District heating in the UK

Citation for published version:
Hawkey, D 2012, 'District heating in the UK: A Technological Innovation Systems analysis', *Environmental Innovation and Societal Transitions*, vol. 5, pp. 19-32. https://doi.org/10.1016/j.eist.2012.10.005

Digital Object Identifier (DOI):
10.1016/j.eist.2012.10.005

Document Version:
Peer reviewed version

Published In:
Environmental Innovation and Societal Transitions

District Heating in the UK: a Technological Innovation Systems Analysis

David J. C. Hawkey

School of Social and Political Science, University of Edinburgh

Chisholm House
High School Yards
Edinburgh
EH1 1LZ

Tel: +44 (0)131 650 2841
Fax: +44 (0)131 650 6345
Email: dave.hawkey@ed.ac.uk

Paper accepted for publication in *Environmental Innovation and Societal Transitions*

DOI: 10.1016/j.eist.2012.10.005

Abstract

District heating infrastructure could contribute to the UK's energy policy goals of decarbonisation, renewable energy deployment, tackling fuel poverty and ensuring energy security. However, while a number of schemes have been developed over the last decade, deployment of the technology remains limited. This paper adopts a Technological Innovation Systems framework to ask what the principal challenges are to significantly scaling up the deployment of DH in the UK. While district heating networks are inherently local infrastructures, they are positioned in regulatory and market contexts organised at larger spatial scales, making geography an important factor and coordination across spatial scales an important policy area for accelerated deployment.

Keywords

Keywords: Technology Innovation Systems; district heating; CHP; urban sustainability;

Highlights

- Deployment challenges for DH in the UK are analysed
- A TIS scheme of analysis is used and adapted to local grid-based infrastructure
- Local authorities play central entrepreneurial roles but face resource constraints
- TIS functions are performed and influenced at and across local and national scales
- Recent central government support has not stimulated investment by firms

Abbreviations

CHP, Combined Heat and Power; CHPA, Combined Heat and Power Association; DECC, Department of Energy and Climate Change; DH, District Heating; ESCo, Energy Services Company; GLA, Greater London Authority; HCA, Homes and Communities Agency; IEA, International Energy Agency; LA, Local Authority; LEP, London Energy Partnership; RDA, Regional Development Agency; SDC, Sustainable Development Commission; TIS, Technological Innovation System; UK, United Kingdom.

1 Introduction

The UK has a long and chequered history of attempts to develop district heating (DH) systems – networks of insulated pipes which deliver heat via steam or hot water to serve the space and water heating demands of multiple buildings (Russell, 1993). UK Government and Devolved Administrations (particularly in Scotland) state that accelerated roll out of the technology would contribute to achieving national energy policy goals (Department of Energy and Climate Change (DECC) 2012; Scottish Government, 2011). However, given a history of failed attempts to establish far-reaching DH programmes in the past, and the small share of DH in the space and water heating market (around 2% in comparison with Denmark's 47% and Sweden's 55%, Euroheat & Power, 2011), the extent to which DH will be deployed, particularly on the timescales established by 2020 carbon and renewable energy targets, is highly uncertain. This paper's central question, therefore is: "what are the principal challenges to significantly scaling up the deployment of DH in the UK?"

While the technical components of DH are relatively mature, having been developed over forty years of widespread use in Scandinavia (Dyrelund & Steffensen, 2004; Ericson, 2009; Rutherford, 2008; Werner, 2010), their deployment in the distinct physical, social and institutional contexts of the UK presents new challenges requiring innovative organisational, contractual and commercial solutions. Two features of the UK context are important here. First, while DH is an inherently local infrastructure (limited to high density areas by financial, rather than physical, constraints, Roberts 2008), it is nonetheless situated in systems of regulation and government, resource flows and markets which operate at local, regional, national and international scales. Liberalisation and privatisation of the UK energy market have altered the scope for public authorities to direct development of energy systems towards social and environmental goals, and have consolidated existing assets under the control of a small number of companies whose international scope challenges development of locally-specific systems (c.f. Rutherford, 2008). Secondly, shifts in the role of local government, from service provision to enabling others to provide services (Bulkeley & Kern, 2006), accompanied by a proliferation of public and private service providers (Cook, 2009; Leach &

Percy-Smith, 2001) has reduced the in-house capacities of local authorities to plan, design and/or operate technically and financially viable schemes. Both features contrast with the municipal energy companies which developed DH in Sweden and Denmark in the twentieth century (Dyrelund & Steffensen 2004; Summerton, 1992; Werner, 2010). While the UK is arguably at an extreme end of these spectrums, given its early energy market liberalisation and history of centralised control over local authorities (Wilson & Game, 2002), these broad issues reflect the direction of travel in other European countries (Ericson, 2009; Monstadt, 2007; Rutherford, 2008). Addressing DH in the UK can therefore shed light on the processes by which contemporary municipal actors can orchestrate or influence local responses to sustainability challenges, and thereby contributes empirical material to a growing literature on the roles of geography in innovation processes (Geels, 2011; Hodson & Marvin, 2010; Truffer & Coenen, 2012).

The paper is organised as follows. Section 2 introduces the Technological Innovation Systems (TIS) analytical framework and source material used. The following three sections apply the analytical framework, section 3 describing the structure of the TIS, section 4 detailing the TIS's functional pattern and section 5 discussing inducement and blocking mechanisms, and key policy issues. Section 6 discusses implications of the analysis for DH in the UK, and draws conclusions.

2 Research approach

2.1 Theoretical Framework

Carlsson & Stankiewicz (1991, p.111). define a Technological System as "a network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion and utilisation of technology." Markard & Truffer (2008) unpack this definition into a *production* system which slowly evolves, accumulating incremental innovations, and a Technological Innovation System (TIS) which brings about radical innovation (which may include the establishment of entirely new production systems). TIS provides a suitable framework for addressing the central question of this paper, for while DH is a well established technology in other countries, new commercial and organisational forms for the development and operation of heat networks are central to the prospects for greater deployment of the technology, which represents a radical break with incumbent heat (gas distribution networks) and power (centralised electricity systems) technologies, in the UK.

The emphasis on the *systemic* nature of a TIS highlights the roles of multiple actors and the networks through which they interact, in mutual learning and knowledge creation which underpins technological change, in contrast with a simplified "point source" view of innovation (Coenen & Díaz López, 2010; Markard & Truffer, 2008; see also Edquist, 2005, on systems approaches to innovation). The roots of this systemic view are in Evolutionary Economics theorising, though TIS scholarship has, in recent years, shifted focus from traditional concerns of economics (in particular, economic growth) to development of "green" technologies (albeit, often under an ecological modernist conception of synergies with economic competitiveness). The use of a *technology* (or technology group) as a focusing device for a TIS allows for a dynamic view of the actors involved in the system, as the emphasis on knowledge flows (rather than flows of goods or services, Carlsson & Stankiewicz, 1991) acknowledges that different sectors may be involved in innovation, and the roles of actors and their configurations change as a technology develops (Coenen & Díaz López, 2010). In particular, this allows analysis to take a broader view of the actors central to innovation than earlier work which focused on the firm. A systems view also broadens the rationales for policy intervention beyond the traditional narrow focus on market failures (Foxon, 2007). From a normative perspective Jacobsson and Bergek (2011) argue that a technology-specific focus in informing policy is important as the closing window of opportunity to mitigate climate change (International Energy Agency (IEA), 2011) means that decarbonisation following sequential adoption of least-cost technologies will be too slow to avert dangerous climate change, and that technology-neutral policies ignore the unique and multi-dimensional growth processes of different technologies.

This paper adopts the TIS scheme of analysis presented by Bergek et al. (2008). This scheme of analysis was developed from meta-analyses (Johnson, 1998; Klein Woolthuis et al., 2005) of "key processes" identified in the TIS and other innovation systems literatures (Bergek, 2002; Jacobsson & Bergek, 2004; Bergek & Jacobsson, 2003; Edquist, 2005; Galli & Teubal, 1997; Hekkert et al., 2007; Rickne, 2000), combined with theoretical insights from a wider set of literature including sociotechnical systems (Bijker, 1997; Hughes, 1983), development blocks (Dahmén, 1988) and industrial networks and clusters (Porter, 2000). Early TIS studies emphasised the structure of a TIS, in terms of the actors involved, networks among them and institutional context. While this remains an important component of analysis, shortcomings in an exclusively structural approach (for example, Jacobsson & Bergek, 2011, suggest that strong networks could either facilitate or stifle a TIS,) have led to inclusion of specific activities which contribute to the overall TIS performance. This "functional TIS" approach abstracts a set of processes from innovation and other literatures, whose fulfilment contribute to a TIS's overall function of achieving technological change (Bergek et al., 2008; Hekkert et al., 2007; Negro et al., 2007). The functional approach also strengthens the capacity of TIS analyses to handle dynamic interactions (Coenen & Díaz López, 2010). For example, the degree to which a given function is or is not performed may enhance or retard the performance of other functions, creating inertia or "motors of change" (Hekkert et al., 2007).

TIS has largely been applied to particular renewable energy generating technologies (Jacobsson & Bergek, 2011) whereas the current study applies it to an infrastructure technology. DH networks, with high upfront costs and long payback periods create powerful interdependencies between subscribers (who regard heat as an essential service) and DH network owner (whose investment recovery relies on long term stability of subscribers) (Summerton, 1992). This close coupling between subscribers and DH network developer blurs the boundaries between categories of actor, particularly when (as is often the case in the UK) major subscribers take on roles in development and financing DH. The focus on production and the "analytical premium" placed on firms by innovation systems approaches (Coenen and Díaz Lôpez, 2010) are therefore relaxed here, as a broader range of actors (including subscriber organisations, and particularly local authorities) play important roles in the TIS (see section 3.2).

The role of space in technological change is recognised in the literature as an underdeveloped area (Truffer & Coenen, 2012). One aspect of spatial relations which has received some attention is the role of cities in low carbon transitions (Bulkeley et al., 2011). Historical analyses of the role of cities in sociotechnical change highlight differences in the spatial scale of technologies (Geels, 2011). However, as Hodson & Marvin (2010) note, contemporary organisations involved in sociotechnical change in cities (either as instigators of change or incumbents resistant to change) often operate at different scales, creating significant coordination challenges. DH in the UK is confronted by these challenges, as development invariably requires actors who operate at a local scale to interact with actors and institutions which operate over larger domains, and have less sensitivity or commitment to the particularities of local areas. These include national and devolved government, incumbent energy firms (whose operations and range of investment opportunities commonly transcend national boundaries) and national and international energy markets. In addition, the ownership and management of local buildings (particularly commercial buildings) in the UK often involves national or international companies. The relationship between scales is explored further in section 4.

2.2 Research methods

The present study used the stages of analysis suggested by Bergek et al. (2008), namely defining the TIS in focus, identifying structural components (section 3), mapping and assessing the functional pattern of the TIS (section 4), and identifying key inducement and blocking mechanisms and policy issues (section 5). While these steps provide a sequential logic, data gathering and interpretation addressed steps simultaneously and analysis was iteratively updated.

A descriptive approach to system delineation was adopted (see section 3), tailoring the boundaries of the TIS to the research question rather than a numerical approach such as technology distance indicators (Markard & Truffer, 2008). An initial review of academic, policy, and practitioner literature was used to identify an initial set of TIS structural components, and to identify key processes constituting performance of the TIS functions proposed by Bergek et al. (2008) for the case of DH in the UK. These structural and functional patterns were then used to identify informants within the TIS, and to develop semi-structured interviews to gather actors' understandings of the issues and structures identified. Interviewees were also asked open questions concerning the opportunities and challenges facing DH in the UK to enrich the set of processes already identified as contributing to TIS functioning. In addition, case study research and attendance (as participant or observer) in practitioner and policy workshops and meetings, as part of a broad collaborative research project into sustainable heat in cities, were used to further enrich the analysis. In total, analysis draws on data gathered between 2009 and 2012 through 35 semi-structured interviews with UK, devolved and local government officers, DH practitioners and current or potential DH subscribers, and 14 meetings and workshops directly addressing DH policy and/or project development at UK, Scottish and municipal scales.

In addition to developing an interpretation of the processes corresponding to Bergek et al.'s (2008) seven generic TIS sub-functions, the definitions of these functions were also refined to reflect the particularities of DH in the UK. Table 1 presents the definitions arrived at. The qualitative approach here adopted does not allow quantitative comparison with other TISs to assess how well the system is functioning. Instead, actors' accounts of how well the different processes and activities (which instantiate the sub-functions) are performed inform appraisal of system functionality.

<< INSERT TABLE 1 ABOUT HERE >>

3 Structure of the UK DH TIS

3.1 Defining the TIS in focus

Defining (and delimiting) the TIS is crucial to determining the outcome of analysis (Markard and Truffer, 2008). Following Bergek et al. (2008), the TIS is understood as an analytical construct, and delineated on the basis of the research question, guided by characteristics of contemporary DH practice.

Many configurations for the supply of heat via insulated pipes are possible. As this paper's research question responds to (*inter alia*) the policy goal of decarbonising heat supply, I restrict analysis, in terms of artefacts and applications, to DH networks which have the potential to supply large quantities of low carbon heat, including by DH network expansion or interconnection with other DH networks. This growth potential is clearly greatest in urban centres, so small rural heat networks are excluded. I include heat generation (or capture) equipment as separation of heat generation from distribution (organisationally and financially) is currently rare in the UK. Common praxis in the UK is to establish heat networks around gas fired CHP, with the value of electricity generated supporting heat sales competitive with onsite gas boilers (Kelly & Pollitt, 2010), so CHP is also included. The flexibility of DH to take heat from different sources is important to its economic and environmental sustainability (Sustainable Development Commission (SDC), 2009) so other heat sources (including biomass, large heat pumps, heat recovery from large centralised power stations) are also included, albeit peripherally. Heat from DH networks can drive absorption chillers for cooling (Roberts 2008), and these too are included, again peripherally. However, systems supplying high temperature heat for industrial applications are excluded because of the different technical and organisational issues they present.

Territorially, this paper focuses on England, Wales and Scotland, reflecting the low levels of deployment of DH across urban centres, and commonalities in the market, regulatory and cultural context within the UK.[1] This spatial focus does not preclude inclusion of actors and institutions based outside England, Wales and Scotland, if they are relevant to the deployment of DH in this spatial domain. Within this territory, activity at local level around specific projects is an important aspect of the TIS, as is activity at national level.

3.2 Identifying structural components of the TIS

Actors, networks and institutions comprise the structural components of a TIS (Bergek et al., 2008a). In European countries with widespread DH coverage, local authorities (LAs) played crucial roles in development and operation of heat networks (Grohnheit & Gram Mortensen, 2003; Werner, 2012). The UK

---

[1] Northern Ireland, whose energy markets are distinct from the rest of the UK (being integrated with the Republic of Ireland), is excluded from this analysis.

follows this pattern: where DH is or has been developed, LAs are key actors (Kelly & Pollitt, 2010), taking often multiple roles including:

- Gathering data and initiating investigation into potential schemes;
- Establishing an area wide, strategic, long term vision for heat into which particular initiatives can be embedded;
- Drawing on established relationships to broker new relationships between local heat users and DH contractors;
- Taking heat for the significant and varied heat demands of the LA estate;
- Integrating DH with local priorities including greenhouse gas emissions reduction, local regeneration, tackling fuel poverty, and waste management (via Energy from Waste facilities);
- Using planning policy to co-locate heat sources and heat demand, requiring or encouraging new development to connect to a heat network, and advising DH developers on planning issues;
- Statutorily, LAs have powers to install and maintain heat networks;
- Contributing low cost finance to project costs;
- Mitigating subscribers' perceptions of risk of monopoly exploitation by taking a role in system governance (that is, participating in ongoing decision making about system operation and policies, relationships with local stakeholders and strategic issue, often through representation on the board of the company operating the DH system).

At a local level, large heat subscribers are also included in the TIS as they are in many cases involved in project development, system financing and governance of DH systems (through formal representation in the decision making procedures of the company operating the system). Project-level interviewees report that formation of local stakeholder networks around a nascent project is often challenging, in part due to the absence of established relationships among local stakeholders creating communication and trust challenges (see section 4.1.2). These challenges can be exacerbated when local buildings are owned and/or managed by organisations operating above a local level.

The scale of DH activity in the UK is described by some industry practitioners as a "cottage industry," and this is reflected in the small number of small scale specialist contractors, who are a mix of UK companies and subsidiaries of European companies, and straddle local and national scales. There is some activity among the UK's six large incumbent energy companies, but this too is at a small scale, particularly in relation to their other activities.

A number of intermediary organisations also contribute to the TIS (including government agencies established to promote efficiency and carbon reduction in energy end-use, low carbon and renewable energy deployment, and research into building-design). A range of DH consultancy services are offered by DH-specialist, engineering, finance and legal consultancies.

Several practitioner networks undertake different activities. The recently (2011) established District Heating Vanguards Network attempts to foster interaction across LAs, and to date has operated as a loose affiliation with biannual issue-specific workshops.[2] Prior to the announcement of their abolition in 2010, some English Regional Development Agencies sought to develop regional networks on various low carbon and renewable energy technologies, including DH. Two well-established industry associations represent the interests of commercial DH practitioners, particularly through lobbying UK Government.

The innovation systems literature identifies various categories of institution relevant to innovation (see Coenen & Díaz López, 2010, for a discussion). Two aspects of the institutional infrastructure stand out as barriers to greater deployment of DH. Regulative institutions (the formal "rules of the game") are weak, particularly as DH is not specifically regulated (falling instead under general consumer protection), in contrast with the extensive regimes of regulatory control and protections which govern electricity and gas supply. As heat is unregulated, subscribers perceive risks not associated with conventional energy supply, and developers and investors perceive risks that future regulation will disrupt the long-term business model of a DH system (Helm's, 2010, time inconsistency problem). Cognitive institutions (the frames

---

[2] The author has contributed to planning and running these workshops through the Heat and the City project.

through which actors understand the world) and habitual patterns of behaviour are also unsupportive: in addition to a reluctance among potential sponsors and subscribers to engage with an unfamiliar form of energy supply, routine organisational behaviours (for example, energy procurement processes and timescales) are often unsuited to the greater degree of participation and long term commitment required by DH network builders of large subscribers.

4 Functional pattern of the UK DH TIS

This section describes and appraises the functional pattern of the TIS. The seven functions derived from Bergek et al.'s (2008) scheme of analysis were used to structure investigation (see table 1). As broad categories abstracted from empirical and theoretical literatures, these functions generally encompass several distinct processes or activities. To aid exposition of these distinctions, to illustrate interactions between functions, and to highlight the scalar dimensions of the UK TIS, the narrative account in this section presents these results organised by the spatial scale to which activities and processes relate. Section 4.1 addresses the instantiation of TIS functions at a local level (i.e. within individual urban settlements), section 4.2 addresses non-local (predominantly regional and national) processes, and section 4.3 interactions across local areas and between local and non-local scales. The embeddedness of local activity in processes and structures at a range of scales means these spatial-scale categories serve as rough organising principles rather than absolute distinctions.

4.1 TIS functions performed at local level

4.1.1 Local entrepreneurialism

Entrepreneurially establishing a DH initiative is currently a *local* activity in the UK, due both to the limited range of DH networks, and to the local particularities into which DH systems must be stitched (especially local configurations of buildings and their managers). Actors within the TIS (at local and non-local levels) generally look to LAs to lead this process, and to shape locally appropriate governance arrangements, business models and organisational forms (London Energy Partnership (LEP), 2007). However, only a minority of LAs in the UK have successfully taken on this role.

Local entrepreneurialism is stifled by challenges in resource mobilisation, particularly critical human resources. Case studies and LA interviewees indicate that where DH systems are successfully developed, this is often due to the efforts of a small number of enthusiastic officers (often just one). Such officers entrepreneurially bring together organisational-internal and -external components into productive alignment, often going well beyond the requirements of their post. This can include linking environmental, asset management, fuel poverty and planning functions along with lifecycle costing (an accounting approach which challenges a traditional local government revenue/capital split) with non-local networks of experience and expertise. As UK LAs have not been directly involved in energy provision since the 1940s, they often lack necessary in-house resources, namely technical, legal, and commercial skills and expertise. LA officers report mobilisation of internal financial resources is also difficult, particularly as (a) budgets have reduced in the wake of the 2008 financial crisis, (b) DH-champions compete with statutory LA functions (such as education and road maintenance), and (c) LA finance departments often require investment payback periods shorter than DH investment can usually produce.

LA officers and national policy makers cite statutory climate change duties, a new carbon tax and planning guidance as influences on the direction of search for LAs. However, interpretations of and responses to these pressures vary. For example, planning guidance from central and devolved authorities encourages LAs to adopt decentralised-energy policies, but gives no indication of where in a hierarchy of priorities this should be placed (Williams, 2010).

Where a programme of DH initiatives has been established, LA officers often identify successful local pilot projects as important in building legitimacy among local elected representatives and other LA officers. This can contribute to building momentum once a programme has begun.

4.1.2 Local market formation

Economies of scope and scale mean large DH systems are generally better able to support robust cash-flow profiles and viable financial models than smaller DH networks (IEA, 2005). However, the complexity of coordinating a large number of stakeholders precludes development of large DH networks in a single phase. Local markets for DH are therefore often scheduled with an initial "catalyst" phase based on a small number of large heat users with subsequent expansion envisaged but uncertain. In addition, timescales for DH financial models are commonly long (often of the order of a decade), so DH developers seek initial subscribers who are able to make relatively long term commitments. For these reasons, public sector organisations in command of large heat loads are regarded as key initial subscribers, as long term insolvency risks for these organisations is perceived to be low. However, project-level stakeholders interviewed report challenges in coordinating different public sector organisations, with individual budgets, different schedules for decision making and heating refurbishment, and organisation-internal carbon and energy management plans. A public sector facilities manager described the challenges of different organisations working together to develop a communal system in the absence of pre-existing relationships thus:

There's no need for us really to interact with the hospital. There's no real need for us to interact with the city council. There's no need for us to really interact with [public sector organisation], and even less with [local housing association]. So, you know, we don't naturally sit together and all meet every week, if you know what I mean. (Interview, 2012, names of organisations removed to preserve anonymity).

Building legitimacy at a local level is another challenge DH developers report in establishing a local heat market. In the absence of formal regulation, perceptions of risk among potential subscribers leads to often protracted negotiation between system developers and subscribers around price, service level guarantees, and redress procedures. Strategies employed to build legitimacy at a local level include connection of well regarded businesses (such as national supermarket stores), open book accounting, demonstration of previous experience and performance (particularly in the UK), and local authority involvement in system governance.

4.2 TIS functions performed above the local level

4.2.1 Knowledge development and legitimation at national level

A key resource for the identification and development of potential DH systems is knowledge of spatio-temporal patterns of heat demand in an area. While some LAs have engaged with “heat mapping,” local-level interviewees report difficulties in accessing data held by utility companies, and industry interviewees suggest the methodology, quality and utility of locally developed heat maps is highly variable. Responding to this issue, national and devolved governments have established methodologies and have constructed (in England, DECC, 2012) or are constructing (in Scotland, Scottish Government, 2011) cross-local heat maps to support opportunity identification and early development.

In addition to supporting local action, heat maps contribute to national estimates of economic potential which in turn influence beliefs in growth potential (e.g. among national policy actors and investors) and hence the guidance of search function. While improved heat map data increases the robustness of such estimates – and has, indeed, increased estimates of economic potential from a maximum of 14% of heat demand (Pöyry Energy, 2009) to around 50% (DECC, 2011) – difficulties modelling communal systems (as compared with more modular technologies) remain. Small changes in assumptions can lead to large differences in estimated potential, and heat networks are poorly represented in the multi-technology, system wide modelling exercises which inform policy development (DECC, 2012; Pöyry Energy, 2009). These weaknesses in the search-guidance function at a national level are compounded by some policy-makers’ concerns that DH with gas CHP will lock in fossil fuels (DECC 2012). As one policy officer interviewee reported of government-internal discussions:

The argument for renewable energy has been made far better than the argument for energy efficiency […] I’ve even had people come back to me and say, when I’ve been talking about support for district heating with CHP, they’ve kind of said, well if it was renewables, yes. […] they didn’t really understand why gas fired CHP with district heating would be given particular support, which astounded me. (Interview, 2009)

Some industry (e.g. Rotheray, 2011) and academic (e.g. Toke & Fragaki, 2008) debates tackle these concerns (i.e. a form of legitimation) by highlighting successful Scandinavian DH heat source diversification, and analyses suggesting DH systems' heat storage capacities can contribute to balancing electricity systems with increasingly inflexible generation technologies (particularly renewables and nuclear). However, broader processes of legitimation are weakened by fragmentation in industry representation, with two competing associations separately advocating the technology. In 2009 the UK Government proposed a Heat Markets Forum with industry, government and consumer representatives, which was intended to enhance legitimacy by considering regulation and other ways of building confidence (DECC 2009), but this has not been established.

4.2.2 National influences on market formation and revenue generation

A key aspect of market formation for DH is establishing long-term revenue streams to recover sunk investment, and the role of CHP often makes revenue from electricity sales critical. However, decentralised generators face various challenges in the UK. Accessing the well established national electricity market is challenging as small generators struggle to connect to distribution networks on acceptable terms, and complain of a lack of price transparency and responsiveness from network operators (Ofgem, 2011). Once connected, they are rarely able to participate directly in electricity markets (lacking the technical capacity, financial scale and balancing portfolio of generating plant necessary to handle the risks of participation in wholesale markets) instead, selling via consolidators who take on balancing and other market risks offer low tariffs (Toke & Fragaki, 2008). Greater value may be captured by direct retail supply of electricity, though the UK's licensing regime restricts the power that small suppliers can deliver (LEP, 2007). Until recently "private wire" electricity networks could ensure CHP operators a long-term market (often supplying electricity along with heat), but a European Court of Justice ruling (the "Citiworks" case) requires third party suppliers have access to these electricity networks, undermining the long-term stability of the revenue they generate.

The context for developing local heat markets is in part shaped by central and devolved governments. Regulations for new buildings, limiting operational carbon emissions, have potential to guide developers towards DH. New developments (particularly large buildings) in dense areas can be important locally in establishing a first market for DH, which could then expand to nearby existing buildings. However, DH is not the only solution to compliance with building regulations, and other technologies are supported by Feed-In Tariffs (including a Renewable Heat Incentive). Some project-level actors suggest this can act as a barrier to market formation as key buildings use tariff-supported onsite technologies making them unavailable as DH subscribers. Thus while the building's own GHG emissions may be tackled, this can come at the expense of an area-wide solution with greater overall GHG emissions abatement.

4.2.3 Mobilisation of resources at a national level and the development of positive externalities

One route by which financial resources have been mobilised for DH is via national grant programmes: the Community Energy Programme (2002-2005), the Low Carbon Infrastructure Fund (2009-2010), and the Community Energy Saving Programme (2009-2012) . While these have been important stimulants to activity their short timescales (relative to project development) have created spikes in demand for consultancy and contractor services, pushing up prices and lead times. Industry representatives suggest that low confidence in future support programmes, however, means firms have not responded to these increased prices by investing in skills and supply chains. This failure to create this positive externality is significant, as the factor and product prices which industry investment could bring down, currently provide relatively weak incentives, limiting the guidance of search function. The small scale of DH industry in the UK means equipment (particularly insulated pipes) is imported, and other factor costs are high relative to other European countries (Pöyry Energy 2009).

Challenges to guidance of the search are also manifested in concerns about volatility in fuel and electricity prices (IEA, 2008). While recent price movements have improved the viability of DH/CHP (Kelly & Pollitt, 2010), the possibility of a "golden age of gas" (IEA, 2012), which could depress competing heat prices, contributes uncertainty. Long term visibility of energy prices in the UK is generally poor due to low levels of market liquidity (CHPA, 2011).

4.3 TIS functions performed in interaction across local areas and national scales

4.3.1 Knowledge sharing and coordination across local areas

LA project teams with experience developing DH systems have much knowledge of project development, commercial arrangements, legal restrictions and organisational forms which other LAs value. However, the limited development of knowledge sharing networks mean this has to date remained fragmented (Lovell et al. 2011). While some LA project teams express interest in using their experience to offer consultancy services or to develop projects in other areas, only one has done so (Woking Borough Council, via its arms-length company, operates a heat network in Milton Keynes). London's Decentralised Energy Programme Delivery Unit (DEPDU) is a notable attempt to coordinate development, facilitate knowledge flows and exploit economies of scale, having secured European funding to provide London boroughs (LAs) and other project sponsors with technical, financial and commercial assistance.

In addition to DEPDU's resource and knowledge sharing, coordination of local planning within London is made possible by the overarching Greater London Authority (GLA) which has established London-wide planning policies requiring new developments to connect to DH networks in certain circumstances (GLA, 2009). Adoption of similar planning approaches to market formation in other areas is made challenging by the lack of coordination across neighbouring LAs. Because DH sits outside many domestic and commercial developers' established models, LA officers report that planning policies for DH create perceived risks of developer flight (to nearby areas where planning requirements are lighter).

4.3.2 Knowledge asymmetries and interaction between local and non-local actors

At project level, non-engineering forms of knowledge crucial to project development, include effective business models, legal structures and implications, finance models, risk and contractual forms. LAs frequently require external sources of expert advice in respect of these. As noted above (section 4.3.1) diffusion of this knowledge across LAs is weak. Independent advice is available, but as the intellectual property of commercial consultants it is often expensive. Some DH contractors offer lower cost advice, but the inherent information asymmetry means LAs run the risk that rather than a project being optimised in terms of the LA's goals, it is instead designed to fit the strengths or established model of the company (Homes and Communities Agency (HCA) 2011).

Beyond project design, the relationship between LAs and commercial contractors is structured in various ways across different places. These include traditional design and/or build contracts, joint venture enterprises, and long term (around 25 year) concession models. From a LA perspective, drawing a commercial partner into a project has advantages of access to commercial expertise and private sector finance, and transfer of risk away from the LA (LEP 2007). However, industry and public sector informants recognise the scope for tensions to emerge from differences in the policy goals of a LA and the commercial goals of a contractor who's domain of activity (and investment opportunities) extends beyond the local area. These tensions have potential to limit the extent to which LAs can orchestrate the expansion of a local DH market. As one public sector interviewee suggested, situations can come about in which:

> *[The partner] says, well we're not doing that, it doesn't meet our trigger rate of worthwhile investment. So then that's shoved back on the council to make more investment. And do they make that investment with another provider, or do they stay with [the company], who increasingly would be hard-hearted in business terms, in doing stuff only because there's a policy reason?* (Interview, 2011)

4.3.3 Drawing non-local financial resources into local projects

Finance interviewees report that, while the low rates of return and long timescales of DH business models can be acceptable to institutional investors (such as sovereign wealth funds and pension funds), the minimum scale these investors consider is larger than the capital required for individual projects, particularly in the early phases. While in the long run these deep pools of capital could be used to refinance a portfolio of projects, they are not available for initial development.

Practitioners report that other sources of commercial finance (including ESCo and utility company sources) require higher rates of return. In part practitioners attribute this to unfamiliarity of funders with investment in heat, the lack of a delocalised, standardised business model, and the sunk-investment character of heat networks. The immobility of insulated pipes once installed means their value is the value of the heat loads connected to it (rather than a re-use or recovery value), so heat off-take and bad debt risks are crucial for funders. Reducing these risks at a local level is a key challenge in mobilising non-local financial resources, but the willingness of LAs to take on risks associated with other (public or commercial) organisations' heat off-take agreements, either by underwriting commercial finance or contributing public finance, is low. The resulting low levels of "bankability" of heat demand for projects that reach beyond the local authority estate is therefore a key challenge to the mobilisation of finance.

5 Inducement and blocking mechanisms and key policy areas

The fifth and sixth steps of Bergek et al.'s (2008) scheme of analysis are identification of key inducement and blocking mechanisms, and specification of key policy areas. Accordingly, this section distils the findings of sections 3 and 4.

Where DH networks with potential to expand, or a programme of DH networks has been established in an area in the UK, the local authority has frequently played a key entrepreneurial role. The capacity and motivation for LAs to exercise leadership in DH system development are both, therefore, crucial to the prospects for greater deployment of the technology. However, the lack of resources available to LAs (skills and expertise as well as finance), and the weak incentives on them to undertake non-statutory local energy planning and development are key blocking mechanisms.

However, the DH development activities of LAs are embedded in local and wider contexts which also strongly condition the scope for DH development. Local influences on the formation of markets for DH (particularly difficulties coordinating different organisations) combine with influences from national level (e.g. building codes, competition with subsidised modular technologies, and the absence of DH regulation). These heterogeneous challenges to formation of markets combine as blocking mechanisms, though none stands out from the rest as *the* key barrier to heat market formation. However, the emphasis on public sector buildings as initial subscribers implies national/devolved policy opportunities to encourage and support public sector organisations to connect to proposed or established DH networks.

The embeddedness of DH in the UK's other energy systems creates a set of blocking mechanisms. DH faces difficulties finding a place in electricity systems physically and institutionally designed around a centralised model of provision. Over the long timescales implied by DH financial models, uncertainties in both energy prices and the mix of other low carbon technologies deployed challenge confidence in future revenue streams. Its exclusion from many policy-informing models of future energy system scenario further marginalises DH.

Some of the structural and functional weaknesses of the DH TIS appear to be related to the low levels of activity in the sector, and so may be ameliorated if deployment increases. An increase in the number of LAs developing DH could increase the population and hence (potentially) the effectiveness of knowledge networks; confidence in growth could stimulate investment in skills and supply chains; and weaknesses in guidance of the search and legitimation could be overcome with greater familiarity. None of these possibilities, however, are certain, and a key policy issue is to identify ways in which interventions in the TIS can ensure these positive externalities are realised, noting the failure of previous grant funding approaches to result in skills and supply chain development.

Finally, while section 4 organised analysis of functional performance in terms of spatial scale, it also indicates that the relationship between function performance and spatial scale is not fixed. In particular, while heat mapping has in the past been undertaken at a local level, the production of methodologies and data at a national level removes one particular challenge of local DH development. Mitigating revenue risks in local projects would facilitate drawing in non-local finance, but the unwillingness of LAs to underwrite heat sales to third parties suggests central government could support greater deployment of DH by some form of underwriting of investment.

6 Conclusions

Development of DH is complex due to its multi-actor and embedded characteristics (Summerton, 1992). Accounts of the historical failure of DH and CHP to play significant roles in the UK's energy system emphasise the long chains of influence from processes and events at a national level to the details of local activity (Russell, 1996). Accordingly, in seeking to assess what are the main challenges to the deployment of district heating in the UK, the TIS analysis has revealed several structural and functional weaknesses spanning local areas, national scales, and inter-linkages between the two.

Analytically, the close coupling and long term relationships between actors involved in a DH initiative (as subscribers, project sponsors, designers, contractors, operators and funders) necessitates looking beyond the traditional focus on firm activities common to early innovation systems work (Coenen & Díaz López, 2010). The critical roles attributed to LAs by other actors in the TIS mean limitations on their ability and willingness to act entrepreneurially are key challenges to establishing DH in new areas. However, even where LAs are engaged with DH the formation of a local heat market is influenced both by the difficulty of coordinating multiple local organisations, and the systems of state incentives which aim to reduce greenhouse gas emissions from buildings.

As has long been the case DH and CHP struggle to find a place within the UK's centralised energy systems, though where earlier research identified the strategic activities of competing interests as key to the marginalisation of the technology (Russell, 1996), the current study emphasises the challenges to participation in established electricity markets and uncertainties in future market conditions. The TIS approach has been accused of "myopia", focusing on internal system dynamics while ignoring the strategic activities of other actors (Markard and Truffer, 2008). An area of further research would therefore be to consider relationships between the DH TIS and other low carbon heat TISs (including biogas and electric heating, particularly with heat pumps).

Analysis in section 4 illustrates how TIS functions are instantiated and influenced differently at local and non-local levels. While some aspects of these spatial relationship may be relatively obdurate (stemming from the resources and competence of actors at different scales) enhanced performance of TIS functions can, in some cases, be achieved by shifting activities across different scales as the example of heat mapping and the possibility of state underwriting of local projects illustrate. Alongside this vertical dimension, there is scope for greater coordination and knowledge network development across local areas. More broadly, this suggests that, rather than cities "receiving" national transitions there is scope for productive, interactive relationships across local areas and between local and non-local levels in fostering sociotechnical change (c.f. Hodson & Marvin, 2010).

Complexity poses a challenge to policy makers seeking to stimulate greater deployment of DH. A number of structural and functional weaknesses could conceivably be improved by an increasing scale of activity (virtuous cycles), though these are uncertain. The failure of grant funding programmes to stimulate cost reductions in DH through firms investing in skills and supply chains is instructive. Policy makers could respond to this by ensuring support programmes are (a) tailored to improving overall system performance and (b) embedded in an ongoing monitoring process to identify potential positive externalities of activity which are not being achieved, and to intervene accordingly.

7 Acknowledgements

I am indebted to the late Dr Stewart Russell (University of Edinburgh) and to Sytze Dijkstra (previously Delta Energy and Environment, currently Energy Research Centre of the Netherlands) for guidance and support through this research. I am also grateful to Professor Jan Webb, University of Edinburgh, for additional support and for assistance in writing this article. Some of the material analysed in this article was collected under the Heat and the City project (www.heatandthecity.org.uk) which is funded by the UK Research Council's (RCUK) Energy Programme (award no. RES-628-25-0052). The Energy Programme is a RCUK cross council initiative supported by the EPSRC, ESRC, NERC, BBSRC and STFC.

8 References

Bergek, A (2002) *Shaping and exploiting technological opportunities: the case of renewable energy technology in Sweden*. PhD thesis. Gothenberg, Department of Industrial Dynamics, Chalmers University of Technology.

Bergek, A & Jacobsson, S (2003) The emergence of a growth industry: a comparative analysis of the German, Dutch and Swedish wind turbine industries. In: J. S. Metcalfe & U. Cantner eds. *Change, transformation, and development*. Heidelberg, Physica-Verlag, pp.197–227.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S. & Rickne, A. (2008) Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. *Research Policy*, 37 (3), pp.407–429.

Bijker, W.E. (1997) *Of bicycles, bakelites, and bulbs: toward a theory of sociotechnical change*. Cambridge, Mass., MIT Press.

Bulkeley, H., Castán Broto, V., Hodson, M. & Marvin, S. eds. (2011) *Cities and low carbon transitions*. Abingdon, Oxon, Routledge.

Bulkeley, H. & Kern, K., 2006. Local Government and the Governing of Climate Change in Germany and the UK. *Urban Studies*, 43(12), pp.2237 - 2259.

Carlsson, B. & Stankiewicz, R., 1991. On the nature, function and composition of technological systems. *Journal of Evolutionary Economics*, 1(2), pp.93–118.

CHPA, 2011. *Consultation on Reform of the Electricity Market: A response from the Combined Heat and Power Association*, London: Combined Heat and Power Association.

Coenen, L. & Díaz López, F.J. (2010) Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities. *Journal of Cleaner Production*, 18 (12), pp.1149–1160.

Cook, I.R., 2009. Private sector involvement in urban governance: The case of Business Improvement Districts and Town Centre Management partnerships in England. *Geoforum*, 40(5), pp.930-940.

Dahmén, E. (1988) 'Development blocks' in industrial economics. *Scandinavian Economic History Review*, 36 (1), pp.3–14.

DECC, 2009. *Heat and Energy Saving Strategy Consultation*, http://hes.decc.gov.uk.

DECC, 2011. *The carbon plan: Delivering our low carbon future*, http://www.decc.gov.uk/en/content/cms/tackling/carbon_plan/carbon_plan.aspx.

DECC, 2012. *The future of heating: A strategic framework for low carbon heat*, http://www.decc.gov.uk/en/content/cms/meeting_energy/heat_strategy/heat_strategy.aspx.

Dyrelund, A. & Steffensen, H., 2004. *Best practice in Danish district heating*, Denmark: Rambøll. http://www.energymap.dk/Cache/65/65ae68be-e645-4a66-b5e4-2a4f4b757f02.pdf.

Edquist, C. (2005) Systems of innovation: perspectives and challenges. In: J. Fagerberg, D. C. Mowery, & R. R. Nelson eds. *The Oxford handbook of innovation. Oxford*, Oxford University Press.

Ericson, K., 2009. *Introduction and development of the Swedish district heating systems: Critical factors and lessons learned*, http://www.res-h-policy.eu/downloads/Swedish_district_heating_case-study_(D5)_final.pdf.

Euroheat & Power, 2011. *District Heating and Cooling: Country by Country 2011 Survey*, Belgium: Euroheat & Power. http://www.euroheat.org/Publications-8.aspx?PID=46&Action=1&NewsId=12.

Foxon, T.J., 2007. The Rationale for Policy Interventions from an Innovation Systems Perspective. In J. Murphy, ed. *Governing Technology for Sustainability*. London: Earthscan, pp. 129–147.

Galli, R. & Teubal, M. (1997) Paradigmatic shifts in national innovation systems. In: C. Edquist ed. *Systems of Innovation: Technologies, Institutions and Organizations*. Routledge, pp.342–370.

Geels, F.W., 2011. The role of cities in technological transitions: Analytical clarifications and historical examples. In H. Bulkeley et al., eds. *Cities and low carbon transitions*. Abingdon: Routledge.

GLA, 2009. *Powering ahead: delivering low carbon energy for London*, Greater London Authority. http://www.london.gov.uk/sites/default/files/powering-ahead141009.pdf.

Grohnheit, P.E. & Gram Mortensen, B.O., 2003. Competition in the market for space heating. District heating as the infrastructure for competition among fuels and technologies. *Energy Policy*, 31(9), pp.817-826.

HCA, 2011. *District Heating Good Practice Guide: Learning from the Low Carbon Infrastructure Fund*, http://www.homesandcommunities.co.uk/district-heating-good-practice-learning-low-carbon-infrastructure-fund.

Hekkert, M., Suurs, R.A.A., Negro, S.O., Kuhlmann, S. & Smits, R.E.H.M. (2007) Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, 74 (4), pp.413–432.

Helm, D., 2010. *Infrastructure and infrastructure finance: The role of the government and the private sector in the current world*, European Investment Bank, Economic and Financial Studies. http://ideas.repec.org/p/ris/eibpap/2010_005.html.

Hodson, M. & Marvin, S., 2010. Can cities shape socio-technical transitions and how would we know if they were? *Research Policy*, 39(4), pp.477-485.

Hughes, T.P. (1983) *Networks of power: Electrification in Western society 1880–1930*. Baltimore, Johns Hopkins University Press.

IEA, 2005. *A Comparison of distributed CHP/DH with large-scale CHP/DH*, Paris: International Energy Agency

IEA, 2008. *CHP/DHC country scorecard: United Kingdom*, Paris: International Energy Agency. http://www.iea.org/g8/chp/docs/UK.pdf.

IEA, 2011. *World Energy Outlook*, Paris: International Energy Agency. http://www.worldenergyoutlook.org/publications/weo-2011/.

IEA, 2012. *Golden rules for a golden age of gas*, Paris: International Energy Agency. http://www.worldenergyoutlook.org/goldenrules/

Jacobsson, S. & Bergek, A. (2004) Transforming the energy sector: the evolution of technological systems in renewable energy technology. *Industrial and Corporate Change*, 13 (5), pp.815–849.

Jacobsson, S. & Bergek, A., 2011. Innovation system analyses and sustainability transitions: Contributions and suggestions for research. *Environmental Innovation and Societal Transitions*, 1, pp.41-57.

Johnson, A. (1998) *Functions in innovation system approaches*. Unpublished Working Paper. Department of Industrial Dynamics, Chalmers University of Technology, Gothenberg.

Kelly, S. & Pollitt, M., 2010. An assessment of the present and future opportunities for combined heat and power with district heating (CHP-DH) in the United Kingdom. *Energy Policy*, 38(11), pp.6936-6945.

Klein Woolthuis, R., Lankhuizen, M. & Gilsing, V. (2005) A system failure framework for innovation policy design. *Technovation*, 25 (6), pp.609–619.

Leach, R. & Percy-Smith, J., 2001. *Local governance in Britain*, Hampshire: Palgrave.

LEP, 2007. *Making ESCos Work: Guidance and Advice on Setting Up & Delivering an ESCo*, London: London Energy Partnership. http://www.lep.org.uk/uploads/lep_making_escos_work.pdf.

Lovell, H. et al., 2011. *Heat and the City workshop on Municipal Leadership and Organisation for District Energy: Workshop report*, Edinburgh: Heat and the City. http://www.heatandthecity.org.uk/our_work/workshop_-_leadership_and_organisation_for_district_energy.

Markard, J. & Truffer, B. (2008) Technological innovation systems and the multi-level perspective: Towards an integrated framework. *Research Policy*, 37 (4), pp.596–615.

Monstadt, J., 2007. Urban Governance and the Transition of Energy Systems: Institutional Change and Shifting Energy and Climate Policies in Berlin. *International Journal of Urban and Regional Research*, 31(2), pp.326-343.

Negro, S.O., Hekkert, M.P. & Smits, R.E., 2007. Explaining the failure of the Dutch innovation system for biomass digestion–A functional analysis. *Energy Policy*, 35(2), pp.925–938.

Ofgem, 2011. *High Level Summary of DG Forum Responses*, London: Ofgem. http://www.ofgem.gov.uk/Networks/ElecDist/Policy/DistGen/Documents1/high%20level%20summary%20of%20DG%20Forum_published.pdf.

Porter, M.E. (2000) Location, Competition, and Economic Development: Local Clusters in a Global Economy. *Economic Development Quarterly*, 14 (1), pp.15–34.

Pöyry Energy, 2009. *The potential and costs of district heating networks: A report to the Department of Energy and Climate Change*, Oxford: Pöyry Energy. http://www.decc.gov.uk/assets/decc/What%20we%20do/UK%20energy%20supply/Energy%20mix/Distributed%20Energy%20Heat/1467-potential-costs-district-heating-network.pdf.

Rickne, A. (2000) *New Technology-Based Firms and Industrial Dynamics. Evidence from the Technological System of Biomaterials in Sweden, Ohio and Massachusetts*. PhD thesis. Gothenberg, Department of Industrial Dynamics, Chalmers University of Technology.

Roberts, S., 2008. Infrastructure challenges for the built environment. *Energy Policy*, 36(12), pp.4563–4567.

Rotheray, T., 2011. *Onsite generation and demand response – the role of the EMR*. http://www.heatandthecity.org.uk/__data/assets/pdf_file/0010/71758/7_-_Tim_Rotheray_-_Onside_generation_and_demand_response_the_role_of_the_EMR.pdf.

Russell, S., 1993. Writing Energy History: Explaining the Neglect of CHP/DH in Britain. *British Journal for the History of Science*, 26(1), pp.33–54.

Russell, S., 1996. At the Margin: British Electricity Generation after Nationalisation and Privatisation, and the Fortunes of Combined Heat and Power. In *SHOT '96*. Society for the History of Technology, Annual Meeting. London.

Rutherford, J., 2008. Unbundling Stockholm: The networks, planning and social welfare nexus beyond the unitary city. *Geoforum*, 39(6), pp.1871-1883.

Scottish Government, 2011. *2020 Roadmap for Renewable Energy in Scotland*, http://www.scotland.gov.uk/Publications/2009/07/06095830/2020Routemap.

SDC, 2009. *Renewable heat in Scotland*, Sustainable Development Commission. http://www.sd-commission.org.uk/publications/downloads/SDC%20Renewable%20Heat%20Report.pdf.

Summerton, J., 1992. *District heating comes to town: The social shaping of an energy system*, Linköping: Linköping University.

Toke, D. & Fragaki, A., 2008. Do liberalised electricity markets help or hinder CHP and district heating? The case of the UK. *Energy Policy*, 36(4), pp.1448–1456.

Truffer, B. & Coenen, L., 2012. Environmental Innovation and Sustainability Transitions in Regional Studies. *Regional Studies*, 46(1), pp.1-21.

Werner, S. (2010) *District Heating in Sweden – Achievements and challenges.* Manuscript for XIV Polish District Heating Forum. http://hh.diva-portal.org/smash/get/diva2:375359/FULLTEXT01.

Williams, J., 2010. The deployment of decentralised energy systems as part of the housing growth programme in the UK. *Energy Policy*, 38(12), pp.7604-7613.

Wilson, D. & Game, C., 2002. *Local Government in the United Kingdom* 3rd ed., Hampshire: Palgrave Macmillan.

9 Table

Function	**Description**
Entrepreneurial experimentation	Efforts to translate potential for viable heat networks into concrete actions by bringing disparate heterogeneous elements together in new configurations, generating new opportunities and learning processes.
Knowledge development and diffusion	Strengthening the breadth and depth of the knowledge base, and how that knowledge is developed, diffused and combined in the system. Basic knowledge development (as would be revealed by R&D activities and patents) is less relevant to DH (as a mature

	technology) than knowledge relating to spatio-temporal patterns of heat demand, and viable financial, business and legal forms.
Market formation	Recruitment and coordination of heat subscribers with DH network initiation and expansion. High upfront costs and long financial models mean system builders seek long term, reliable revenue streams, often associated with both heat and electricity generation.
Legitimation	Increasing social acceptance and compliance with relevant institutions, including overcoming the "liability of *oldness*" and articulating contribution of DH to policy goals.
Influence on direction of search	Incentives and pressures on organisations to direct resources towards DH, for example as producers, sponsors or participant-subscribers.
Resource mobilisation	The extent to which financial resources, skills and expertise (particularly technical, legal and financial) can be mobilised by actors within the TIS.
Development of positive externalities	The extent to which activities and investments in one area of the TIS produce additional benefits to the functioning of other parts of the TIS.

Table 1. The seven sub-functions of a TIS, adapted from Bergek et al. (2008) and Jacobsson and Bergek (2011) to reflect particularities of DH in the UK.