next 25 years, however, demands of existing commitments, long asset lifecycles and the extent of change required are creating key decision points to be navigated within much shorter time periods.

In 2019, the UK moved from a legally mandated 80% emissions reduction (relative to 1990 levels) in 2050 to Net Zero by 2050. Attention for decarbonisation was already turning to the more difficult to decarbonise sectors of transport and heating but renewed focus, realising there would be no space for any carbon intensive areas, came with the move to Net Zero: the future of the gas grid is a key point for attention. An important report from the Committee on Climate Change (CCC, 2016) outlined the need for a decision on the future of heating in the first half of the 2020s, the Clean Growth Strategy (2017) committed to this timeframe for national policy and decision-making and the government department for Business, Energy and Industrial Strategy (BEIS) has a key role in responding to these requirements (BEIS, 2018; 2020). A policy roadmap for how and when decisions on the future of heating and decarbonisation will be made is being developed by BEIS's Clean Heat Directorate and publication (pushed back from Summer 2020) is expected soon.

The need, and short timescales, for this transition away from natural gas for space and water heating appears to have consensus within national policy. However, what that transition is towards and how that is to be determined (and by whom) is still open. The existing approach to heating sees a single core approach (natural gas in combi-boilers) used across much of the housing stock (85%) despite considerable differences in characteristics of the built environment, spatial geography and population. Current low-carbon alternatives to natural gas boilers do not present a single direct replacement for this technology and there is variety across not only performance levels but also performance criteria and usage practices that accompany different low-carbon alternatives. The national Net Zero target provides attention at a national policy level and this is reinforced by the national character of existing natural gas usage. The idea of creating low-carbon heating progress in the UK is sometimes framed as a decision around 'the future of the gas grid' – which captures the state of a system to be transitioned away from. It has also sometimes been framed as hydrogen versus electrification for heating (e.g. CCC, 2016) – again captured as a national policy 'decision'.

It is also of note that, unlike technological transitions of the past or even expectations surrounding the previous 80% emissions target, the heat decarbonisation options will need to be implemented across all water and space heating in the UK by 2050. So, whether deployed by diffusion and individual householder decisions or more planning based approaches (at local/regional/devolved scales), the national Net Zero target will require not only co-ordination in the development of low-carbon options but also in their selection and implementation.

To examine potential developments for decarbonisation of heat and to reflect upon potential policy processes and interventions, this paper builds upon key concepts, branching points and pathways, from transitions studies. Branching points are "key decision points at which choices made by actors, in response to internal or external stresses or triggers, determine whether and in what ways the pathway is followed" (Foxon et al., 2013). Key decision points or processes, inherently connected to the pathways which they guide and/or disrupt, Rosenbloom et al. (2018, p23-24) argue that a branching point can "be understood as a window of opportunity whose outcome is defined by a politically mediated choice taken in the presence of alternatives" and that "orient system configurations along new or existing trajectories that endure over time, reconfiguring the envelope of future options as some possibilities are opened up and others are closed down". Previous use of the branching point concept has tended to look to past developments or use the concept to tell stories of a potential future. However, the research developed here uses branching points and pathways to better understand the current state, and socio-technical characteristics, of development of a transition-in-progress towards heating decarbonisation in the UK. Four separate socio-technical pathways of development are identified but co-ordination between them will be needed for a sector-wide response to Net Zero requirements. One area with potential for branching in the individual pathways and to begin to build a sector-wide decarbonisation pathway is where selection or co-ordination is happening between these pathways. The analysis developed here identifies and examines potential points of co-ordination between the four socio-technical pathways and considers the potential to use this approach to support actors engaged in the policy challenge of ensuring this sector responds to Net Zero.

Method

This case study of UK heat decarbonisation development and decision-making draws on three main types of data: policy documents, semi-structured interviews and two development workshops with policy actors. Eleven interviews were conducted with expert actors these discussed heat decarbonisation developments, policy and implementation as well as pathways to decarbonisation (not specified as the four socio-technical pathways discussed below). Four interviews were with actors within national policy active organisations (one of these interviews focused on local/regional scale developments), two with actors from gas distribution networks and five interviews with actors working on implementation (2 of these were energy engineering consultants, 2 were heat network actors and 1 a local public sector project support professional). Two workshops were conducted with policy and modelling actors. Workshop 1 (February 2020) trialled a pathways exercise to open-up key decisions set to shape pathways of system change. Considering national and local scales separately the workshop built up pictures of criteria, key actors and assessment approaches for decarbonising heat. Workshop 2 (February 2021, conducted remotely) discussed socio-technical pathway connection points and unpacked the development and potential impacts of two contrasting examples: hybrid heat pumps and local area planning. Both workshops built on the branching points and pathways concepts introduced briefly in this paper and both used a framework from Cherp et al. (2018), distinguishing between techno-economic, socio-technical and political perspectives in energy, to structure discussions and mapping.

An initial reading of key policy documents was used to identify and frame the four socio-technical pathways (discussed below) also seen in the interview data. These four pathways were also used as a starting point for inductive coding of the expert interviews, to identify development activities and decision moments within and between the socio-technical pathways; this identifies different characteristics of change within the four socio-technical pathways and a wide range of potential connection points between the pathways relevant for system transition. Policy document coding then checks for and expands upon the pathway connections (see table 2, below) identified in the analysis of the interview data. Interview data and outputs from workshop 2 are combined in the two pathway connection case studies.

Results

Decarbonised heating developments: four socio-technical pathways

The question of how to achieve low carbon transition in UK space and water heating, and understanding of what the transition is to be, are yet to be resolved at national or sub-national levels of governance. This is a complex environment in terms of variety in actors, technological developments, priorities and scales involved for changes to heating.

In this research four key areas of technological (and socio-technical) development are identified from policy reports and supported in the analysis of the interviews:

1. Demand reduction – focused on but not limited to building fabric measures to increase energy efficiency
2. Electrification – centred around air source heat pump technology but including other electrification methods focused on individual dwellings
3. Heat networks – this includes district heating as well as smaller scale (perhaps single building) networks
4. Hydrogen – to be distributed via the existing natural gas network and consumed by (dwelling based) hydrogen combi-boilers

It should also be noted that biofuels are also expected to be part of a decarbonisation solution but that there is only expected to be capacity for biofuels to contribute a relatively small proportion of heating demand sustainably (e.g. biomass providing 5-15% CCC, 2018a). This means the position of a biofuels area of development is important but has become less central (than these four areas) to the visioning and decision-making around the selection and/or emergence of low carbon heating system(s) for the UK.

Analysis of the interviews, conducted with expert actors with a range of perspectives, on heat decarbonisation confirmed the importance of these four socio-technical pathways and examined more closely actors' interactions with them. The analysis also highlighted the distinctiveness of these four separate pathways – they are associated with different groups of actors, different performance characteristics and priorities and different scales and mechanisms for development and implementation. For example, implementation of heat network and district heating initiatives involves multiple homes and is heavily influenced by the buildings, governance and resources of a particular location leading to distinctive place-based solutions that are delivered through projects and sometimes shaped by local governance arrangements; whereas electrification using air source heat pumps tends to be considered as an individual household, consumer decision. Summarised in table 1, below, the research shows, not only four pathways of development, but how difficult it will be to construct an assessment basis for selecting between and/or combining implementation options across these socio-technical pathways. Importantly, the synthesis presented in table 1 shows, not only differences in the knowledge bases, knowledge development and technological actors, but also differences in the contexts within which these approaches are applied. At this stage it seems that it would be rare for these technological options to compete directly for installation in a building project and the prospect of two identical building developments selecting different options from amongst these four, unlikely. Where there is selection, solutions might expect to be co-developed alongside the wider characteristics of the development concerned and/or combined to form bespoke solutions.

Considering development from the perspective of socio-technical systems and using the concepts of socio-technical pathways and branching points, indicates that this is does not currently represent four elements of a single pathway (/developing market) for decarbonising heating but four separate pathways with potential points of connection and interdependence (Lovell & Foxon, 2020, Working paper). A policy roadmap for heat decarbonisation then would need to consider co-development of these socio-technical pathways and connection points between them.

Connection points between socio-technical pathways can allow for the selection and/or co-ordination between pathways. They also have the potential to generate combined pathways capable of covering implementation across a wider range of settings. For example, deep retrofit combined with electrification offered at the household level and combined with subsidy provision may reach a higher proportion of owner-occupied homes than these elements offered separately as the combination reduces barriers to access. However, in this example, further access provisions would be needed to reach rented accommodation and social housing and if this were to be combined further with city/district network options, the geographical spread of uptake would also need to be considered/managed. To reach the full coverage required for decarbonisation, co-ordination between pathways will be needed over time. This is both to avoid gaps (so that some provision is suitable and accessible to each setting) and to consider impacts (and usefulness) of pathway overlaps (some overlaps can adversely affect system viability while others might provide welcome competition). Whether to set supportive conditions for this developing decarbonisation sector or to select and shape development (perhaps to co-ordinate with other sectors' decarbonisation routes), tracing pathways, assessing their potential directions, and identifying and mapping potential connection points between pathways will need to form part of ongoing strategic management by policy actors. The next section of the analysis addresses connection points emerging amongst these four decarbonisation pathways.

Table 1 Four socio-technical pathways of development

	System characteristics	Development characteristics
Demand reduction	A wide range of interventions are possible including physical changes to buildings as well as interventions more focused on education/information. This type of change involves a wide range of actors, including end-users, building designers and retrofitters, technology suppliers and policy-makers but is consistent with existing systems.	Often framed by individual dwelling/consumer and diffusion issues but also represented in co-ordinated retrofit projects. Policy tends to be adoption/diffusion based. Arises connected to different scales in the data – choices available for how this pathway is framed and co-ordination treated. Potentially complementary to all of the other pathways but crucial for low-temperature solutions. Skills development in this pathway is an area of potential policy intervention identified across pathways.
Electrification	Including but not limited to heat pumps, that are operated by electricity. Substantial uptake will involve changes to the electricity grid systems	Framed and treated in a variety of ways throughout the data. There are dwelling by dwelling viewpoints; project (conversion or development) perspectives and approaches involving regional/national considerations.

	(more low carbon generation, more demand side management). Would potentially involve wider reconfiguration of systems to ensure reliable and timely supply of electricity in sufficient volume. User changes can be approached in a distributed way	National perspective on electrification links to distribution networks and national grid situation as well as national policy decisions approach. Electrification includes a variety of heat technology options (heat pumps, direct electric and links to heat networks) but individual dwelling based heat pumps are dominant. Some configurations have necessary co-ordination connections with demand reduction. This pathway also links to considerations of other uses of electricity (e.g. transport).
Heat networks	High degrees of co-ordination needed between a range of elements. Systems can be connected with a variety of technologies for heating water distributing heat through the network. Local configurations of source, network and use. There are close connections between HN performance and demand reduction measures.	Development of knowledge and expertise is built through projects and as part of localised/place-based approaches. HN performance is dependent on implementation and use – so can be considered place-based. Individual projects can add to a broader pathway - building knowledge and altering the context for future projects. Recent policy developments have included work on a market framework and regulation for heat networks. Other potential co-ordinating elements within the pathway include: learning across projects, developing skills & expectations in suppliers, consumers and commissioners, industry bodies, policy communications, funding sources and regulation.
Hydrogen through the gas grid	Based on existing network of pipes, existing distribution actors and exising user practices (using a combi-boiler for high temperature based space and water heating). However, changes to the development, planning, building and operation of these systems needed and high degrees of co-ordination needed between a range of elements.	Development is centred on existing actors and assets from gas distribution (and the existing boiler supply chain) – co-ordinating distributers to develop on national scale (GB). This is a purposeful pathway, co-ordinated around shared vision. It is sometimes characterised as a technological response based around the existing heating system and its practices, leading to low user ‘disruption’. Key decision-points within the pathway include research projects set up, regulatory changes etc. Potential

	Safety and operation testing needed for demonstration.	collision points with opinions and alternatives outside the pathway could also influence development.

One important element to note here for considering fit and co-ordination between these pathways, is that there appears to be some flexibility in scales used to consider the demand reduction and the electrification developments. This may mean a consideration of which scales should be used for policy to best support implementation these developments. However, it may also mean it is possible to consider several scales to allow comparisons with other pathways that may be advantageous in co-ordination for policy decisions.

Co-ordinating pathways: identifying connection points

Having found the four distinct socio-technical pathways of development discussed above represented in the interview data, inductive coding analysis went on to identify potential connection points between the pathways. These were policy, technological or organisational developments that required selection or more nuanced co-ordination between these pathways (the technologies, their development or their selection). These connection points are not only important sites for considering the overall reach and scope of heat decarbonisation; they are also potential sites where pathways can influence each other's development. For example, developing a business model where two areas of development are used (e.g. Hybrid heat pumps) may lead to adjustment for co-ordination emerging in each pathway as much as a selection mechanism (e.g. heat as a service business model) for technologies will shape the way they compete.

Table 2 Pathway connection points identified

Pathway connection point	Description	Development implications
Building regulations	Different types of building regulations affect the performance requirements and processes needed in developing and maintaining buildings.	The regulations applying to relevant projects can influence all the pathways. Demand reduction through building energy efficiency, in particular.
Green hydrogen	Production of hydrogen through electrolysis links electric and hydrogen systems. Hydrogen production using this approach is very energy intensive but it can also act as a way of storing excess energy for later use.	Needs of the electricity system and hydrogen production considered together. Potential for energy storage where variable electricity generation is high. Co-location of networks and facilities
Hybrid heat pumps	Heat pump and combustible (usually gas) systems are combined so that the heat pump takes consistent load and the gas (natural or hydrogen) is used to top up. A smaller heat pump can be specified than would otherwise	Part of the motivations behind this approach is the potential to introduce users to heat pump technology without feeling the risks of moving fully to low temperature systems in the first instance (however, as discussed further below, this is

	be required and gas consumption is reduced.	complicated).
Low or no regret	Several analyses/strategies looking across the sector for decarbonisation have sought developments that would be beneficial (or at least not harmful) under multiple directions of development and/or are low investment and support potential future developments.	Giving the go-ahead to a selection of projects based on quick wins/low risk investment can be a good way to prime support for future developments but is also presents the possibility of inadvertent uneven support and development as some pathways may be able to take advantage of low regrets investments where the needs of others are more expensive/specialised.
Off gas grid	Set of decisions made to decarbonise heating for buildings not connected to the gas grid	Another way of segmenting developments to allow relatively easy investments before decisions are made about the future of the gas grid. However, there may be structural disadvantages developing solutions tailored to this group.
Place-based local planning (including zoning & local area plans)	Planning for decarbonisation of heating at city/local scales.	Local plans are co-dependent with pathway development. Availability of options in each location can be uncertain. Local processes and decision-making provide a different set of opportunities for engagement and considerations of user and citizen needs and attitudes to transition.
Built environment projects	Development/redevelopment of buildings as a site for implementing different heating configurations	Format and accessibility of socio-technical options to project development and business models is key.
Heat as a Service	Business model offering heat as a service where customers pay for heating plan (based on temperatures achieved at certain times)	This approach has the potential to be technology agnostic with users paying for comfort levels rather than energy system and energy use. This could include deep retrofit developments as well as changes in heating generation.
National level futures approach	Tackling and framing heat decarbonisation within national pathways to net zero	Analyses and policy actors sometimes view developments at a national scale with respect to the net zero target. This can shape the expectations of many actors and shift emphases

		between pathways and connection points.
R&D or Innovation funds	Research and funding for heat decarbonisation.	Often applied across technologies and possible site for competition between pathways for funding/development attention.
Replacement decision	Existing heating reaches end of life. Low-carbon options can be considered for replacement.	Replacement decisions have different characteristics to development decisions for installation. These can be crisis purchases and access to alternatives, information and trusted expertise, quickly are important for this point of comparison.

In the context of the need for development direction changes for decarbonisation across the sector, these connection points between the distinct socio-technical pathways can provide a starting point for the development of branching points. This could be branching points within individual socio-technical pathways; for example, to co-ordinate with another pathway, new parameters of interest are identified and developed for. However, by setting co-ordination in development between pathways or a common basis for implementation, these connection points have the potential to provide the blueprint for a new direction of development/scope of implementation. As such, strategic oversight of the developments across heating decarbonisation should include not only mapping/tracking of these connection points but also the prospect of supporting and shaping them. Tools will be needed to consider their potential and to consider mechanisms to facilitate development and experimentation within key sites/periods. To investigate the further understanding of developments at connection points and their potential use as levers of influence on a required transition, this research now investigates two embedded cases of the connection points identified within the heat decarbonisation case study. The next section presents outputs from workshop 2 considering the emergence and potential of these cases: hybrid heat pumps and local energy planning.[1]

Development of pathway connection points

For potential pathway connection points identified in a developing system to be used not only to better understand the socio-technical development picture but also as platforms to facilitate developments towards decarbonisation and structure decisions towards it, the connection points and what they might contribute need to be critically examined. Workshop 2 conducted as part of this research worked with policy and modelling actors in the heat sector to consider two contrasting examples: 1) hybrid heat pumps offer a technological basis for connecting two pathways of development into a combined heating offering and 2) local energy planning presents a policy/strategic development that shifts scale from the national and makes decisions about positions of all the development pathways in responding to the needs of a particular place. The aim of the workshop was to unpack the situation and potential contribution of the pathway connection points as well as to consider what might be done to support developments in this space.

[1] The techno-economic, socio-technical and political perspectives considered, and the descriptions given in tables 3 & 4, are adapted from Cherp et al., 2018.

Hybrid heat pumps

This is a technological development combining heat pump technology with a top up from a combustion system (this can be natural gas or alternatives such as hydrogen). Key motivations for heat decarbonisation connected with this approach include the opportunity for users to trial heat pumps (their sound, space usage, responsiveness etc.) without losing the high temperature systems and possibility of a quick heating response that has been the norm for UK heating and users are expected to wish to maintain.

> *"Actually this hybrid option has got a lot of value in the flexibility it provides, so yes, you can fit in a heat pump alongside an existing oil or gas boiler and then have people switch between the two depending on a price signal..." (Interview with local energy actor)*

However, an important step in the serious consideration of this approach has been the national policy challenge of selecting the path ahead and one important motivation for hybrid heat pumps may also be as a measure to buy time for longer term decisions to be made.

> *"The Committee on Climate Change have advocated the roll out of hybrids in the short-term. It's the hybrid first approach and they see that as independent of whatever future decision comes next as a way of making a dent in heat emissions quickly." (Interview with gas distribution actor)*

> *"...particularly around the hybrid heat pumps, the idea is that this is a potential stepping stone to, potentially, a full heat pump rollout or a decision about investing more in a hydrogen future." (Interview with policy actor)*

Table 3 Hybrid heat pump - unpacking a pathway connection point

	Techno-economic: *focused on energy flows associated with energy extraction, conversion and use processes involved in energy production and consumption as coordinated by energy markets*	**Socio-technical:** *focused on knowledge, practices and networks associated with energy technologies*	**Political:** *political activities influencing energy-related policies and developments*
Drivers for connection point development	-Reducing peak demand for electricity, immediate demand for gas and maintaining a high temperature system. -While new low-carbon markets	-Potential to get people more comfortable with heat pumps without demanding shift to low temperatures and it's a way to trial some of the practicalities of	-Responds to an idea of consumer disruption and perceived dislike for low temp heat -Keeps powerful players (of gas and electric spaces) in the game -'buys time' for

	develop, HHPs can start reducing emissions before key decisions/ developments are made.	heat pumps. -Building up skills and market formation in heat pumps, installation, building fabric, smart controls etc. (and still possible in hydrogen and heat networks)	potentially disruptive decision
Needed to overcome barriers or develop this connection space	-Smart controls that suit people and homes; installation; demand for decarbonised heat/subsidy? -Maintenance of 2 infrastructures (And additional needs to co-ordinate them?)	Maintenance and installation skills and services -Learning ...how people and homes respond and use patterns… -From research by Parrish et al. (2021): Indication that hybrid heat pumps could have the perverse impact of convincing people that heat pumps on their own are not sufficient to provide heating and hot water at cold external temperatures.	-Leaves decision over gas grid unresolved and potentially shifts demand (and demand patterns) for natural gas/low-carbon alternative gas -Managing powerful actors by bringing in vested interests in electric & hydrogen pathways
Potential to aid co-ordination of development towards net zero	An interim measure that is a stepping stone but leaves further questions to resolve whilst changing the context for those decisions. Risks of duplication of resources and skills development with high investments in interim complex systems Maintains consumer use patterns whilst potentially getting used to aspects of heat pumps and starting to develop market for installation and maintenance etc. Leaves future of gas grid open (whilst changing context) Diffusion could limit alternative zone based responses… As a high temperature system - Potentially leaves building fabric and behaviour changes needed unaddressed (opening the door for hydrogen?)		

Place based planning

There are a number of actors developing place-based plans for heating decarbonisation. Approaches can include zoning parts of an area for different technologies, modelling activities to assess and compare the area's characteristics, developing engagement processes to connect with local citizens and connecting heating developments to other priorities in an area such as economic development or commitments to responding to the climate emergency. These approaches vary and there are also a range of sub-national scales being considered.

> *"Well, I think one of the things we are aware of is that lots of local authorities have genuine aspirations in this space. A large number of councils have declared a climate emergency recently in response to growing interest and salience of the issue. Their aspirations, ambitions at present are probably not matched by what they can realistically do. Partially that's a question of what powers exist to give them the ability to just get on and do stuff but also there are questions of resources, questions of teams, questions of what they can do in practice." (Interview with policy actor)*

Table 4 Place-based planning - unpacking a pathway connection point

	Techno-economic: *focused on energy flows associated with energy extraction, conversion and use processes involved in energy production and consumption as coordinated by energy markets*	**Socio-technical:** *focused on knowledge, practices and networks associated with energy technologies*	**Political:** *political activities influencing energy-related policies and developments*
Drivers for connection point development	-Energy system characteristics are local and areas differ. Solutions/responses need to be adapted to local conditions. (demand/resources/infrastructure)	-Help with supply chain/skills. Local plans can serve to help identify solutions for an area and bring relevant education institutions to help with skills	-All areas are different so solutions must be appropriate for local situations. -Through the process of generating local plans, citizens can become engaged in what net zero may mean to their area - can be platform for behavioural change and engagement
Needed to overcome barriers or develop this connection space	-National to local infrastructure connections. Boundaries and how to co-ordinate	-Pathfinder areas - some local areas to lead and learn, then share with others / act as exemplars	-Sit within a national framework - one element for requirement/encouragement for LAs to do place-based plans -Socialisation of costs – How to serve the range

		-Capacity building (in LAs) for planning at local level -in terms of resources/skills etc.	of different users - household costs, access, fairness/justice (Links to area size)
Potential to aid co-ordination of development towards net zero	Gives all users the agency to feel like they can be part of the energy transition solution helps to show the scale of local markets for different solutions Can help to attract investment into local areas by providing certainty of what is going to happen Helps network operators understand what changes might occur when and where across their 'patch' Social housing is an area where it could be easier to act and address decarbonisation; Some Local Authorities (LA) starting here Possible tensions between national government and LA (who gets to do - resources & responsibilities) National planning framework review - Funds & planning framework could be the basis for supporting local plans and connecting back into national policy		

Discussion and conclusions

The heat decarbonisation challenge for the UK is an acute one, not only for the technological actors and developers within the built environment but for citizens and policy actors seeking to support and enact a transition to sustainability that continues to function socially as well as in techno-economic terms. Pathways and branching points ideas from the field of transition studies provide one tool to map and better understand the socio-technical developments in this complex and uncertain setting as well as considering the political framings and processes in play.

This research develops three stages in examining the case of heat decarbonisation. The first 1) identify socio-technical pathways of development for low carbon heating, and having shown the difficulty in developing a single decision space to configure these pathways into a single pathway for decarbonisation 2) map potential pathway connection points. The final stage sought to 3) unpack the position, potential and needs of two example pathway connection points.

Identifying and characterising the four separate socio-technical pathways is a way of capturing the socio-technical environment within which policy actors need to operate. The separateness of these areas of development, and the different settings and actors important for installation decisions, highlight both the extent of the challenge to resolve how the sector will decarbonise and the importance of reflection on how areas of development and cross-sector installations are co-ordinating. Without spaces to interact – whether this is to connect developments of a selection environment providing common requirements/points of competition – pathways are liable to continue to develop separately with political energies also going into shaping potential selection stages to fit/disrupt invested pathways. Understanding this socio-technical situation and potential dynamics emphasises the need for strategic policy action to facilitate connection and to develop legitimate selection spaces - these are unlikely to emerge unaided.

The case study demonstrates the identification of potential connection points between pathways. Here this is done through analysis of interview data but in ensuing practitioner-led work it could be developed through workshops and other engagement activities. These connection points are one type of setting for potential branching, with pathways altering course – by changing mechanisms or aims of development – being influenced by one another. These sites presenting potential for branching can be identified without hindsight, they can be seen in current development patterns. Understanding, selecting and seeking to develop these connection points, then, offers potential action and influence for policy actors in facilitating alternative configurations and branching in the sector's pursuit of net zero targets.

Some of the connection points identified for the UK heat case are potentially inadvertent connections that could steer developments in unexpected ways. For example, low/no regrets framings for decarbonisation decisions in pursuit of low-cost measures in the short-term could reshape long-term options with some pathways needing high commitment steps next in their development being stalled. Other connection points considered here are more conscious developments intended to change the game for heat decarbonisation – shifting mechanisms and values – for example heat as a service business models or building regulations. However, these sites too have potential to differentially influence pathways; this is both part of their power and a demand for reflection on how moves to destabilise and support cross-sector development might shape relevant socio-technical pathways.

Mapping out pathway connection points further allows consideration of their interactions and potential for combined impact. For example, the connection points identified here could suggest strategic linking of hybrid heat pumps and heat as a service business models to decouple installation concerns from consumer choices based on use and this increased understanding of in-use concerns identifying areas for additional support. Or to better understand potential take up of heat pumps by linking their installation to deep retrofit and a section of the 'market' (e.g. social housing/terraced houses). Finally, as illustrated in the examples discussed above, pathway connection points can be considered opportunities to nurture sites of connection that allow for learning and experimentation. The closer study of the hybrid heat pump and place-based planning cases highlight the existence of choices over the shape and priorities of such sites. Policy actors can facilitate engagement and reflection over these sites accelerating development of strategic and supportive selection and co-operation settings for decarbonisation actions.

The stages of analysis developed and applied here show potential for supporting policy-actors aiming to facilitate this sector's transition and achievement of Net Zero by 2050. The nature of the challenge in this sector, a need to decarbonise without a ready technological response and with a large diversity of needs and settings to be addressed, means active and enabling strategies will be called for from these policy actors. This transitions approach highlights that tracing pathways, assessing their potential directions, and identifying and mapping potential connection points between pathways will need to form part of ongoing strategic management by policy actors. Further there is potential to use pathway connection points identified as platforms to support and shape elements of the transition and analyses like that presented here can critically assess their potential and mechanisms to facilitate development and experimentation in these key spaces.

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