Barriers and drivers of retrofit: a methodological proposal for studying the diffusion of energy-saving measures in UK housing

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I. Introduction

As is the case for many industrialized countries with a temperate climate, the UK's residential buildings contribute a large share of national energy consumption and CO2 emissions (Ürge-Vorsatz et al 2015)[1]. In 2014, the UK's housing stock accounted for 29% of total final energy consumption and 12% of national GHG emissions, second only to travel (Department for Energy and Climate Change 2015)[2]. Wealth inequality issues compound the environmental impact of housing, as shown by the correlation between household emissions and income, with the highest-income households emitting twice as much as the poorest 10% (Preston et al. 2013)[3].

The UK's major policy for advancing energy efficiency in existing building stock is the Energy Company Obligation (ECO), which has been running since 2012. Although successful in the mass deployment of certain retrofit measures, the policy has been challenged in the installation of measures suitable for hard-to-treat homes, such as solid wall insulation (Fig. 1). The challenges faced by the ECO has resulted in ongoing low building energy performance and continued fuel poverty, with 40% of properties in England and Wales retaining Energy

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[1] Ürge-Vorsatz, Diana, Luisa F. Cabeza, Susana Serrano, Camila Barreneche, and Ksenia Petrichenko. 2015. "Heating and Cooling Energy Trends and Drivers in Buildings." *Renewable and Sustainable Energy Reviews* 41 (January): 85–98. doi:10.1016/j.rser.2014.08.039.

[2] Department of Energy and Climate Change. 2015. "Green Deal and Energy Company Obligation Annual Update 2015." 10 November. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/476863/UnAct_GreenDeal_Accessible.pdf.

[3] Preston, Ian, Vicki White, and Katharine Blacklaws. 2014. "Fuel and Poverty." Joseph Rowntree Foundation Centre for Sustainable Energy. www.cse.org.uk.

Performance Certificates (EPC) of E or lower (based on CO_2 emissions) and 2.3 million English households remaining in fuel poverty, in 2014 (DECC 2016)[4]. According to a report by the Tyndall Centre (2016)[5] a substantial number of homes still require basic improvements for energy savings, including interventions to the building fabric, to which the ECO has contributed only a small percentage.

The challenges of advancing the retrofit transition under the ECO, alongside the failure of previous schemes such as the Green Deal, suggest the existence of a number of barriers to the deployment of energy-saving measures in UK households. These manifest themselves at the consumer (e.g. Caird et al. 2008)[6], investor (e.g. Dowson et al. 2012)[7] and political (e.g. Steg 2008)[8] level alike, and do not appear to be adequately addressed in policy design and implementation, whose main focus has been to support the financing of retrofit and remove cost-related barriers**.** Arguably, cost and financing barriers are major factors contributing to the slow diffusion of particularly expensive retrofit measures, however they are not unique nor isolated from a range of other social, cultural, institutional and political barriers (Mallaburn and Eyre 2014)[9]. The problem of retrofit diffusion has yet to be addressed from a holistic perspective which analyses the existing barriers as part of a heterogeneous, complex system, where they manifest themselves at different levels and to different actors in the retrofit sector.

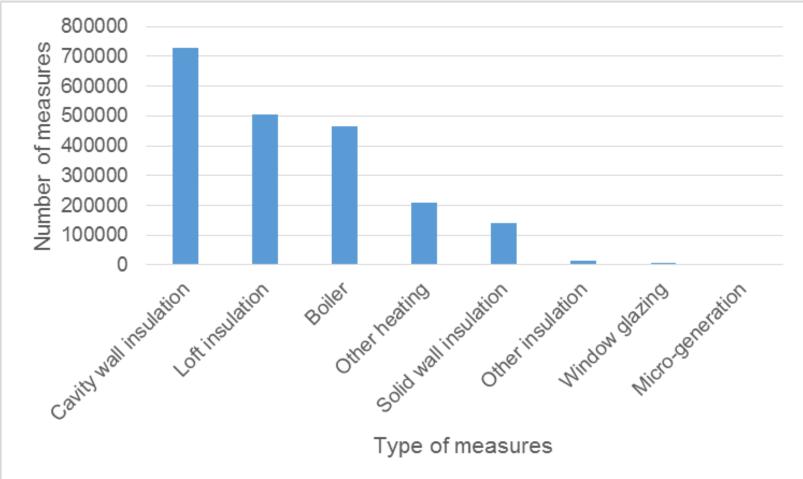

Figure 1. Number of measures installed under the ECO between 2012 and 2017.

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[4] Department of Energy and Climate Change. 2016. “Annual Fuel Poverty Statistics Report, 2016 – England.” 30 June. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/557400/Annual_Fuel_Poverty_Statistics_Report_2016_-_revised_30.09.2016.pdf

[5] Urbed and Carbon Co-op. 2016. “Retrofit factfile”. Available at: http://carbon.coop/sites/default/files/attachments/2016-09-12/2016%20URBED%20Tyndall%20The%20Retrofit%20factfile%20-%20facts%20and%20publications.pdf

[6] Caird, Sally, Robin Roy, and Horace Herring. 2008. “Improving the Energy Performance of UK Households: Results from Surveys of Consumer Adoption and Use of Low- and Zero-Carbon Technologies.” *Energy Efficiency* 1 (2). Springer Netherlands: 149–66. doi:10.1007/s12053-008-9013-y.

[7] Dowson, Mark, Adam Poole, David Harrison, and Gideon Susman. 2012. “Domestic UK Retrofit Challenge: Barriers, Incentives and Current Performance Leading into the Green Deal.” *Energy Policy* 50 (November): 294–305. doi:10.1016/j.enpol.2012.07.019.

[8] Steg, Linda. 2008. “Promoting Household Energy Conservation.” *Energy Policy* 36 (12): 4449–53. doi:10.1016/j.enpol.2008.09.027.

[9] Mallaburn, Peter S., and Nick Eyre. 2014. “Lessons from Energy Efficiency Policy and Programmesin the UK from 1973 to 2013.” *Energy Efficiency* 7 (1). Springer Netherlands: 23–41. doi:10.1007/s12053-013-9197-7.

The current challenges on the ECO make it imperative that policy design and implementation are assessed on the basis of a deep understanding of the UK residential retrofit sector and the barriers which it faces as a supplier and user of energy-saving measures. The premise of this project is that the diffusion of mature retrofit measures is shaped by non-techno-economic barriers and drivers. The objectives of the research are to identify and analyse these barriers and drivers related to the most common retrofit technologies present in the UK residential sector, as perceived by the main actor groups operating in the sector. These groups have unique thresholds and constraints for overcoming barriers and responding to drivers, in order to progress their decision-making with regards to participation in the retrofit process. The groups interact with each other and with the retrofit technologies, based on their pre-existing relationships, as well as their individual attitudes and norms. The diffusion of retrofit technologies is thus subject to complex rules of actor behaviour and interaction, and its analysis must be based on empirically-grounded frameworks capable of handling these behaviours, occurring within the adaptive boundaries of an evolving sector.

II. Theoretical background

The diffusion of "clean" energy technologies, such as retrofit measures, can only be understood if it is analysed against a robust, systemic understanding of sustainability transitions. The application of sustainability transitions theory to this innovation diffusion enables the deeper understanding of technological and socio-economic dynamics, as well as the linkages between networks of actors in a system (Ruth et al. 2011)[10]. However, it is not sufficient for the diffusion to be qualified and characterised through transitions theories; rather, it must be translatable as an input into quantitative modelling frameworks, in order to contribute to the energy scenario analysis over a range of timescales. This section presents a brief theoretical background to the two main transition theories employed in this research, and to the conceptual modelling framework selected for further simulation of the retrofit sector.

II.1 Transition theories

The main class of sustainability transitions theories which incorporate the necessary holistic view of innovation diffusion are the systems innovation frameworks (Elzen, Geels and Green 2004)[11]. From this class, the socio-technical systems (STS) approach and actor-network theory (ANT), part of the Science and Technology Studies sub-class, were selected for application to the analysis of the UK retrofit sector. The selection of these frameworks was based upon their ability to analyse the diffusion of technologies into a system of heterogeneous actors and complex relationships, and the resulting transformation of the system. Table 1 outlines the different systems innovation frameworks and their main characteristics.

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[10] Ruth, Matthias, Eugenia Kalnay, Ning Zeng, Rachel S Franklin, Jorge Rivas, and Fernando Miralles-Wilhelm. 2011. "Sustainable Prosperity and Societal Transitions: Long-Term Modeling for Anticipatory Management." *Environmental Innovation and Societal Transitions* 1: 160–65. doi:10.1016/j.eist.2011.03.004.

[11] Elzen, Boelie, Frank W. Geels, and Kenneth Green. 2004. *System Innovation and the Transition to Sustainability : Theory, Evidence and Policy*. Edward Elgar. https://books.google.co.uk/books?hl=en&lr=&id=lEb7LWOcQXsC&oi=fnd&pg=PR7&dq=transition+management+theory&ots=tK-KMl5fBS&sig=eUmxh1FtjCQvnQLMOFbAO0HuJSQ#v=onepage&q=transition management theory&f=false.

Socio-technical systems (STS) approach

The STS approach was selected as the most appropriate framework to define the current situation of the UK retrofit sector, while accounting for the heterogeneity of the actor network responding to innovation diffusion. This framework argues that systems are the product of heterogeneous actor activities, and that the successful diffusion of a technology is reliant on its alignment with these activities, which results in a system transformation (Geels 2002)[12]. The STS framework can be analysed through a three-tier perspective with the following levels:

i. Technological niches, which are incubation spaces where innovation occurs radically and disruptively. Niches are the location of learning processes, but also of emerging, precarious social networks such as new supply chains. They are rapidly adaptive loci of production, where deviation from components is not difficult.
ii. Socio-technical regimes, which are semi-coherent sets of rules produced by distinct social groups and which exist in a dynamic stability where innovation occurs incrementally. They have a higher structuration than niches and are characterised by multiple inter-linked trajectories (scientific knowledge, technology, markets, culture etc.), created by actor activities. The rules determine perceptions, expectations and activities of actor groups, and deviation from them is difficult.
iii. Socio-technical landscapes, consisting of deeply embedded structures and slow-changing factors such as long-term economic development, large material constructs or widely shared cultural beliefs, but also global shocks such as wars and price recessions, which impact the regime. Landscapes have the highest structuration of all 3 levels, and deviation from their components is very difficult.

Framework	Characteristics
Point-source approaches	
Technology life cycle	Focuses on technology evolution journey Primarily interested in market structure and firm strategies Little focus on wider socio-economic system
Economic path-dependence	Like technology life-cycle, but incorporates organisational processes, network externalities and informational increasing returns Relevant for the diffusion of new technologies Little focus on wider socio-economic system
Science and technology studies	Focus on socio-cognitive processes Introduce the idea of linkages between artefacts and system components Characterises the technological diffusion journey as a change in system configuration Little focus on wider technological displacement processes The three main theories (Sociology of Technology, Large Technical Systems and ANT) use different indicators to measure technological diffusion

[12] Geels, Frank W. 2002. “Technological Transitions as Evolutionary Reconfiguration Processes: A Multi-Level Perspective and a Case-Study.” *Research Policy* 31: 1257–74. http://doc.utwente.nl/58685/1/Geels02technological.pdf.

Replacement approaches	
Technological/economic substitution	Focuses on substitution of old by new technologies, competition and disruptive innovation Operates mostly at meso and macro level Focuses on replacement, little concern with the diffusion of new technologies Criticised as technologically deterministic
Punctuated equilibria	Characterises technological development as an evolutionary process punctuated by disruptive innovation Assumes instantaneous replacement of old technologies by innovations Assumes that the system is in equilibrium until the appearance of a disruptive innovation Neglects the possibility of innovation being triggered by non-technical drivers
Long-wave theory	Focuses on long-term, economy-wide technological changes (techno-economic paradigm shifts) occurring as a reaction to issues of an existing paradigm Proposes that innovation diffusion is a result of cross-sectoral clustering of materials and technologies Criticised as treating technological change superficially and not accounting for social innovations, institutional and market shifts and political changes as drivers of innovation
Transformation approaches	
Sociological literatures	Focus on user side of innovation diffusion Incorporates the gradual nature of cognitive changes leading to system transformation Limited characterisation of actor interaction
Socio-technical systems	Focus on user side of innovation diffusion Incorporates process alignment as a component of system transformation following innovation diffusion Accepts analysis through a multi-level perspective Much broader consideration of the societal context More sensitive to process alignment as part of innovation pathway

Table 1. Characteristics of the main systems innovation frameworks (Elzen, Geels and Green 2004)[11].

The 3 levels of the STS approach are proposed to exist in a form of "nested hierarchy", leading to a multi-level perspective (MLP) on innovation diffusion (Fig. 2), which is one of the most strongly featured approaches in sustainability transition theories (Li et al 2015)[13]. The diffusion of technologies is viewed as the emergence of a dominant design from the niche level, when the regime offers a window of opportunity. This is followed by competition between the innovation and the existing regime, which results in replacement only when the trajectories of the regime have been shifted and aligned with the needs of the innovation (e.g. necessary supply chains or regulations), i.e. when the niche is "empowered" (Haxeltine et al 2008)[14]. Following this alignment and stabilisation of the new regime, it may exert pressure on the socio-technical landscape and cause an eventual change in its structure.

[13] Li, Francis G.N., Evelina Trutnevyte, and Neil Strachan. 2015. "A Review of Socio-Technical Energy Transition (STET) Models." *Technological Forecasting and Social Change* 100 (November): 290–305. doi:10.1016/j.techfore.2015.07.017.

[14] Haxeltine, Alex, Lorraine Whitmarsh, Noam Bergman, Jan Rotmans, Michel Schilperoord, and Jonathan Köhler. 2008. "A Conceptual Framework for Transition Modelling." *Int. J. Innovation and Sustainable Development* 3 (12). http://www.inderscienceonline.com/doi/pdf/10.1504/IJISD.2008.018195.

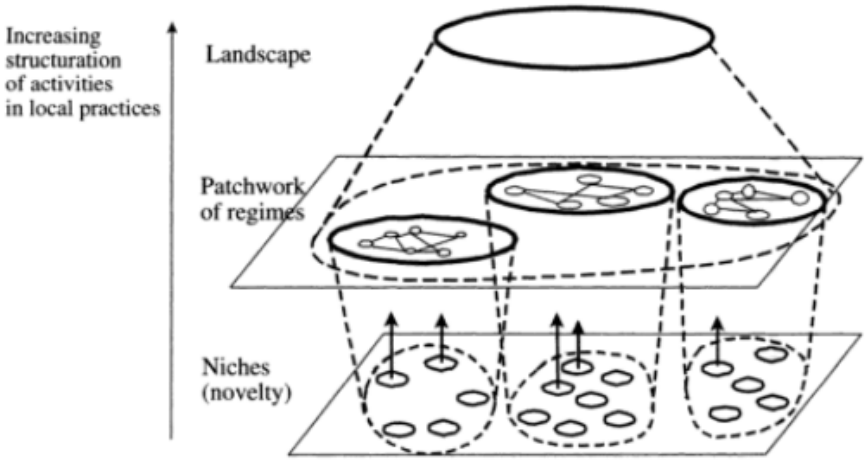

Figure 2. The 3 main levels of the STS framework (Geels 2002)[11].

The STS framework has been applied to explain multiple transitions, ranging from the emergence of individual innovations, such as the automobile (Geels 2004)[15], to the evolution of large-scale systems such as electricity networks (Verbong and Geels 2007)[16] and even the breakthrough of musical trends (Geels 2007)[17]. In the context of this research, STS is a particularly suitable framework for application, due to its representation of complex actor networks, such as those operating in the fragmented supply chain of the UK retrofit sector (Gooding and Gul 2017)[17]. It is also capable of representing the behavioural strategies and interactions of different actor groups, which is particularly important in the case of end-user groups (tenants and homeowners), whose energy consumption patterns form a core behaviour and are heavily influenced by their cultural and social interactions (McMichael and Shipworth 2013)[18]. Lastly, with the diffusion of retrofit being heavily affected by a number of non-technical factors, it is essential that the political, economic, social and cultural trends are analysed in tandem with the techno-economic characteristics of the diffusing technology; this is offered by the STS approach through its definition of trajectories at the regime level.

[15] Geels, Frank W. 2004. "From Sectoral Systems of Innovation to Socio-Technical Systems Insights about Dynamics and Change from Sociology and Institutional Theory." *Research Policy* 33: 897–920. doi:10.1016/j.respol.2004.01.015.

[16] Verbong, Geert, and Frank Geels. 2007. "The Ongoing Energy Transition: Lessons from a Socio-Technical, Multi-Level Analysis of the Dutch Electricity System (1960–2004)." *Energy Policy* 35 (2): 1025–37. doi:10.1016/j.enpol.2006.02.010.

[17] Gooding, Luke, and Mehreen S. Gul. 2017. "Achieving Growth within the UK's Domestic Energy Efficiency Retrofitting Services Sector, Practitioner Experiences and Strategies Moving Forward." *Energy Policy* 105 (June): 173–82. doi:10.1016/j.enpol.2017.02.042.

[18] McMichael, Megan, and David Shipworth. 2013. "The Value of Social Networks in the Diffusion of Energy-Efficiency Innovations in UK Households." *Energy Policy* 53. Elsevier: 159–68. doi:10.1016/j.enpol.2012.10.039.

Actor-network theory

Although the STS framework is a powerful theory for analysing the UK retrofit sector and its dynamics, it suffers from several drawbacks, three of which are of particular concern to this research. Firstly, it lacks a theoretical foundation for actor behaviour, at a micro-level (Ulli-Beer 2005)[19]. Secondly, the MLP tends to be biased towards the innovation itself, which must be overcome through explicit focus on the ongoing regime-level processes (Geels 2005)[20]. Finally, the STS framework cannot readily handle the simultaneous diffusion of multiple technologies. Similar to many sectors (Geels 2005)[21], it is likely that the diffusion of retrofit measures in the housing sector will occur through the combination of multiple mature technologies; for example, through deep, whole-house retrofit interventions. The framework for analysis for this sector should, therefore, incorporate the capability of analysing the diffusion of multiple, interacting technologies.

In this research, actor-network theory (ANT) is proposed as an addition to the STS framework which addresses some of these drawbacks. First proposed in the 1980s, this theory was evolved in tandem with the development of the social constructivist school of thought (Miettinen 1999)[22], and its fundamental premise is that innovation consists of artefact development, simultaneous with the development of a network of actors and resources around said artefact (Latour 2005)[23]. It is part of the Science and Technology Studies sub-class of system innovation frameworks, along with the LTS and SCOT theories (Elzen, Geels and Green 2004)[11].

Many of the assumptions and characteristics of ANT derive from the idea of “linkages”, or connections formed between a diffusing technology and actors, under the pressures of innovation (Elzen, Geels and Green 2004)[11]. The underlying hypothesis of the framework is that, following the emergence of an innovation, system elements gradually link together in a co-evolutionary process, resulting in a stable end configuration. There is a noticeable transition from the initial stages, where linkages are heterogeneous and sparse, to the final stages, where linkages are consistent and numerous, of an artefact (Law 1992)[24]. Thus, innovation is related to the accumulation of elements and the formation of linkages as part of an operational socio-technical configuration. Furthermore, the focus of ANT is on the linkages between human and non-human actors, i.e., in this case, actors and diffusing technologies (Latour 2005)[23].

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[19] Ulli-Beer, Silvia. 2005. “Dynamic Governance of Energy Technology Change,” 206. doi:10.1007/978-3-642-39753-0.

[20] Geels, Frank W. 2002. “Technological Transitions as Evolutionary Reconfiguration Processes: A Multi-Level Perspective and a Case-Study.” *Research Policy* 31: 1257–74. http://doc.utwente.nl/58685/1/Geels02technological.pdf.

[21] Geels, Frank W. 2005. *Technological Transitions and System Innovations : A Co-Evolutionary and Socio-Technical Analysis*. Edward Elgar..

[22] Miettinen, Reijo. 1999. “The Riddle of Things: Activity Theory and Actor-network Theory as Approaches to Studying Innovations.” *Mind, Culture, and Activity* 6 (3). Taylor & Francis Group : 170–95. doi:10.1080/10749039909524725.

[23] Latour, Bruno. 2005. *Reassembling the Social : An Introduction to Actor-Network-Theory*. Accessed August 10. https://books.google.co.uk/books?hl=en&lr=&id=AbQSDAAAQBAJ&oi=fnd&pg=PR7&dq=actor+network+theory+latour&ots=9i-RCo0fBN&sig=k4zbu5sgpV5O5U4VgqWYHFADppU#v=onepage&q=actor network theory latour&f=false.

[24] Law, John. 1992. “Notes on the Theory of the Actor-Network: Ordering, Strategy and Heterogeneity” 5: 379–93. http://ww.heterogeneities.net/publications/Law1992NotesOnTheTheoryOfTheActorNetwork.pdf.

ANT has been applied to explain a variety of transitions, from the failure of metro systems in Paris (Latour 1996)[25] and the modernisation of big IT programmes in the UK National Health Service (Greenhalgh and Stones 2010)[26] to wider studies of urban architectural practices (Farias and Bender, 2010)[27]. Although presented as a theory, ANT is better defined as a methodological approach which enables the application of analytical tools to narrative knowledge (Alcadipani and Hassard 2010)[28]. It is challenged by several identified problems: the lack of definition of the nature and scope of actor groups, the exclusion of "silent" actors (those not classified as innovators, managers or politicians) and the lack of provision of a model for human behaviour (Miettinen 1999)[22]. The first two gaps can be addressed through the accurate mapping of the actor network present in the identified socio-technical regime, accounting for passive, as well as active, actor groups, in order to not exclude "silent" communities. The last gap must be addressed through the provision of a behavioural model supporting the characterisation of actor groups, based on their pre-defined attitudes and beliefs, as well as their linkages with each other and with the technology in question. By combining ANT with the STS approach and a behavioural modelling framework (Section II.2), these problems can theoretically be overcome, allowing for a comprehensive analysis of a specific sector of innovation.

II. 2 Agent-based modelling

There is a need for the extension of quantitative energy modelling frameworks from the simulation of purely technical and economic factors, to include social and behavioural aspects. Several studies have applied STS approaches to the development of energy modelling frameworks, but there is still a wide scope for incorporating the constructs of socio-technical transition theories into quantitative simulations (Pfenninger et al, 2014)[29]. Sector-specific energy models, including those focusing on buildings, tend to exclude the behaviour of heterogeneous actors from the quantitative analysis, incorporating it instead into the qualitative narrative accompanying the model (Li et al 2015)[13]. On the other hand, technology diffusion models adequately simulate the heterogeneous behaviour of actors over long timescales, but treat the uptake of technology as a binary choice, similar to the class of replacement sustainability transition theories (Table 1). In order to map the UK retrofit sector, as a socio-technical system, to an energy modelling framework, there is need for a model which adequately incorporates a portfolio of technologies, heterogeneous actors with complex relationships and a long time horizon (Li et al 2015)[13]. We focus on agent-based modelling

[25] Latour, Bruno. 1996. *Aramis, Or, The Love of Technology*. Harvard University Press. http://www.hup.harvard.edu/catalog.php?isbn=9780674043237.

[26] Greenhalgh, Trisha, and Rob Stones. 2010. "Theorising Big IT Programmes in Healthcare: Strong Structuration Theory Meets Actor-Network Theory." *Social Science & Medicine* 70 (9): 1285–94. doi:10.1016/j.socscimed.2009.12.034.

[27] Farias, Ignacio, and Thomas. Bender. 2010. *Urban Assemblages : How Actor-Network Theory Changes Urban Studies*. Routledge.

[28] Alcadipani, Rafael, and John Hassard. 2010. "Actor-Network Theory, Organizations and Critique: Towards a Politics of Organizing." *Organization* 17 (4). SAGE PublicationsSage UK: London, England: 419–35. doi:10.1177/1350508410364441.

[29] Pfenninger, Stefan, Adam Hawkes, and James Keirstead. 2014. "Energy Systems Modeling for Twenty-First Century Energy Challenges." *Renewable and Sustainable Energy Reviews* 33 (May): 74–86. doi:10.1016/j.rser.2014.02.003.

(ABM) as a framework to model the behaviour and interaction of multiple actor groups, within a wider technology-rich energy systems modelling framework (see Section III).

ABM is a type of computational modelling which simulates the actions and relationships of rationally-bounded autonomous agents (individual or collective) within a pre-defined environment (Kiesling 2012)[30]. Agent-based models (ABMs) have proven extremely useful for both theoretical and empirical approaches to the analysis of innovation diffusion, including the simulation of socio-technical systems. This is particularly due to their ability to overcome some of the challenges posed by traditional aggregate models for the diffusion of innovation, such as the Bass model, (Kiesling 2012)[30]. As a result, these models have been used in a variety of research fields to simulate the uptake of innovations, for example water-saving measures (Schwarz and Ernst 2009)[31] or agricultural technologies (Berger 2001)[32].

The power of ABMs, in the context of this research, lies in their capability to simulate the behaviour and interaction of heterogeneous actor groups. This is reliant on the detailed decomposition of any socio-technical system into specific actor groups and their characterisation, which is highly sector-specific and results in a loss of generality (van Dam et al 2013)[33]. However, for sector-specific modelling requirements, ABMs have a history of successful application in behavioural studies. Snape et al. (2011)[34] constructed an ABM, based on the Theory of Planned Behaviour (TPB) and founded in an STS approach, to simulate the uptake of smart meter devices by households connected to a smart grid. Lee and Malkawi (2014)[35] use ABM to simulate the behaviour and energy consumption of multiple users in commercial buildings, on the basis of a "Perceive-Think-Act" cycle of individual agents (Fig. 3). Azar and Menassa (2012)[36] used dynamic occupancy parameters to construct an ABM which simulates the energy consumption behaviour of commercial building occupants, while Natarajan et al. (2011)[37] docked an agent-based model to an equational model, to model UK domestic energy consumption.

One aspect of particular interest in ABMs is their ability to incorporate network externalities driven by of social processes (Kiesling 2012)[30], recognized as important elements in the

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[30] Kiesling, Elmar, Markus Günther, Christian Stummer, and Lea M. Wakolbinger. 2012. "Agent-Based Simulation of Innovation Diffusion: A Review." *Central European Journal of Operations Research* 20 (2). Springer-Verlag: 183–230. doi:10.1007/s10100-011-0210-y.

[31] Schwarz, Nina, and Andreas Ernst. 2009. "Agent-Based Modeling of the Diffusion of Environmental Innovations — An Empirical Approach." *Technological Forecasting and Social Change* 76 (4): 497–511. doi:10.1016/j.techfore.2008.03.024.

[32] Berger, Thomas. 2001. "Agent-Based Spatial Models Applied to Agriculture: A Simulation Tool for Technology Diffusion, Resource Use Changes and Policy Analysis." *Agricultural Economics* 25: 245–60. https://pdfs.semanticscholar.org/7435/4b3508e3d56696b0c86de2a1c753649f3ecf.pdf.

[33] Van Dam, Koen H., Igor Nikolic, and Zofia Lukszo, eds. 2013. *Agent-Based Modelling of Socio-Technical Systems*. Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-4933-7.

[34] Snape, Richard, Katherine Irvine, and Christophe Rynikiewicz. 2017. "Understanding Energy Behaviours and Transitions through the Lens of a Smart Grid Agent Based Model Introduction: Energy Consumption in the Environmental Context." Available at: http://www.iesd.dmu.ac.uk/~cascade/static/publications/8-245_snape_reviewed_final.pdf.

[35] Lee, Yoon Soo, and Ali M Malkawi. 2014. "Simulating Multiple Occupant Behaviors in Buildings: An Agent-Based Modeling Approach." *Energy & Buildings* 69: 407–16. doi:10.1016/j.enbuild.2013.11.020.

[36] Azar, Elie, and Cc Menassa. 2011. "Agent-Based Modeling of Occupants and Their Impact on Energy Use in Commercial Buildings." *Journal of Computing in Civil Engineering* 26 (August): 506–18. doi:10.1061/(ASCE)CP.1943-5487.0000158.

[37] Natarajan, Sukumar, Julian Padget, and Liam Elliott. 2011. "Modelling UK Domestic Energy and Carbon Emissions: An Agent-Based Approach." *Energy and Buildings* 43 (10). Elsevier B.V.: 2602–12. doi:10.1016/j.enbuild.2011.05.013.

diffusion of technological innovation (Stremersch et al. 2007)[38]. In a widely debated study, Goldenberg et al (2010)[39] incorporate global and local network externalities in an ABM, by setting rules for adoption of a technology by consumers. Kiesling (2012)[30] uses an ABM to simulate word-of-mouth information flows, a driver for innovation diffusion which has been neglected in traditional models.

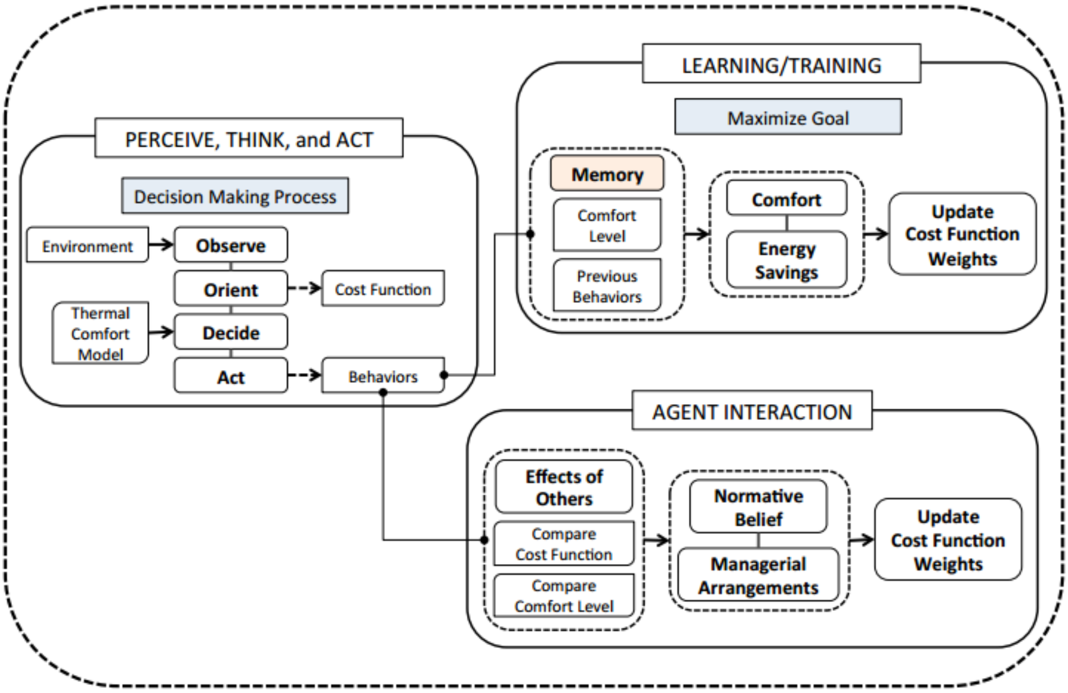

Figure 3. Example behavioural planning framework for undertaking thermal adjustments in a household (adapted from Lee and Malkawi 2013)[35].

In summary, ABMs provide a powerful framework for the modelling of behaviour and interaction in multi-actor complex systems. Although not without its challenges, it offers multiple opportunities in the modelling of systems described in socio-technical terms, the simulation of social networks and informal information flows such as word-of-mouth, and the differentiation of agents based on their aversion to innovation. This last opportunity is highly important in the provision of robust policy recommendations for variable targeting of households. Furthermore, agent-based modelling can be docked against other models to form integrated frameworks, such as network models and cellular automata structures, to provide a more comprehensive picture of the complex behaviour of residential retrofit actor groups.

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[38] Stremersch, Stefan, Gerard J Tellis, Philip Hans Franses, and Jeroen L.G Binken. 2007. "Indirect Network Effects in New Product Growth." *Journal of Marketing* 71 (3). American Marketing Association : 52–74. doi:10.1509/jmkg.71.3.52.

[39] Goldenberg, Jacob, and Sol Efroni. 2001. "Using Cellular Automata Modeling of the Emergence of Innovations." *Technological Forecasting and Social Change* 68 (3): 293–308. doi:10.1016/S0040-1625(00)00095-0.

II.2 Methodological proposal

In light of the above review, this research proposes a combined application of the STS and ANT frameworks to qualitatively describe the diffusion of the most common retrofit measures in the UK housing stock, and to inform the construction of an agent-based model (ABM), based on the Theory of Planned Behaviour (TPB), to simulate the uptake of retrofit measures in private households of UK urban areas. The ABM will be docked to MUSE ®, a bottom-up, technology-rich global energy systems modelling framework under development at Imperial College London[40].

The methodology consists of 5 main steps:

1. Identify and characterise the major actor groups (Fig. 4, left), define their attitudes, normative beliefs and behavioural beliefs, using constructs from TPB;
2. Identify and characterise the main retrofit technologies of interest (Fig. 4, right);
3. Identify and characterise the linkages between the actor groups and retrofit technologies (single or part of a package), in terms of number, relative strength, barriers, drivers and impact on decision-making processes of actors;
4. Qualitatively assess the evolution of technology and actor-specific linkages, in order to determine the speed of diffusion and susceptibility to niche and landscape processes;
5. Conceptualise and construct an ABM to simulate the behaviour of tenant and homeowner actor groups, based on linkages to the individual and package retrofit technologies, their attitudes and beliefs.

Major groups of actors active in the UK retrofit sector
Tenants
Homeowners
Landlords
Housing associations
Public authorities
Energy suppliers
Property developers
Consultants
Manufacturers
Capital providers

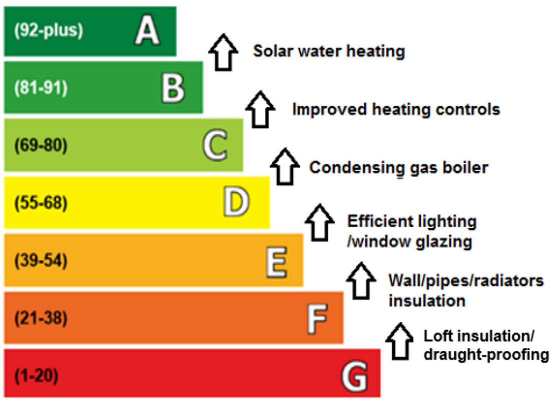

Figure 4. Left: major actor groups active in the UK retrofit sector; right: most common retrofit technologies deployed in UK households and their associated Energy Performance Certificate (EPC) upgrades. Source: Gov.uk (2016), Energykey (2016), Dowson and Poole (2012).

The first two steps of the methodology will use the STS framework to define the baseline, or current situation, of the UK's retrofit sector, as a network of actors with specific attitudes, beliefs and relationships, operating within a stable regime. It is assumed that the retrofit measures have emerged into the regime, whose technological and policy dimensions are

[40] Giarola, Sara, Daniel Crow, and Adam Hawkes. 2016. "MUSE Beta Version : Model Documentation." London.

aligned with their requirements. Landscape effects and niche-level disruptions, are considered as external inputs affecting the linkages surrounding the technologies.

The following two steps of the methodology use ANT to refine the analysis of this baseline network configuration, by defining the interactions between actors and technologies as dynamic linkages. These linkages are characterised by number (relative to one technology or actor group) and relative strength (time since linkage formation and probability of change in one to induce change in the other), but crucially they are also defined by the barriers and drivers to actor adoption of technology which are embedded in them. The impact of these barriers and drivers are time and event-dependent (i.e. their impact may decrease with time, e.g. as a technology becomes more widely adopted; or it may decrease following a change in one of the characteristics of the actor groups, e.g. the attrition of a feature, such as home ownership), and they dictate the decision-making processes of the actor groups. If these processes are defined as stepwise, the barriers and drivers will appear or disappear at different points, as the actor groups adjust to, and drive change in, the relevant linkages.

The characterisation of actor groups, technologies and linkages will be supported by empirical data gathered from qualitative field studies (interviews, surveys and focus groups) and reviews of the existing academic and policy literature.

The main output of the first 4 steps will be a qualitative assessment of the characteristics, barriers, drivers and linkages of all actor groups and technologies, as well as the decision-making steps of the tenant and homeowner actor groups. These decision steps will be defined as a sequence, and the quantified barriers, drivers and thresholds will be assigned to each step. In the last step of the methodology, an ABM will be developed, centred on these decision-making processes of the tenant and homeowner actor groups. This step enables the translation of the qualitative actor-technology network into a quantitative modelling framework, capable of simulating the uptake of retrofit measures by the UK housing stock over long timescales (up to the year 2100).

The inputs for all required components of the ABM (agent attributes, environment and rules) will be provided by the outputs of steps 1-4, specific to the tenant and homeowner actor groups:

- Agent attributes, attitudes and beliefs resulting from the characterisation of actor groups, via qualitative field data collection;
- Agent environment, resulting from the characterisation of actor-actor and actor-technology relationships, via literature reviews and qualitative field data collection;
- Agent decision-making processes, resulting from the identification and characterisation of decision-making steps, barriers, drivers and thresholds manifested within each actor-technology linkage, via qualitative field data collection;
- Agent interaction rules, resulting from the identification and characterisation of actor-actor relationships, via qualitative field data collection and literature reviews;
- Agent learning rates, resulting from the characterisation of actor groups, via qualitative field data collection.

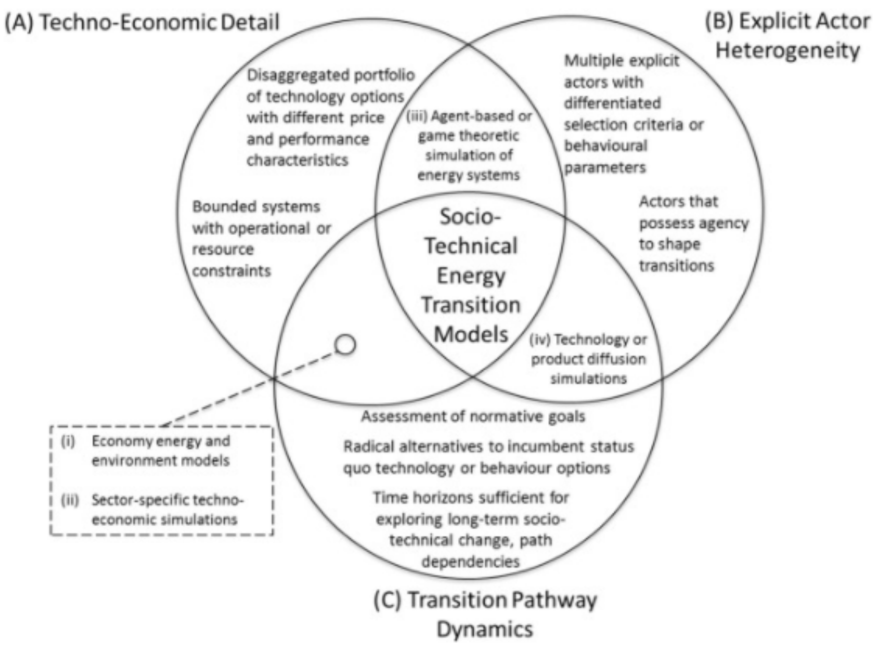

Figure 5. Required components of quantitative models simulating socio-technical systems. Source: Li et al. (2015)[13].

The construction of the model will follow the recommendations of Li et al. (2015)[13] on the characteristics of models required for simulating socio-technical systems (Fig. 5), providing a portfolio of disaggregated technologies (10 retrofit measures), explicitly defined actor groups and time horizons up to the year 2100. The attributes of agents included in the model will be defined discretely (e.g. age of dwelling) or fuzzified (e.g. social status of principal agent in household). A preliminary list of agent attributes for inclusion in the model is shown below:

- Dwelling type;
- Age of dwelling;
- Retrofit levels (insulated (Y/N), double glazing (Y/N), draught-proofing (Y/N), solar water heating (Y/N), type of boiler);
- Combined income of household;
- Household composition (family/non-family; one or more elders present; one or more infants present);
- Type of ownership (tenant/homeowner);
- Education levels of household;
- Social status of principal agent in household;
- Innovation category of household;
- Fuel type;
- Type of heating system.

The agents will be constrained by 4 main goals: the maximisation of comfort, the minimization of cost, the reduction of emissions and the maximisation of convenience. Their decision-making process will be defined as a highly deliberative "Perceive – Think – Act" sequence (Fig. 3, Barthe et al. 2011[41]), and coupled with learning and interaction modules under a TPB

[41] Barthe, Gilles, Alberto. Pardo, and Gerardo. Schneider. 2011. "Software Engineering and Formal Methods : 9th International Conference, SEFM 2011, Montevideo, Uruguay, November 14-18, 2011 : Proceedings". Springer.

framework. These modules are represented by a learning process cycle (represented by a step-wise change in the value of barriers, drivers and thresholds, unique to each actor group) and an agent interaction module, which will simulate peer-to-peer information flows.

For the purpose of the interaction and learning modules, the tenant and homeowner agents will be defined by a particular social status, based on diffusion-of-innovation theory (innovator, leader, follower, and laggard) and a level of reactivity to information transfer (the length of the “Perceive” and “Think” cycles). Two agent states will be defined (never undertaken retrofit or has undertaken retrofit), with the potential to add intermediary states (weak intent to retrofit and strong intent to retrofit), based on the rules of interaction between the cell with its neighbours, its social status and its reactivity. The rules for interaction will be defined using concepts of relational, positional and central diffusion networks (Valente 1996)[42], and validated through qualitative data collection.

The combined use of transition theories, superimposed on the foundation of a hierarchical system perspective such as the MLP, has been conceptualised before (Geels 2005)[21]. The novelty of this research stems from its empirical foundations and application of transition theories to a specific sector. In addition, the construction of an ABM capable of simulating dynamic socio-technical relationships provides a new contribution to the field of quantitative energy modelling, acknowledging the importance of incorporating social and behavioural aspects as more than an accompanying narrative to simulations. It is expected that the application of social network diffusion theory and the TPB framework will also generate additional insights into the complex behaviour and relationships of actors in the retrofit sector, in response to the diffusion of retrofit technologies.

IV. Conclusion

Research into sustainability transitions and has attracted considerable interest in the management of clean energy technologies diffusion. However, none of the major transitions frameworks have been applied to the uptake of residential retrofit measures, and most have been used conceptually, rather than linked to a quantitative modelling output. In line with a recent call for research rooted in the STS approach (Arup 2016)[43], this paper proposes the application of a combined transitions framework, where the theory of STS is used to define the baseline state, and ANT the dynamic linkages, of the UK retrofit sector. The framework is supported by the empirical analysis of qualitative data, gathered through a mixed-methods approach, and is linked to an agent-based model, to simulate the uptake of retrofit measures and estimate the resulting cost and emissions savings. The application of this framework in a geographically and sectorally specific context can provide a better understanding of the response of agents in the retrofit sector to diffusing technologies, as well as where the major barriers and drivers lie. Ultimately, this understanding can contribute to the formulation of robust, effective policy which drives residential retrofit through sustainable, beneficial incentives and effectively contributes to the decarbonisation of the UK energy system.

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[42] Valente, Thomas W. "Network models of the diffusion of innovations." Computational & Mathematical Organization Theory 2, no. 2 (1996): 163-164.

[43] ARUP. 2016. “Towards the Delivery of a National Residential Energy Efficiency Programme,” May. Available at: http://publications.arup.com/publications/t/towards_the_delivery_of_a_national_residential_energy_efficiency_programme

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