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Scaling up local energy infrastructure; An agent-based model of the emergence of district heating networks

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ABSTRACT

The potential contribution of local energy infrastructure – such as heat networks – to the transition to a low carbon economy is increasingly recognised in international, national and municipal policy. Creating the policy environment to foster the scaling up of local energy infrastructure is, however, still challenging; despite national policy action and local authority interest the growth of heat networks in UK cities remains slow. Techno-economic energy system models commonly used to inform policy are not designed to address institutional and governance barriers. We present an agent-based model of heat network development in UK cities in which policy interventions aimed at the institutional and governance barriers faced by diverse actors can be explored. Three types of project instigators are included – municipal, commercial and community – which have distinct decision heuristics and capabilities and follow a multi-stage development process. Scenarios of policy interventions developed in a companion modelling approach indicate that the effect of interventions differs between actors depending on their capabilities. Successful interventions account for the specific motivations and capabilities of different actors, provide a portfolio of support along the development process and recognise the important strategic role of local authorities in supporting low carbon energy infrastructure.

1. Introduction

Local energy infrastructure[1] is becoming increasingly important in the transition towards a low carbon economy (Burt et al., 2012; Realising Transition Pathways Engine Room, 2015). Delivery and operation of infrastructure at a local scale can contribute to multiple aims of energy policy; reducing carbon emissions, providing affordable energy and securing local economic benefits and control (Hall and Roelich, 2015; Roelich and Bale, 2014). However, those attempting to engage with local energy infrastructure currently face many barriers to scaling up (i.e. increasing the size and/or number of projects), which limits their potential to contribute to these aims.

There is currently a lack of policy support for energy infrastructure at the local scale and the focus of regulation on national-scale actors serves to increase the challenges for those attempting to deliver or operate local energy infrastructure (Hall and Roelich, 2015). While the role of local energy infrastructure in a successful energy system transition is acknowledged (Realising Transition Pathways Engine Room, 2015; Seyfang et al., 2013) there has been little focus on scaling up of these schemes, which further marginalises its potentially valuable contribution (Ekins et al., 2013).

This paper addresses the question of how scaling up the role of local energy infrastructure can be accelerated through appropriate policy intervention. We use the example of the development of heat networks in the UK, but the methods and analysis are broadly applicable in both technical and geographical terms. In Section 2 we review key literature in the field and propose a modelling approach to address this challenge. In Section 3 we present our methods and discuss key results in Section 4. In Section 5, we discuss the systemic insights gained and the usefulness of the agent-based approach when considering scaling up local energy infrastructure. We conclude in Section 6 with recommendations for energy policy.

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[1] We use the term 'local energy infrastructure' (otherwise frequently called decentralised or distributed infrastructure) to refer to that infrastructure which is delivered locally by non-traditional actors in energy provision, who operate at a local scale, including local authorities, communities and social enterprises. This includes, for example, district heat networks, microgeneration, demand management, smart grid technologies and small-scale storage.

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2. Context

In the UK, as in some other countries, there are clear and ambitious targets for greenhouse gas emissions reductions (HM Government, 2008). Current public policy related to energy systems is focused mainly on micro-level demand-side efficiency measures and macro-scale regulatory interventions on the supply-side. Micro-level demand-side measures include schemes to encourage retrofit in households such as the Energy Company Obligation (HM Government, 2012). Macro-scale measures on the supply-side include the Renewable Obligation, which aims to stimulate investment in renewable generation technologies by placing an obligation on UK electricity suppliers to source an increasing proportion of the electricity they supply from renewable sources (Ofgem, 2015).

These measures overlook the local scale of activity and the important role of business models in driving system change, as well as technology adoption. In the following sections we outline (i) why local energy infrastructure is important to energy system transition in the UK, (ii) why local actors may engage in infrastructure for different reasons, with different outcomes and (iii) the important influence of business models in driving system change. (vi) We go on to describe an approach to modelling that will enable us to explore the scale up of local energy infrastructure in a way that better reflects some of the key characteristics and benefits of local infrastructure. We use the case study of the development of heat networks in the UK to explore these issues.

2.1. Local energy infrastructure

Driven in part by challenging targets for greenhouse gas reduction, there is an increasing trend for localisation of physical energy infrastructure; towards smaller units of generation and smarter distribution and control systems to connect supply more closely with managed demand (Burt et al., 2012; Rydin et al., 2013). Infrastructure delivered at the local scale is cited as have many advantages over more centralised systems including resilience (O'Brien and Hope, 2010), increased potential to incorporate renewable technologies (Alanne and Saari, 2006) and reduced transmission losses (Burt et al., 2012).

Heat networks are one example of local-scale, and potentially low-carbon, energy infrastructure. These networks have the potential to significantly reduce the energy intensity and carbon emissions of heat provision, particularly when heat is sourced from sources such as biomass combined heat and power (CHP) generators or waste industrial heat (Eriksson et al., 2007). In the UK, only 1% of the population is currently supplied with heat from a network, as compared to more than 60% in Denmark, Poland and Estonia (Euroheat, 2009).

However, the technology itself is considered mature, and the barriers to adoption of heat networks in the UK are found to be related to the challenge of complex interactions between stakeholders and overcoming the lock-in of building-level heating technologies and the centralised provision of gas and electricity (BRE et al., 2013). This work is focused on the challenge of stakeholder interaction in heat network development.

2.2. Local actors

The smaller scale of technologies and closer connection between supply and end-users presents an opportunity for new actors to engage in local energy infrastructure, including municipalities, community groups and social enterprises. There is increasing evidence that the motivation of local actors for engagement in energy provision is very different to mainstream actors and much more focussed on social and environmental outcomes (Roelich and Bale, 2014; Seyfang et al., 2013).

Local authority and community involvement in energy infrastructure provision has, however, been minimal since nationalisation in the 1940s (Fouquet and Pearson, 1998). The UK has a highly centralised system of infrastructure provision, supported by regulation that is intended to create competition between providers wherever this is not prohibited by natural monopolies (Mitchell and Woodman, 2010). Particularly in the utilities, this has resulted in national scale planning and operation of infrastructure.

Recent policy shifts, however, have seen a devolution of power to municipal scale actors through the 2011 Localism Act (HM Government, 2011) and City Deals (Deputy Prime Minister's Office, 2011), which include an increasing responsibility for local infrastructure placed in the hands of local authorities and city regions. Furthermore, local government and community groups are noted as being key to delivering a host of energy strategies in the UK, including the heat strategy (Department of Energy and Climate Change, 2013).

Local authorities have the opportunity to use this increased autonomy to plan for the development and operation of infrastructure locally. This creates space for new actors at the local scale and allows local authorities and community organisations to become infrastructure providers and capture the benefits that this may bring. In addition to the national level strategies for development of heat networks, there is interest at the municipal scale, where local authorities recognise the potential for heat networks to contribute to fuel poverty reduction by providing a lower cost source of heat, as well as other economic and environmental benefits (Bale et al., 2014b).

Examples of local development of heat networks already exist (e.g. Islington Bunhill and Aberdeen Heat and Power (Bale et al., 2014a)), but as isolated niche examples that are far from becoming mainstream in the UK. They are implemented by a range of different actors (i.e. instigators) including municipal authorities, community organisations, cooperatives and private enterprises. A multitude of barriers hold back these organisations unless they have a very specific set of capabilities and a favourable local context (Department of Energy and Climate Change, 2013).

2.3. Business models and decision making

The development of local energy infrastructure is more complex than a simple decision to invest in a single technology. This is particularly the case when involving non-traditional actors who: have a broader range of motivations; target different customer segments; and target the creation of different forms of value, beyond economic outcomes (Foxon et al., 2015). Determining how to deliver benefits and capture value and with whom to engage (often referred to as a business model (Chesbrough and Rosenbloom, 2002; Teece, 2010)) is crucial to scaling up local infrastructure delivery and operation (Foxon, 2011; Hannon et al., 2013), but is frequently overlooked when analysing local infrastructure (Hall and Roelich, 2015). Therefore, it is important to understand heterogeneous non-traditional actors with different motivations and capabilities, who interact with other actors and organisations in the system.

The development of a viable local infrastructure business models requires instigators to navigate a series of project stages, including mobilisation, feasibility assessment, securing finance, procurement and operation (BRE, 2013). Decisions in relation to these project stages are made within the constraints of the social, technical and policy environment. Instigators' ability to navigate these stages will also be impacted by their experience and capacity, and the requirement for them to interact with other actors involved in heat network development, as well as with potential customers. It is therefore not an instantaneous decision nor is it undertaken based solely on techno-economic criteria. This makes analysis of how to accelerate scaling up more challenging than determining how to improve the financial viability of isolated investment decisions. Instead, it requires analysis of a process of connected decisions and interactions within a specific social, technical and policy setting.

2.4. Modelling approach

The great majority of modelling of energy system transition has focussed on techno-economic aspects of transitions. The purpose of these studies is to assess the impacts of a transition in terms of environmental impacts (mostly carbon emissions) and costs, or their technical or economic feasibility (Li et al., 2015). This overlooks the coevolution of techno-economic and social aspects of transitions, described in Section 2.3, that are essential to scaling up local energy infrastructure. An agent-based modelling (ABM) approach allows a better reflection of the complexities of local energy infrastructure business models and decision making than standard techno-economic modelling approaches (Chappin and Dijkema, 2008; van Dam et al., 2013). In such models, actors can be represented as heterogeneous agents with different heuristics, the ability to learn, and to interact with each other and their environment (Grimm and Railsback, 2005). The possible impacts of policy interventions can be investigated through scenario simulations where patterns of systemic behaviour emerge from individual agents' interaction and behaviours and the initial conditions of the environment.

ABM has been widely used to study socio-technical systems, including the adoption and diffusion of low carbon technologies (Eppstein et al., 2011; Faber et al., 2010; Hicks et al., 2015; Jensen et al., 2015; Maya Sopha et al., 2011; Robinson and Rai, 2015; Wolf et al., 2015). These studies demonstrate the effects of actor heterogeneity, learning and interactions between actors and within social networks but focus on technology adoptions, primarily by end-users. However, they neglect the role of supply chain actors which is of specific importance for analysing local energy infrastructure.

Researchers have recently begun to apply ABM to the long-term evolution of infrastructure systems (Bergman et al., 2008; Kempener et al., 2009; Knoeri et al., 2014; Rylatt et al., 2013, 2015; van Dam et al., 2013). These infrastructure-focused studies demonstrate significant progress in understanding how the impact of policy and social dynamics on supply chain actors' decisions influence the evolution of infrastructure systems. The majority of models include explicit actor heterogeneity (Li et al., 2015) but the distinction between heterogeneity of end-use demand actors and supply chain actors is not always clear. When analysing local energy infrastructure it is important to clearly articulate the heterogeneity of supply chain actor such as instigators of district-heating networks.

Furthermore, actors' decisions in these infrastructure models are still generally conceptualised as instantaneous actions to adopt a technology or practice (Bergman et al., 2008) or to trade, produce or consume energy in response to price signals (Rylatt et al., 2013) rather than a continuous development and engagement process.

3. Methods

The model we developed in this work addresses the gaps identified in Sections 2.3 and 2.4 by conceptualising development of local energy infrastructure as implemented by actors that follow individual project development timelines. The model takes an agent-based approach and is developed with the participation of stakeholders who are actively engaged in the development of district heating in the UK. In the following, we outline the model development and describe our model of heat network development, using data based on a UK city, and outline the underlying assumptions. The model description loosely follows the ODD (overview, design concepts and details) protocol (Grimm et al., 2010, 2006), by describing the model purpose, agents and entities included and the scheduling of actions taken by agents.[2]

[2] A complete ODD is included in the Supporting Information as Part A.

3.1. Model development

The decision processes and actor heuristics encoded in the model are based on qualitative data. The development of the model on a qualitative basis was done through a participatory process using companion modelling (Guyot and Honiden, 2006; Heckbert et al., 2010; Le Page et al., 2015; Moss, 2008). Two workshops with a group of stakeholders engaged with heat network projects, were held, using a decision theatre methodology (Walsh et al., 2013). The stakeholder group included representatives from local authorities, estates managers for organisations with potentially large heat demand (such as hospitals and universities), community organisations and consultants. The stakeholder group was first engaged in a workshop to validate[3] a conceptual model of the timeline of actions of instigating actors, and to identify the most significant barriers faced by these actors along this timeline and the capabilities they would need to overcome them. An operational model was then implemented based on this conceptual model. The second workshop with the stakeholder group was used to evaluate the operational performance of the model and develop and explore policy intervention scenarios to be tested. The details of how these workshops were used in the model development process are described elsewhere (Bale et al., 2015).

3.2. Purpose

The model is intended to enable exploration of the development of heat network business models at the city scale in the UK, and in particular how development can be accelerated. The focus is on the decisions and actions of local actors in developing projects, and there are four key features of business models that the agent-based model is designed to reflect:

Decision Chains – enacting a business model requires a sequence of actions, not single instantaneous actions.
Actor Heterogeneity – the actors that instigate and develop heat network projects have different institutional forms and capabilities, and their decision making can be based on different heuristics.
Actor Learning – actors build capacity through previously successful projects, increasing the likelihood of future success. Some agents influence others e.g. the local authority can support other actors.
Interaction – business models are not implemented in isolation, actors work in the context of a social and political environment and interact with other actors in their industry and with potential customers.

For the model to have explanatory power in relation to these features, significant simplifications are made in other domains. We do not aim to represent the technical details of developing heat networks, or provide a precise financial evaluation. Our purpose is not for the model to be predictive but to provide explanatory guidance for how policy can create a more supportive environment for local infrastructure development.

3.3. Agents, entities and scales

3.3.1. Agents

The model includes three basic types of entities: instigators, projects and grid cells (patches). Instigators represent the organisations driving the development of a project and are responsible for beginning the development process. Projects represent the project

[3] Conceptual validation is important for agent-based models where operational validation can be very difficult or even impossible. Stakeholder engagement in workshops is an established approach to carry out conceptual validation (Knoeri et al., 2011).

Table 1
Listing of instigator parameters including those related to instigator type, capabilities to complete development actions, and development and operational capabilities.

Parameters	Description	Value set
Instigator Type	The type of organisation that describes the instigator. This impacts on their actions in the development process.	{LA, Commercial, Community}
LA Type	*[Only applicable to LA instigator types]* The archetype that the instigator conforms to.	{Energy Leader, Running Hard, Starting Blocks, Yet to Join}
LA Strategy	*[Only applicable to LA instigator types]* LA actions that support heat network projects in the city e.g. heat mapping.	[0,1]
Idea rate	Building consensus within the organisation that a heat network project should be pursued.	[0,1]
Feasibility finance	Securing feasibility financing to carry out a feasibility study.	[0,1]
Capital finance	Securing capital finance for projects that are deemed to be economically feasible.	[0,1]
Procurement	Managing the procurement process with external contractors.	[0,1]
Contracts	Negotiation of contracts with customers and heat suppliers.	[0,1]
Development capacity	maximum number of simultaneous developments the instigator can support.	LA: 10 Commercial: 5 Community: 1
Operational capacity	maximum number of operational projects the instigator can support.	LA: 50 Commercial: 10 Community: 1

Table Notes: {…} denotes a discrete set of options, [0,1] denotes a value in the range 0–1 inclusive.

management entities and carry out actions on behalf of the instigator, deriving their characteristics and capabilities from their parent instigators. Patches represent the spatial units, which all together stand for the socio-technical environment of instigators and projects. The dynamics of the model are entirely driven by the actions of instigators and the projects they own.

Instigators have a set of parameters that influence their actions, summarised in Table 1. The parameters comprise three categories: first defining the type of instigators; second defining capabilities in completing project development actions; and third defining capacities for the number of simultaneous developments and operational projects.

We include three distinct types of instigators: local authorities, commercial developers and community organisations. These are chosen as representations of the types of organisations that can be involved in delivering and operating heat networks. We assume they differ in their decision making processes and their capabilities in completing actions in the project development process, reflecting the varying significance and severity of barriers identified in (BRE, 2013).

The model is run at the scale of a large UK city, which includes just a single local authority so only a single one of these instigators is included. The number of commercial and community instigators depends on the size of the city, and we base it on the number of commercial addresses and households respectively. For the city size we use to demonstrate the model in this paper, we include 12 commercial instigators and 32 community instigators.

Local authorities (LAs) are assumed to play an important role in urban energy infrastructure (c.f. Bale et al., 2012) and their level of engagement in heat network development is represented by the LA being assigned one of four archetypes: *Yet to Join*, *Starting Blocks*, *Running Hard*, or *Energy Leader*. These archetypes reflect the level of experience and knowledge the local authority has in energy infrastructure planning. The categories are taken from the work of Hawkey, Tingey and Webb on local engagement in energy systems (Hawkey et al., 2011). In the model, these archetypes determine the values of the *LA Strategy* and *Idea rate* capability parameters that the LA agent possesses.[4] The *LA Strategy* parameter is intended to reflect the local authority's concerted efforts to support the development of heat networks in the city through, for example, the development of city wide heat maps and energy masterplanning. This impacts on the action of securing feasibility financing that instigators must complete, through a reduction in the cost of feasibility studies. The *Idea rate* capability reflects the instigators ability to develop consensus across the organisation to pursue heat network development.

Commercial developer instigator agents represent private sector companies that install and operate heat networks. Like LAs, commercial instigators act across the full geographical extent of a city and are not tied to a particular location.

Community organisation instigators represent third sector organisations such as community groups, housing associations, tenant associations or cooperatives that are interested in taking action on energy provision or demand (c.f. Seyfang et al., 2013). We assume that these organisations exist in a specific geographical location and their actions are limited to this area. Community organisations are also assumed to attempt to develop a heat network project only once – following this they are removed from the model and a new community organisation is created in a new location. The choice of location for a community is made in the model on the basis of there being a sufficient density of private or social housing.[5]

Each instigator in the model has a set of 5 capabilities (i.e. idea rate, feasibility finance, capital finance, procurement, contracts) that determine their ability to complete set actions in the project development timeline. Different types of instigators possess these capabilities to a different extent. As the capabilities impact on the likelihood of completing an action we encode them on a scale of 0–1 for a probabilistic representation. The choice of capabilities to include in the model was made on the basis of a review of academic and grey literature, and the workshops used for the participatory model development.[6]

Each instigator continuously attempts to develop projects but they have a limited capacity to simultaneously develop and operate projects. These are represented by the development capacity and operational capacity parameters that are also listed in Table 1. The default values for these capability parameters, used in a baseline scenario, are shown in Fig. 1.

3.3.2. Passive entities

Aside from the active instigator agents, the model includes passive project and gird cell entities. The project entities, as already mentioned, carry out project development takes on behalf of the instigators. All other social, technical and financial characteristics of the system considered relevant are included as properties of the grid cells which represent the geographical landscape or as global model parameters. The model takes the geographical extent of a large UK city. With a model world consisting of 66×66 patches and the diameter of our demonstration city at approximately 33 km, each patch covers an area of about 25 ha.

We consider the relevant socio-technical characteristics for agent decision making to be:

- The presence of sufficient heat demand density to support a project
- the availability of ECO funding[7] for projects in eligible areas

[4] Details of these parameter settings for different LA types are given in Table 5 of the Supporting information.
[5] The threshold used for this and its value are described in Part A of the Supporting Information.
[6] Details of the workshop process are given in Part B of the Supporting Information.
[7] ECO (Energy Company Obligation) funding is a government scheme that obligates large energy suppliers to pay for energy efficiency measures in areas identified as having a

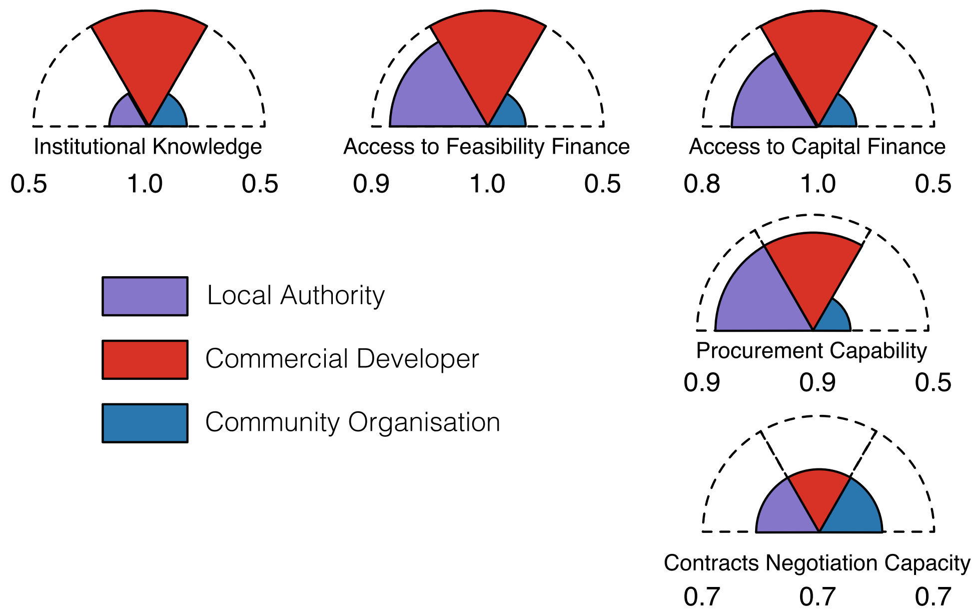

Fig. 1. Representation of the capability parameter values of the three instigator types as used in a baseline scenario..

(Department of Energy and Climate Change, 2012)

- the socio-economic characteristics of the area – namely whether there are significant levels of fuel poverty that could potentially be alleviated by a heat network.

For the model, the heat demand densities are derived from the number of households, number of commercial properties, number of public properties and large demand centres present in output areas.[8] The five categories we use (private households, social households, commercial addresses, public addresses and large demand centres) are derived from the address classifications used in the AddressBase database (Ordnance Survey, 2014), details of the mapping procedure used between AddressBase categories and ours are given in Part A of the supplementary materials. The level of fuel poverty and eligibility for ECO funding are derived from statistics that provide these at a lower level super output area scale (details of procedure and data sources again provided in Part A of the supplementary materials).

3.4. Heat network project development and process overview

This model is based on recognising that the development of heat networks involves a chain of decisions and actions that must be successfully passed for a heat network project to be completed. This is reflected in the model by a timeline of actions that instigator and project agents follow in developing projects. It is the enactment of this timeline that primarily drives the dynamics of the model.

Developing a successful heat network project is assumed to take a total of 4 years. This is split into a feasibility phase that is estimated to take six months (Ove Arup & Partners Ltd, 2011), and a procurement and build phase that is estimated to take 3 years to reflect a development timescale of 18–30 months (Ove Arup & Partners Ltd, 2011) extended to account for project expansion that is commonly carried out after approximately 19 months (BRE, 2013) but not otherwise represented in the model. The model is run over a suitably long time to allow for a transition pattern to emerge – 40 years, and one time step represents 3 months. We assume that all instigators are attempting to develop heat network projects each time step (i.e. every 3 months).

The actions included in the model timeline were selected on the basis of reflecting key points of failure for heat network project developments, as identified by previous studies (BRE, 2013; Hawkey et al., 2013; Poyry and Faber Maunsell, 2009) and our participatory process (details of which are described in Part B of the Supporting Information). To match the actions, instigators possess the set of capabilities described in Section 3.1 that determine how likely they are to be successful in completing each action.

Model simulation runs are initiated with a set number of each type of instigator present but no existing heat networks. A simplified timeline of actions followed from this point is shown in Fig. 2, split into three broad phases: an *Idea Phase* where instigators have the idea and build internal consensus, a *Feasibility Phase* where the feasibility of a project is determined, and a *Procurement and Build Phase*.

The success or failure of every action in a heat network project development can depend on a broad range of factors. We narrow this down in the model to three possible determining factors: the capabilities of the instigators, the physical and socio-economic characteristics of the landscape and interactions with other agents. The actions in each phase and their determining factors are now outlined.

3.4.1. Idea

Project development will only begin if the instigating agent has the capacity to develop further projects. The *get DH-idea* decision is the only one in this phase for which instigators have an associated capability, which is intended to reflect the organisations internal commitment to heat network project development. This decision is also influenced by learning from the instigators own previous success and the previous success of other instigators, this being an interaction with other agents.

The two actions following the *get DH-idea* decision in this phase, choosing a project location and setting its size depend only on the landscape and instigator type. These actions reflect the heterogeneity in decision heuristics between different instigator types: communities develop projects only at their location and do not develop large projects (defined by being connected to large demand anchors) and commercial instigators choose locations only on the basis of their private housing density whereas LAs also consider social housing density.

3.4.2. Feasibility

Determining the feasibility of a project requires three things: for a

(footnote continued)
high proportion of low income and vulnerable households.

[8] Output areas are defined using census records under guidance to contain approximately 125 households (Office for National Statistics, 2015).

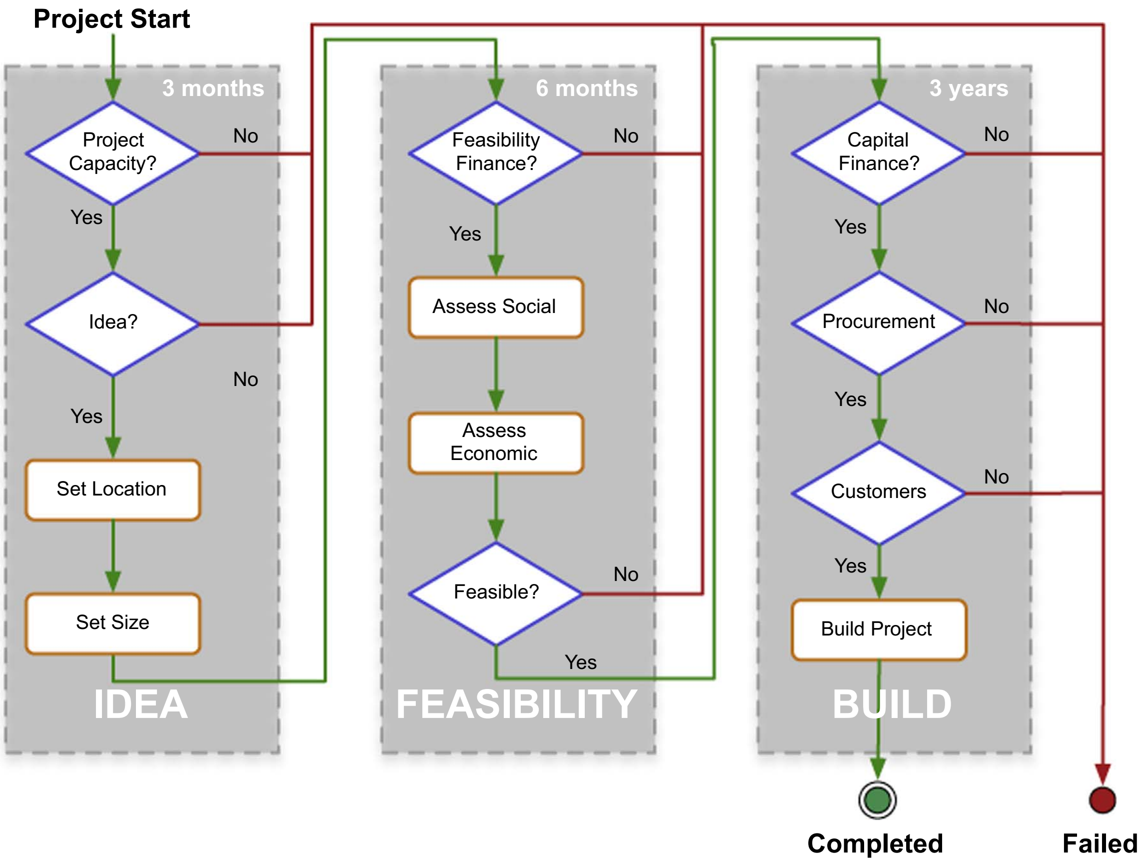

Fig. 2. Generalised state diagram for projects showing the sequence of actions (rectangles) and decision processes (diamonds) where a project can fail. The process is divided into three general phases: idea, feasibility and build. The Idea phase is completed in a single time step, taking 3 months, the feasibility phase takes 6 months and the build phase takes 3 years.

feasibility study the instigator must secure feasibility financing, social and economic outcomes have to be assessed, and the project must be considered feasible. Since feasibility funding has been identified as a key barrier (BRE, 2013) and already the focus of policy intervention (Department of Energy and Climate Change, 2015), we choose for this to be influenced by an instigator capability. Interventions to ease feasibility financing can include providing easier access to finance or reducing the cost of carrying out feasibility studies (e.g. by providing data and tools for heat mapping). This is implemented through the LA-strategy parameter, which affects the instigators' likelihood of getting feasibility finance to reflect the decreased cost and hence requirement for funding. The task of attaining feasibility financing is hence influenced by two separate parameters in the model: the feasibility finance capability parameter that the instigators possess, and the global LA-strategy parameter.

The actual feasibility study outcomes depend on the available heat demand and socio-economic characteristics of the chosen location and instigators attributes. In the model, this is reflected by a set of thresholds that vary depending on the heuristics used for decision making. Projects in a location where the heat demand density is above 260 MWh/ha/year[9] are deemed economically viable and pass as feasible by all three types of instigators. Projects in locations where the heat demand density is above 230 MWH/ha/year (approximately 10% lower than required for economic viability) and the proportion of households in fuel poverty exceeds 10% are deemed socially viable and LA and community instigators deem these as feasible; commercial instigators do not. The availability of ECO funding in the project location acts to reduce these thresholds by 10%.

3.4.3. Procurement and build

Although the procurement, contracting and building phase signify the completion of a project, the actions we include in this phase represent processes that take place throughout a project development. In reality, contract negotiations with possible customers and demand anchors begin at the very start of the process. Each of the three actions – capital financing, procurement and customer contracts – we have chosen to represent in the model constitutes a significant barrier and we hence associate an instigator capability with each of them. Each of these actions is also subject to the instigators gaining capacity through learning from previous success.[10] The representation of this phase strongly reflects the purpose of the model – it is simplified to focus on the institutional and governance barriers and the capabilities of instigators to overcome them.

3.5. Model scenarios

A set of scenarios that represent different possible policy interventions were developed in the second workshop described in Section 3.1. Policy interventions were first discussed by stakeholders and then implemented in the model by changing the instigator capability parameters and the LA-strategy parameter. This allows for a very flexible application of interventions by externalising the space for policy-to-action translation from the model. The complete set of scenarios proposed by stakeholders is included in Part C of the supplementary materials, here we focus on a selection of three

[9] This value is based on a 3000kW/km^2 calculated in a DECC report (Poyry and Faber Maunsell, 2009) and commonly quoted in industry guidance literature (Ove Arup & Partners Ltd, 2011).

[10] for details of the learning process and how it affects the capabilities of instigators, see Part A of the Supporting Information.

Table 2
Scenarios and the parameter values to implement them in the model..

Instigator	Parameter	Baseline	1: LA Strategy	2: Capital Finance	3: Communities
	LA Type	Starting Blocks	Starting Blocks	Starting Blocks	Energy Leader
	LA Strategy	0.6	1	0.6	1
LA	Idea	0.5	0.5	0.5	1
	Feas. Finance	0.9	0.9	0.9	0.9
	Cap. Finance	0.8	0.8	1	0.8
	Procurement	0.9	0.9	1	0.9
	Contracts	0.7	0.7	0.7	0.7
Commercial	Idea	1	1	1	1
	Feas. Finance	1	1	1	1
	Cap. Finance	0.9	0.9	0.9	0.9
	Procurement	0.9	0.9	0.9	0.9
	Contracts	0.7	0.7	0.7	0.7
Community	Idea	0.5	0.5	0.5	0.75
	Feas. Finance	0.5	0.5	0.7	0.9
	Cap. Finance	0.5	0.5	0.9	0.6
	Procurement	0.5	0.5	0.9	0.75
	Contracts	0.7	0.7	0.7	0.8

representative scenarios, in addition to a baseline. The scenarios included here where selected because they illustrate a diverse set of possible interventions and are motivated by clear narratives.

A summary of the selected scenarios with the LA Type, LA Strategy and capability parameter values used to implement them is shown in Table 2. The LA Type for the baseline is “Starting Blocks” as this is identified as the most common type by Hawkey et al. (2011), and this is retained in scenarios 1 and 2. Only scenario 3 includes an LA of a different type, namely an Energy Leader, which results in the LA Strategy and LA Idea rate parameters being set to 1.

Scenario 1, the “LA Strategy” scenario, is based on the simple intervention of forcing the LA to have a heat strategy, setting the LA Strategy parameter to 1. Scenario 2, the “Capital Finance” scenario focuses on increasing the availability of capital finance for all instigators. This is assumed to also result in easier access to feasibility financing for communities as they are more likely to access loans for feasibility studies with the decreased risk in subsequent capital financing, and increases in procurement capability due to access to consultants. LAs are assumed to not benefit in easier feasibility finance because access to capital finance was already less of a barrier to them than communities. Scenario 3, the “Communities” scenario, aims to support community instigators throughout the development process. This scenario includes a very proactive LA (*Energy Leader*) and support at every stage of the development. The idea rate is assumed to be boosted by awareness and information campaigns, government provides financial support for feasibility studies and underwriting for capital financing as well as producing standard forms for procurement and contracts.

4. Results

In this section, the results of running simulations of the baseline and policy intervention scenarios are presented. We begin by showing the results for the baseline scenario and then go on to the other three scenarios. The collated results for the number of completed projects by type at the end of the simulation runs for each scenario are shown in Fig. 3.

4.1. Baseline scenario and sensitivity analysis

Fig. 4 shows the result of a typical baseline simulation run showing how a large number of initialised projects that fail at the various stages of the development timeline resulting in only 40 projects that are eventually successful, over 40 years. These results are an aggregation of all projects without distinguishing between the different types of instigators for a single simulation run.

Due to the stochastic nature of the decision processes in the model there could be a high degree of variation between different model runs. This is illustrated in Fig. 5 which shows a box plot of the number of projects completed by instigator type for 100 runs of the baseline scenario, indicating the interquartile range and whiskers showing the

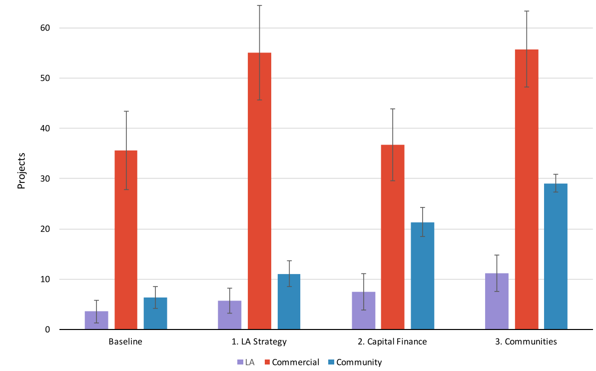

Fig. 3. Average number of completed projects under the baseline and three alternative scenarios. Bars show the mean of 100 simulation runs with error bars showing the sample standard deviation.

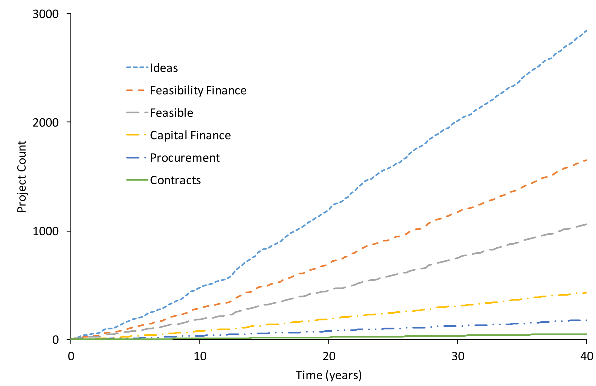

Fig. 4. Accumulated project developments for all instigators over the 40 year simulation run of the baseline scenario, showing the number of projects that have reached each action point in the timeline. In this run there were 40 successfully completed projects after 40 years.

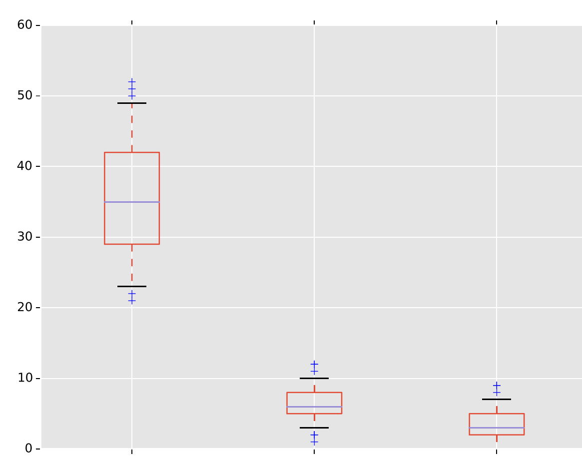

Fig. 5. Box plot of the number of projects completed over 40 year simulation runs by instigator type for 100 runs of the baseline scenario. The interquartile range is indicated by the box whiskers show the 95% confidence interval.

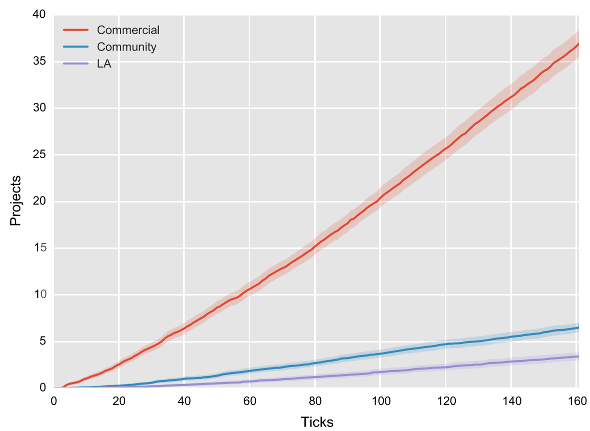

Fig. 6. Mean number of completed projects by instigator type for 100 simulations of the baseline scenario. A 95% confidence interval is indicated by the filled area around the lines.

95% confidence interval. A statistical analysis of the four scenarios shown in Fig. 3 shows that 100 runs is sufficient to show a statistically significant difference between the number of each type of project at the 95% significance level for all but the commercial project numbers in scenarios 1 and 3 (see Part B of the supplementary materials for details). Detailed sensitivity analysis was also carried out for each of the model parameters, and these are presented in Part B of the supplementary materials. We find that, as might be expected, the final number of completed projects is most strongly sensitive to the number and capacities of instigators active in a simulation, but also the learning rate experienced by instigators.

Fig. 6 shows the growth of successful projects for each instigator type over the simulation time for the baseline scenario, averaged for 100 runs. The slight upward curve of the line for commercial projects shows the effect of learning in the model. The same curve should be present in the lines for LA and community projects, but the numbers are too small to clearly show this. In the baseline scenario, commercial instigators are much more successful than both community instigators and the LA.

4.2. Scenario results

The LA strategy scenario is designed to reflect the local authority being mandated to have a heat strategy. In this scenario, the LA-strategy parameter is set to 1 and no other parameters are altered. The significance of this is that, although the LA is mandated to support heat network projects through a heat strategy, it does not have the internal commitment to carry this through for itself and the LA idea-rate parameter remains low to reflect this. The results of this scenario in Fig. 3 show that all three of the instigator types are more likely to be successful than in the baseline, showing an increase of more than 60%, 50% and 75% over the baseline for LA, commercial and community projects respectively. This reflects the positive impact of an LA strategy on the feasibility financing action that all instigators must carry out, although the instigators own capability in this phase has not changed from the baseline.

Scenario 2, “Capital Financing”, is designed to reflect increased access to capital financing for all instigators. The results show a significant increase in success for both the LA and communities, but no significant change for commercial instigators as these were already capable of raising capital finance in the baseline scenario. The time-series results of this scenario (Fig. 7) also show that community project success initially accelerates and then begins to saturate as most of the 32 community organisations in the model world already have completed projects.

The third scenario, “Communities”, is intended to represent a

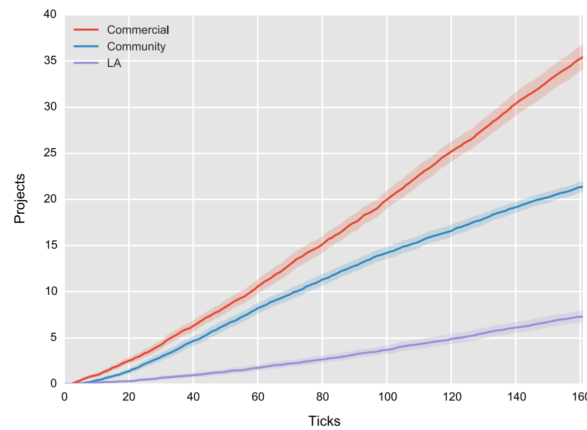

Fig. 7. Successful projects by instigator type for 100 simulation runs with the 95% confidence interval indicated for Scenario 2: Capital Financing.

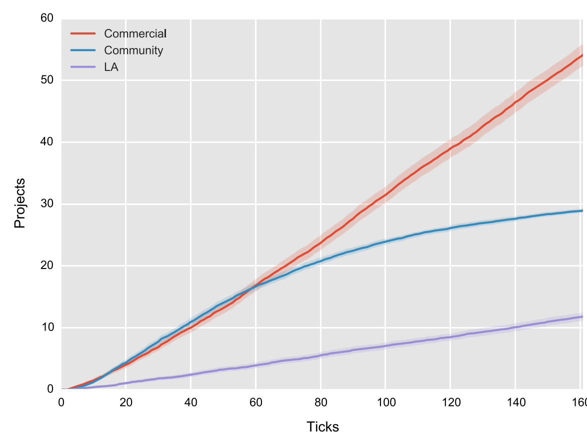

Fig. 8. Completed projects by instigator type for scenario 3, with 95% confidence interval indicated.

portfolio of support for community organisations. The results show a significant increase in success across all three instigator types. For the LA and commercial instigators, the increases can be explained by the LA-strategy and, just for the LA, by the idea-rate parameter changes. Fig. 8 shows that the community projects are highly successful early on, outstripping even commercial projects. They begin to tail off after 50 ticks only because the capacity for the 32 community instigators to develop projects begins to be saturated.

5. Discussion

The results described in Section 4 demonstrate some of the key concepts of the modelling approach when applied to the case of heat network development but these concepts have benefits that could be applied to other cases of local energy infrastructure, which we outline below. Furthermore, the model and scenario development point towards some generic policy recommendations that could accelerate the scaling up of local energy infrastructure. The model is not without its limitations so in Section 5.3 we summarise these limitations and discuss future work to extend the application of this modelling approach.

5.1. Key concepts

Using agent-based modelling, and the modelling approach used in this paper in particular, has several advantages over more conventional techno-economic analysis of local energy infrastructure business models. The three scenarios presented above were chosen to illustrate the key features that were described in Section 3.1. We now discuss each of these in relation to the results of the scenario simulations.

5.1.1. Decision chains

ability to represent a more complex decision making process. The development of new local energy infrastructure business models is represented as a series of decisions, not one individual decision. This allows us to more realistically reflect the stages of project and business model development and to incorporate time delays between decision stages. Importantly, it also allows us to represent the fact that different capabilities are required to pass different decisions. This is illustrated by the results of the baseline scenario in Fig. 4 showing the dropout of projects through the different phases resulting in only a small number of finally completed projects. This demonstrates the importance of improving the ability of instigators to navigate a series of project stages, not just removing isolated barriers. Overall the most successful scenario is scenario 3 which supports community instigators throughout the development process. Comparing this to scenario 2 where only capital financing was supported highlights how much more successful an approach that uses a portfolio of policies across the decision making process can be.

5.1.2. Actor heterogeneity

is implemented in two ways: firstly, we represent initiating actors as having different capabilities and thresholds which explains the different scale of projects and success rates between different instigator types and highlights different areas for intervention between instigators. Secondly, actors are characterised as having different criteria for specific parts of the decision process; representing a broader range of motivations than just economic. This second aspect is reflected, for example, in the results of scenario 3 where between 25–30% of LA and community projects are feasible only because they address fuel poverty. These projects would not have been developed by a commercial instigator.

5.1.3. Actor learning

as an actor successfully develops projects, their capacity to develop projects and capabilities required to pass subsequent decision processes increase, asymptotically reaching a maximum. This allows us to represent the increasing capabilities that arise from experience of successful projects. This is illustrated by the upward sloping curve of completed projects over time in, for example, Fig. 6.

5.1.4. Interaction between actors

we represent the important strategic role of local authorities by reducing barriers to feasibility analysis if a co-ordinated strategy is available (Bale et al., 2012) through the provision of data at reduced cost. Scenario 1 illustrates the effect of a local authority strategy, showing that this interaction between the local authority and the other two instigators has a significant effect. We also include for knowledge transfer between actors – showing an increase in capabilities if local authority projects are successful to represent the increase in knowledge and confidence if there are successful pilot projects nearby.

5.2. Policy implications

The approach to simulation used in the model presents advantages for both national and local policy makers who are exploring how to create more supportive conditions for local energy infrastructure business models. We specifically chose to parameterise solutions using generalised, not policy specific inputs and as a result have not limited model simulation to application of prescribed policy levers. This creates a very broad space for simulation, in which policy makers can change any number of conditions and analyse the consequences. The model will not make the link between the change in conditions and the specific policy instruments; it is up to the user to define how policies will result in the specific changes they implement. In this way it is not dissimilar to experimental science (Bankes, 2009) and is a quick and effective way to conduct systematic and controlled, what-if analyses to explore the effects of different policies (Holtz et al., 2015). This means that the model can not only be used to assess policy effectiveness but could also encourage a re-assessment of the nature of policy intervention itself (Gilbert and Bullock, 2014).

The scenarios explored by stakeholders during model development represented a wide range of policies and policy approaches and allow us to propose some generic policy implications to create a more supportive environment for local infrastructure business models. These include:

- The importance of creating policy specific to the motivations and capabilities of different actors. The decision making processes of local authorities and community groups are based much more strongly on creating social value, therefore policies which target carbon emissions or techno-economic criteria could be less effective for these groups. Furthermore, the capabilities of the different instigators differ significantly, with some groups requiring support at different stages of the decision process. Policy support should recognise the heterogeneity of project instigators and provide support specific to those instigators.
- The need to enable learning. Agents in the model are both social and adaptive (Gilbert and Bullock, 2014) which provides an additional route through which to increase capabilities. A focus on enhancing capabilities through networking and learning could accelerate the rate of development of local infrastructure business models.
- The significant, strategic role of local authorities. Local authorities can increase the rate of idea formation and reduce the costs of feasibility studies by developing authority-wide strategies and datasets (Bale et al., 2012). They can also increase confidence in other instigators by leading early stage projects. Their strategic and leadership roles should be encouraged and supported to accelerate the positive effects of interaction with other actors.
- Supporting all stages of the decision process. Interventions which targeted individual stages of the decision process had limited impact on increasing the development of local infrastructure business models. This is because the development of local business models is made up of a series of stages, which must all be completed for a project to be successful. If success at one stage is increased it will increase the number of projects in the pipeline but subsequent stages still need to be passed. A more systemic approach, which recognises that a range of capabilities and decision stages must be addressed, is more likely to be successful.

The model allow users to move beyond simple linear, cause and effect thinking and using extrapolation of existing trends to explore future system behaviour (Ligtvoet and Chappin, 2012). Representing heterogeneity and interaction allows us to more effectively explore the emergent patterns of behaviour that result from this interaction as well as from feedback, time delays and non-linearity (Holtz et al., 2015). This could result in new, more effective approaches to policy intervention, which reflect the complex and interconnected nature of local infrastructure business model evolution.

5.3. Model limitations and further research

The model we have developed here is tailored to address a specific purpose, and strategically limited in its complexity to avoid losing explanatory power. As a result, the conceptualisation of the system that underpins the model was formulated with reduced technical complexity and limited interaction between actors. In the following we reflect on these limitations and those arising from limited data availability.

Technical complexities could include a more detailed modelling of heat networks technical attributes such as the length of pipes and capacities of boilers needed for different projects. Further, dynamic building stock would provide a more accurate basis for the likely development rate of projects instigated by commercial developers as new development projects might provide an excellent opportunity for district heat networks. A third technical complexity neglected was the continuous extension of existing heat networks. For all three characteristics considerable variations between projects and over time have been found in regions with high district heating adoption rates (e.g. Hecher et al., 2016). In this research these characteristics were intentionally neglected because it was assumed that they add significantly more complexity than affecting the conditions for business models. However, the model could benefit from such extension, especially regarding the future analysis of scale and spatial distribution of projects.

Given the explorative character of this study and its focus on policy interventions on acceleration of heat networks we choose to limit the complexity of interaction between actors involved. In reality, heat network project development involves interaction between many different actors including the instigator, consultants, major stakeholders, suppliers, costumers, etc. throughout the development process (Bale et al., 2012). Many heat network projects started by LAs adopt business models in partnership with commercial developers. Representing these types of relationships in the model would result in significantly increased complexity, but also in the potential to address barriers beyond instigators' capabilities. Given that agent-based modelling is particularly suited to address complex actor interactions this would be a promising avenue for further research.

A further significant limitation for this kind of modelling (i.e. adoption of emerging technologies or business models) is in the lack of data available for validation and calibration. Whilst some data is available on the number and scale of projects that are successful (BRE, 2013), knowing how or where projects have failed is more difficult to capture. Furthermore, the prospective nature of the modelling endeavour makes empirical validation as suggested for example by Janssen and Ostrom (2006), close to impossible. In response to this, we have adopted a participatory approach to model and scenario development that uses expert stakeholders in conceptual and operational validation of the model. This corresponds to proposed alternative approaches to empirical validation of agent-based model (Moss, 2008), such as companion modelling (Bousquet et al., 2007) or general participatory modelling approaches (Garrod et al., 2013). Both approaches generally stress the increasing importance of the conceptual models validation compared to operational validation as highlighted by Knoeri et al. (2011). It is important to note, however, that a model developed on this basis can provide valuable insights into the types of interventions policy makers can make to create a supportive environment for heat networks, but it cannot provide realistic and quantified forecasts.

6. Conclusions

Local energy infrastructure can contribute to many of the principal aims of energy policy but faces several barriers to being scaled up. In this paper we explore the impact of removal of barriers to local energy infrastructure delivery and how its contribution to energy policy aims can be accelerated.

Local energy infrastructure can involve non-traditional actors, who are motivated to deliver a broader range of benefits (such as fuel poverty alleviation), create different forms of value (beyond economic outcomes), and have different capabilities and experience. This means that an understanding of business models – how to deliver benefits and capture value – is crucial to analysis of how to accelerate local energy infrastructure development but is overlooked in the majority of studies. Therefore, new analytical approaches are needed that go beyond techno-economic energy system modelling.

In this article we describe a model that has been developed to enable the exploration of local energy infrastructure with a specific focus on heat networks to illustrate the benefits of our approach. The modelling approach employed addresses a series of limitations identified in existing modelling of energy system transitions;.

- it recognises that instigators must navigate a series of project stages, rather than making an isolated decision to invest in or adopt a technology;
- it represents decisions as being taken within the constraints of social, technical and policy environments, rather than being a purely techno-economic decision;
- it reflects the differing capabilities of different instigators and the impact these capabilities have on their ability to pass certain decision stages;
- it requires them to interact with other instigators and supply chain actors; and
- it enables them to learn from experience or from interaction with other instigators to increase their capabilities.

This not only provides a more accurate representation of the system but also provides advantages when identifying policy implications and potential interventions. Firstly, we identified the need for systemic intervention and policy portfolios that support multiple stages of the decision process and increase the different capabilities required at different stages. Secondly, that policy may need to be specifically targeted at different instigators as a result of their differing capabilities and motivations. Thirdly, that support for networking and learning could be an effective way to increase capabilities and project success rates. Finally, our work highlighted the important strategic role of local authorities in co-ordinating and promoting local energy infrastructure.

Whilst this research uses the case of heat networks to demonstrate the advantages of our modelling approach these principles and advantages could apply to other forms of local energy infrastructure and local infrastructure more broadly.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2016.10.011.

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