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Abstract

There is evidence that the housing and community sector in the UK is unsustainable, in CO2 emissions, overuse of land and other resources, social and economic indicators such as a lack of good quality housing, and institutional problems of a conservative building system and a planning and regulatory system that is slow to respond to changing needs and demands. We review previous work on the housing and communities sector in the UK, showing it to be not only unsustainable, but to have the characteristics of a systemic, persistent problem. We then use the notion of systemic change or 'transitions' to analyse this sector and implement it as a case study using our previously developed transitions model. Our model results show that the landscape changes of climate change (perception) and rising fuel prices can in themselves lead to a 1/3 reduction in direct CO2 emissions from the residential sector in 2050 relative to 2000, despite countervailing demographic changes. Policies supporting renovation and demolition of inefficient housing and high quality new-build, combined with regulations and subsidies supporting actors who encourage low CO2 emission practices, increase emission reductions to nearly 1/2. However, if the present regime of property developers, house-builders, and city planners remains unchanged, the CO2 reductions are greatly reduced. This is the case even if the business-as-usual agenda is altered to incorporate more energy efficient housing ideas, since the deeper structural changes needed for serious emission cuts are impeded. Policies supporting actors with good social sustainability practices improve indicators such as community strength and accessibility in 2050. These policies can also improve CO2 emission reduction through cuts to indirect household emissions, as social cohesion and mixed-use zoning encourage localism and reduce traffic.

1. Introduction – transitions and transition modelling

We report on research from the EU Framework Six MATISSE project[2] to model and assess transitions, or long-term systemic shifts, to sustainable development. This paper discuses our case study on housing and communities in the UK, where we find signs of unsustainability, not in one context alone, but as a long-term, cross-sectoral issue, involving social, environmental and economical aspects. We present a brief overview of transition theory, including our own modelling work, and a review of the unsustainable situation of housing and communities in the UK. We then focus on implementing this

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[2] Methods and Tools for Integrated Sustainability Assessment (MATISSE). See: www.matisseproject.net

case study in our transition model to analyse future changes in sustainability indicators and system dynamics under different policy assumptions.

1.1.Transition theory

There are some problems, at national or international level, which cannot be easily solved through incremental, single-sector policy changes alone. The systemic nature of these problems suggests they are cross sectoral, and are embedded in infrastructure, institution and paradigms of business and behaviour (Geels, 2005a). Such problems are often called *persistent problems*. The notion of *transitions*, or radical systemic changes, has been proposed as a framework for analysing such problems. The transitions framework addresses the underlying structural determinants of the problems, and the possibility of system-exceeding transformations as being an eventual way of moving beyond them (Rotmans *et al.*, 2001).

The institutions, paradigms and regulative subsystems which tend to self-regulate and oppose radical change in the system are represented by the concept of a *regime*. A regime then can be understood as a particular set of practices, rules and shared assumptions, which dominate the system and its actors (Geels, 2005b; Rotmans *et al.*, 2001). Regimes typically focus on system optimisation rather than system innovation, because habits, existing competencies, past investment, regulation, prevailing norms, worldviews and so on, act to *lock in* patterns of behaviour and result in path dependencies for technological and social development (Geels, 2005b; Smith *et al.*, 2005). However, transitions require organisation-exceeding, qualitative innovations, realised by a variety of participants, which change the structure of the system (Loorbach & Rotmans, 2006). Some research has therefore highlighted *niches* – individual technologies and actors outside or peripheral to the regime – as the loci for radical innovation (Geels, 2005a; Rotmans *et al.*, 2001; Smith *et al.*, 2005). The regime may be threatened from the niche level, or from changes at the broader *landscape* level, which represents the slow, large-scale changes in economic, ecological, cultural and behavioural trends. Once a threat is recognised, regime actors will mobilise resources from within the regime, and in some cases from within niches, to respond to it (Geels & Schot, 2007; Smith *et al.*, 2005). A transition occurs when a regime is transformed or replaced; in either case this includes a significant change in the system's structure, culture and practices.

1.2.Agent based modelling

Agent-based modelling (ABM) is a means of generating simulations from a rigorous set of rules rather than extensive explicit data. ABM can be described as a means of conducting thought experiments, acting as an aid to intuition rather that merely finding patterns in data (Axelrod, 1997). In other words, ABM acts as a tool for exploring scenarios, assumptions and different proposed rules for societal or other complex systems. This field draws on complexity science among others, and is used where more traditional modelling tools are less applicable. It is a distinctly different paradigm from traditional modelling tools, with new characteristics. For example, ABMs are often inherently non-deterministic in their results, even if general patterns can be predicted. ABM can be a useful tool in studying social systems, economic systems or other systems which include social aspects. For example, in modelling individual decision making in the context of group behaviour or a broader system, ABM can capture the emergence of a higher social order or other patterns (Bonabeau, 2002; Macal & North, 2005). These emergent properties are properties which are hard to predict from individual behaviour, and are thus integral to complex systems, and even simple forms of interaction can lead to surprising consequences (Axelrod, 1997).

An agent in this context is a discrete, autonomous component of a model with its own characteristics which distinguish it from its environment. While opinions and definitions differ, it is fairly well agreed that an agent must (e.g., Macal & North, 2005):

- have decision making capability and behaviour rules
- exist in an environment, and interact with the environment and with other agents
- have a memory of previous environmental parameters or agent interactions
- have the ability to learn and possibly modify its rules of behaviour accordingly
- not be able to completely control its environment

In modelling societal systems, an agent may represent an individual person, an institution, a company or another group. Transition theory, which combines elements of complexity theory with social studies, and which relies on emergent properties from the behaviour of individuals and groups in interaction with a changing environment, is well suited to agent-based modelling techniques.

1.3. Transition modelling

In previous work we constructed a conceptual framework for applying transition theory to persistent problems at national or EU level (Haxeltine *et al.*, 2008). In parallel, we constructed a modelling framework combining agent based modelling and systems dynamics modelling, which we applied to historical examples, such as the transition from horse-based transport to motorcars (Bergman *et al.*, 2008). Our model implementations are used to explore the dynamics of socio-technical transitions, from a transitions theory perspective; they are not deterministic (and therefore not strictly predictive), but can be used to study proposed future scenarios under different assumed conditions and policy changes. Full details of our model appear in Bergman et al. (2008), here we offer a summary model description with the basic equations only.

We attempt to capture the 'sub-systems' of *regime* and innovative *niches* and the dynamics between them as they change their structure, culture and practices, as well as the changing *landscape* - slow changes in macro-economics, demographics, world views and cultural paradigms. To the transition theory notions of regime and niche we add the concept of *empowered niche,* a niche which has grown powerful enough to be a potential threat to the regime (Haxeltine *et al.*, 2008).

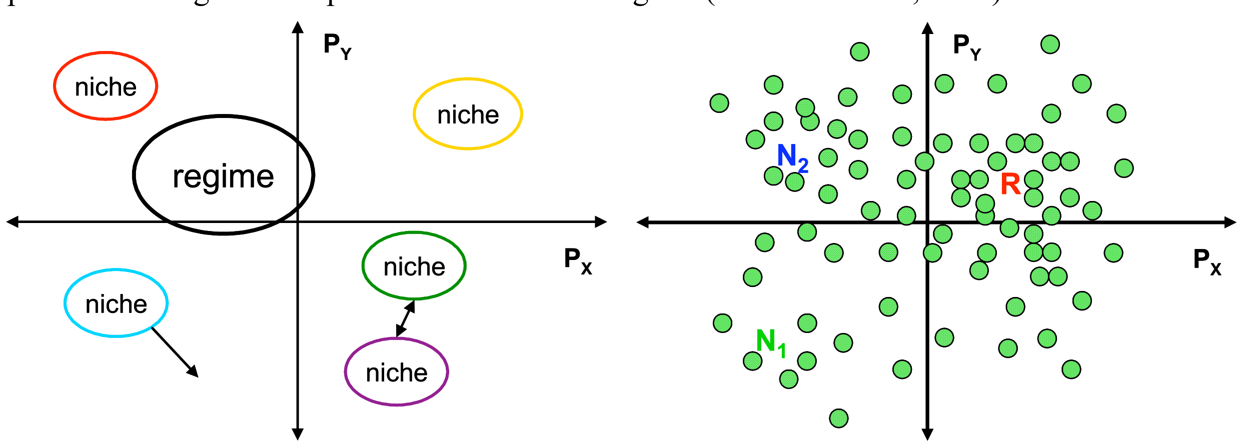

Figure 1: Two illustrations of a two-dimensional practices space, with practice axes P_X and P_Y. *Left*: regime agent and several niche agents, which can move in the space and interact with each other. *Right*: supporters scattered in the practices space, coloured by the agent they support, red = regime (R), green = niche 1 (N1), blue = niche 2 (N2). From Bergman et al. (2008).

The regime and niches are modelled as complex agents, each of which represents a constellation of actors, with internal dynamics, an infrastructure, and norms of practice. The sub-systems of regime, niches and empowered niches are referred to as **agents** in the model context. The model also includes a large number of simple agents called **supporters**. These represent consumers, citizens, or small groups. We use one to ten thousand supporters, which can represent millions of people and groups.

We choose for each model implementation a number of **practices** relevant to the case study and which distinguish the agents from each other, such as the energy efficiency of houses, or promotion of mixed-use zones in urban areas. Each practice is quantified as an axis with a minimum and a maximum value. The collection of practices can therefore be seen as a multi-dimensional space. Both the agents and the supporters are positioned in this space: the agents' position represents their current practices (e.g., the energy efficiency of the houses in planning, building and renovation), while the supporters' position represents their ideal practices, or their preferred practices based on their perceptions of the system. The practices space and the positioning of agents and supporters within it are illustrated in Figure 1. The supporters preferred practices are varied, forming a 'cloud' within the practice space.

At each timestep, every supporter chooses which agent to 'support', based on the *attractiveness* of the agents. The attractiveness is a type of utility function, and is calculated from the *distance* of the agent from the supporter in the practices space, the relative *strength* of the agent, and a simplistic *price* parameter. Together, these elements of price and agent characteristics (distance, strength) capture both the economic and social/institutional influences on decisions in this context (e.g., Wilson & Dowlatabadi, 2007). The attractiveness of agent *j* to supporter *i* is:

(1) $$attractiveness_{i,j} = \alpha \times s_j - \beta \times price_j - CDL_{i,j}^2$$

where α is the relative weight of the agent's strength, default value 0.05, and β the relative weight of price. *CDL* is the *cumulative dissatisfaction level*, where dissatisfaction is defined as the normalised distance *D* between the supporter and the agent. *CDL* at time *t* is calculated as:

(2) $$CDL_t = 0.5CDL_{t-1} + 0.5D_t$$

The agents can slowly change their practices over time, and attempt to position themselves within the cloud of supporters so as to maximise their **support**. Support determines the agent's flow of resources, needed to upkeep its internal structure (physical infrastructure and institutional power). The **strength** of an agent is modelled as the normalised institutional power stock, i.e., the agent's share of the total institutional power. The regime, by definition, has the highest institutional power and strength. The basic equation for the resources flow *R* is:

(3) $$R = price \times support \times CONST_1$$

and for the institutional power stock at time *t*:

(4) $$power_t = power_{t-1}(1-\delta) + R \times CONST_2$$

where δ is the depreciation, set at 0.05 per year. This stocks and flows method means strength changes slower than support, allowing an unpopular regime to persist for some time through its institutional power, but ultimately forcing it to gain support or collapse.

The changing landscape is represented as external **signals**, which affect the system through changing the preferences of supporters over time. These signals include **policies**, which encourage specific agents or practices through subsidies or regulations.

Over time, supporters change their preferences due to landscape signals, and agents change theirs in an attempt to gather support and compete with other agents. The changing system can shift strength between the agents. A transition in the model occurs either through *regime change*, when the regime collapses and another agent takes its place, or through *regime transformation*, when the regime shifts its position significantly in the practices space, through adaptation and sometimes absorption of niches, signifying a change in its practices and paradigm. If a regime loses strength and collapses without another agent strong enough to take its place, there can be a period of no regime.

2. The unsustainability of the housing and communities sector

The residential sector in the UK, including planning, building and renovating houses, and planning and managing the larger community area, including density, zoning, traffic management and community support, shows unsustainability in various contexts, as we discuss in Bergman et al. (2007). Here we give a short analysis of the unsustainable practices and paradigms in the housing and community sector, and how we use this case study to implement our transitions model. We implicitly focus on urban communities, discussing the problem facing towns and cities more than those of rural areas.

2.1.Sustainability of housing and communities

We began this case study as Sustainable Housing, but soon broadened to include Sustainable Communities. This is because the two are intricately linked when looking at environmental, social and economic strands of sustainable development in the residential sector. Sustainable housing refers to energy and material resources used in building houses, and to energy and material resources used by, and waste produced from, households. Sustainable communities refers to environmental, social and economic sustainability of the built (residential) environment, including land use, transport and connectivity, satisfaction with neighbourhoods and communities, etc.

A key feature of more sustainable communities is more energy efficient housing. Other features include planning communities which are land-efficient, with community recycling schemes, and easy access to public transport. In large scale developments, planners and architects design both the individual houses and the layout of the neighbourhoods, including public spaces and other community facilities. Users (i.e., residents) care both about their own home and about the communities they live and work in. Providing affordable housing is not only about cheap, decent homes, but also about the neighbourhoods and communities in which they are situated.

Sustainable development in the context of housing and communities has many definitions. The importance of global warming has led to CO2 emissions and their reduction taking a major role in defining sustainability in the housing sector as in other sectors. Some studies, such as 40% House (Boardman *et al.*, 2005) focus on addressing climate change and the many changes in policy, market and skills development necessary in the residential housing stock if the UK is to reduce its CO2 emissions by 60% by 2050. Other studies look at sustainable development of houses and communities through the use of resources, e.g., the WWF promotes sustainable development of communities in a fashion which reduces global environmental impact and increases worldwide equity in resource use, and uses indicators such as the ecological footprint (e.g., WWF, 2006). Focusing more on communities, the Egan Review (ODPM, 2004) use this definition: "Sustainable communities meet the diverse needs of existing and future residents, their children and other users, contribute to a high quality of life and provide opportunity and choice. They achieve this in ways that make effective use of natural resources, enhance the environment, promote social cohesion and inclusion and strengthen economic prosperity" (p. 7).

In MATISSE we choose not to add another definition of 'sustainable development' to the many existing ones. We recognise that it must be defined in a way relevant to each case study by the relevant stakeholders, but that it broadly includes environmental, social and economic pillars (Weaver & Rotmans, 2006). We therefore take the above definitions and comments as guidelines for sustainable communities for our case study.

2.2.The current unsustainability

There is evidence for unsustainability in the residential sector in the UK from environmental, social economic and institutional perspectives. The climate change impact of UK housing is apparent: approximately 27% of the UK's emissions in 2004 came from *direct* energy use in homes, with energy consumption for heating and cooking decreasing, but consumption related to appliances and lighting increasing (HMG, 2006). Household ownership of electronics, such as televisions, domestic IT and other gadgets, has increased dramatically, and is expected to continue to rise over the next few years: by 2010 consumer electronics is predicted to become the biggest single sector of home electricity consumption (EST, 2006). Indirect energy usage from travel and goods and services is also increasing. There is also an urgent need for adaptation to climate change which is already inevitable or highly likely, including changing regulations and practices to cope with future changes in climate, changing patterns of urban heat islands, and increased flood risks (EA, 2006; UKCIP, 2003).

Other environmental issues include new developments using a lot of greenfield sites, unsustainable given the UK's limited available land, and creating (sub)urban sprawl (ODPM, 2003; SDC, 2007). The available productive land around the world gives an area of 1.8 global hectares (gha) per person (WWF, 2004). The UK has an ecological footprint of 5.4 gha per person and rising, with regional and local variations (WWF, 2006). This is three times the available per capita worldwide, and therefore unsustainable in a global perspective. Housing is itself only a small portion of the ecological footprint, with energy taking up more than half of the footprint (WWF, 2006).

From a social and infrastructural perspective, there is a lack of affordable housing in decent surroundings, with housing shortage in some areas and collapse of housing market in others (ODPM, 2003). There are still plans for extensive demolition of occupied homes in the North and Midlands, which would break up communities (SDC, 2007). Meanwhile, long-term planning of communities is inadequate and lacks coordination, resulting in some new communities being without vital facilities when people move in (bus routes, community centres) (ODPM, 2003). The planning system is slow and unresponsive to changing needs and demands (ODPM, 2003), and has a poor record on consultation with residents (SDC, 2007).

Finally, changing demographics, and especially an increase in one-person households, mean several sustainability problems are expected to get worse. More, smaller households require more houses – therefore more land and other resources. Smaller households have higher direct and indirect energy requirements per person than larger households (Moll *et al.*, 2005). For example, one-person households use 60% more products per capita (in weight) than large (4 person+) households, and their energy consumption is 138% higher (INCPEN, 2001). An increase in the number of people living alone, some of whom are 'regretful loners', also has social implications (Williams, 2006).

In summary, material, resource and land consumption in the UK are unsustainable in the residential sector, while lack of affordable housing is leaving some vulnerable people needing better houses and surroundings.

2.3.Not just unsustainability: lock-in

The mainstream residential building sector in the UK is not only unsustainable, it is *locked-in* to unsustainable practices, and favours optimisation and incremental change over radical change. There is much evidence that a paradigm shift in structure, behaviour and communication strategies are needed to address sustainability issues (Boden, 1996; Rohracher, 2001). Rohracher (2001) found that this sector traditionally has low levels of innovation, mass production from large suppliers, and separation of design from construction, all incompatible with social and ecological optimisation. Studying innovation in Scottish social housing, Dewick and Miozzo (2004) found that "[t]he different aims of the parties involved in the construction chain may not be easily reconciled and traditional approaches to construction may reinforce these differences, hindering efforts to introduce innovation."

The inertia is also clear from studies such as Williams (2006), who engaged developers as stakeholders on various environmentally-friendly designs. She found that developers do not see the house-building sector changing of its own accord, and favoured statutory controls for higher environmental standards, concerned that without them such building would suffer from competition with cheaper, lower standard building. But it goes beyond inertia into actively opposing change, as is evident from the fact that "discussions with planners and local authorities in many of the areas reveals that the approach to developments under the banner of the [government's Sustainable Communities] Plan have, in practice, been very much 'business as usual', and such practice is likely to continue" (SDC, 2007).

Smith (2006) tells us that large volume house builders lobby to resist change to energy efficiency regulations, yet many still fail to comply with them. While tougher building regulations have been introduced, compliance with Part L1 (conservation of fuel and power in dwellings) is weak compared with other elements. This is partly due to local authorities having limited resources for enforcement and lack of specialisation in this area, but there is also a need for attitude change as officers are not likely to refuse completion certificate or prosecute on a Part L issue (St John Cox, 2006). Finally, Lovell (2007) analyses the inertia of the UK housing sector from a political perspective, demonstrating how the dominant actors in the sector effectively withstood major changes in building regulations, and showing that the system favours incremental change over radical change, and that technical decisions are highly politicised.

There are other institutional difficulties: Pett (2004) claims that forward-thinking builders sometimes have trouble promoting sustainable housing because it fails to meet targets or requirements of, for example, a local building committee. The planning system is slow and unresponsive in the face of changing needs and demands (ODPM, 2003).

The above behaviour points to the mainstream residential building sector being *locked in* to present practices. It acts as a regime using its power to resist change and maintain the status quo - although the attempts at new practices by some can be seen as an internal misalignment between different regime actors (Geels, 2005b). This behaviour is typical of the *meso-level* (i.e., regime) dynamics which are "determined by dominant practices, rules and shared assumptions which are most geared towards optimising rather than transforming systems" (Rotmans & Kemp, 2003).

2.4. Recent changes

It is worth noting that some institutional changes have been evident in recent years. Rydin (2006) reviews the huge reform agenda in the planning system over the last few years, and concludes that while sustainable development is higher on the political and planning agenda, there is no guarantee that the reforms will deliver more sustainable communities due to the great effort in changing processes. However, she sees great potential to use the reforms to further the sustainability agenda.

There is also evidence of the government putting pressure on the regime, specifically the conservative building sector, by putting sustainable housing and communities higher on the agenda. For example, in a recent consultation paper, the Department for Communities and Local Government (DCLG, 2006a) proposes improved energy and carbon performance in building regulations, requiring new-build homes from 2016 to be 'zero carbon', an ambitious target set to combat climate change and fuel poverty, and improve the UK's energy independence. The Code for Sustainable Homes (DCLG, 2006b) presents a wider range of sustainability parameters, developed "to enable a step-change in sustainable building practice for new homes". Reports on government progress on sustainable communities (e.g., SDC, 2007) add to the pressure on government at all levels to deliver these objectives.

From a transition theory perspective, all of these recent changes amount to a landscape change putting pressure on the regime. While these changes will inevitably cause some change in house-builders' and planners' practices, we propose to research under what conditions this pressure might result in a transition, and if so whether this results in more sustainable housing and communities.

2.5. Mainstream and innovative actors

In the above discussion, we identified actors and behaviour consistent with that of a meso-level regime in transition theory. However, there are also a variety of innovative actors working towards more sustainable urban development and renovation, which can be identified as micro-level niches. These include researchers in low-energy/low-carbon housing, such as the 40% House project (Boardman *et al.*, 2005), and a variety of mainstream and alternative developments and communities, such as 'green building activists' (Smith, 2006). An example is BedZED – a South London development built to be energy and resource efficient, as well as a good example of spatial urban planning for sustainable living. Mixing social, economic and often environmental sustainability objectives are co-housing developments; these are built as small neighbourhoods with many shared facilities, such as kitchens, dining halls, workshops and children's play facilities, and in some cases shared evening meals, and comprise 'intentional communities'; decisions are made by the members, rather than an outside authority, sometimes from the designing and building stage onwards; this is a major departure from mainstream development (Field, 2004). Focusing more on social sustainability and well being are a variety of community groups, which work at a local level to improve quality of life and solve local problems, regardless of government policy (Darnton, 2004). From these various actors, which include small groups, NGOs, or even individual actors, we identify and define appropriate niches for the case study (see 3.1).

3. From case study to model

In the housing and communities case study, we recognise that there are different aspects of a complex process. These include planning, construction and managing of the built environment at different levels from the individual house to neighbourhood or higher levels, as well as energy and material aspects of the houses and the appliances therein, and various community-level decisions and practices.

We find it useful to look at the problem at two levels. At the level of **the house itself** occupiers and landlords take decisions involving energy and material use in the house, including issues such as insulation, refurbishment and appliance use. This level includes primarily environmental sustainability (energy and resource use), although social and economic issues such as fuel poverty and energy efficient social housing are also present. **The community outside the house** involves decisions of planning and renovation, population density and single- or mixed-use zones, as well as issues ranging from transport to engagement with other members of one's community. This level includes social, economic and environmental sustainability. We have not implemented the model in two parts, but have kept the different levels in mind in the implementation. An addition to the model in this implementation, which refers primarily to the house itself, is a **housing stock** which changes over time as supporters can decide to *refurbish* old houses, lowering the emissions from them, and the agents' dynamics determine the rate and quality of *new-build* houses.

The main part of the implementation consists of identifying the agents, practices, landscape signals and policies appropriate for this case study, and how they affect each other. Our choices are discussed in detail below, as is the addition of the housing stock to the model. The simulations run from 2000 to 2050, with twelve timesteps a year, i.e., one timestep is one month.

3.1.Agents

As discussed above, we identify a regime and various niches in this case study. Each of these is an *agent* or sub-system, representing a constellation of actors and their practices and paradigms (see 1.2). In our implementation, we group the niche actors together and define 4 aggregate niches, for a total of five agents:

3.1.i. **The Regime** includes mainstream property developers, house-builders, architects, city planners and property sellers. The actors of the regime have an economic, business-as-usual agenda, and many of them tend to resist innovation, especially radical innovation.

3.1.ii. **Niche 1** includes actors with practices aimed at making houses and appliances more energy efficient and reducing CO2 emissions from houses. This is done primarily through technology – better insulated and more energy efficient houses, and energy efficient appliances. Only relatively minor behaviour change is expected, i.e., consumers preferring more efficient houses and appliances, installation and use of smart meters, etc. On sustainability issues other than energy and CO2 emissions, niche 1 follows regime practices. The *40% House* report (Boardman *et al.*, 2005) is an example of niche 1.

3.1.iii. **Niche 2** includes practices of change to the larger built environment, such as mixed-use zoning, integrated spatial planning and integrated public transport. Housing developments such as BedZED, and energy saving schemes such as community Combined Heat and Power systems (CHPs) would be in this niche. Niche 2 gives more emphasis to social sustainability than the regime. However, it includes no change to the existing power structure, with such initiatives coming from local authorities or otherwise top-down.

3.1.iv. **Niche 3** also looks at changes to the built environment, but in contrast to niche 2 it stresses community-based, bottom-up initiatives and behaviour change. Power is shifted down from local authorities to community level for much decision making, although some individual power may be lost to the community. Co-housing projects which are planned, developed and managed by the residents are an example of niche 3.

*3.1.v.***Niche 4** includes local community groups, such as those trying to improve their quality of life regardless of government policy. Darnton (2004) reviews how the large number of local community groups in the UK act to improve sustainability or otherwise improve their communities; their local and voluntary nature often puts them outside the control of the state. These individual groups or networks of such groups are niches focusing on social and sometimes economic sustainability, but unlike niche 3 these are often limited to local goals, and do not necessarily have an environmental focus.

The four aggregate niches are thus differentiated by their attention to different aspects of sustainability: environmental, social and economic. They are also distinguished by their relative compatibility with the regime; niches 3 and 4 represent a more radical departure from the mainstream than do niches 1 and 2.

3.2.Practices

The choice of practices for this case study was nontrivial. There are many choices and decisions made at a household level, or by various actors at local or regional government, in the private construction sector and by various NGOs. We attempted to find practices that could capture major sustainability indicators, such as those in the Egan review (ODPM, 2004), and were reasonably quantifiable or at least could be estimated in a qualitative manner. However, each chosen practice needed to have added value, e.g. clearly distinguishing the different niches from each other, so as to keep the number of practices small enough for the model to be manageable and the results easy to analyse.

We chose six practices. Starting with the house itself, *CO2 emissions* from energy use in the house is the first practice. Moving from the house to the built residential area are the practices of *density* of the built environment and *mixed-use zoning*. *Public transport and slow modes* includes both infrastructural and behavioural sides. *Social cohesion* refers explicitly to community and social sustainability, and finally we added *waste to landfill* as an environmental practice not focused on climate change. These practices are not entirely independent of each other, e.g., social cohesion is affected by zoning, density and other built residential factors, but we feel they are distinct enough to act as mathematically independent practices in out model. While we use literature based values where possible, the assignment of exact values for each practice to each agent is to some extent our arbitrary estimate; this is especially true for the social cohesion practice. We also note that our focus is on urban and suburban areas; rural areas require a different analysis.

We considered other practices such as water use, strictly economic practices and more detailed social practices, but found these were either beyond the scope of our study, or greatly increased the complexity of the model.

3.2.i.Household energy use, expressed as CO2 emissions

This practice is at the household level; it refers to energy use in houses, including insulation measures, energy supply, appliance efficiency and behaviour. We look at net energy used in households, represented as CO_2 emissions. Table 1 summarises our assumed energy usage in old, fully refurbished, and new houses. We use this in conjunction with estimates of average household emissions:

I. A British Gas commissioned survey (Simmons & Gonzalez, 2006) estimates average emissions at just under 5,600 kg CO_2 per household for 2003. There are large regional and local variations, e.g., by city: 4,395 in Kingston-upon-Hull to 6,189 in Reading.

II. Calculating for 2002: total UK emissions were 148.6 million tonnes carbon equivalent (Friends of the Earth: www.foe.co.uk). An estimated 25% comes directly from households (Anderson *et al.*, 2005), of which there were 25,641,000 (Boardman *et al.*, 2005). This is equivalent to ~5,300 kg CO2 per year per household, a fair match.

We assume a rough figure of ~5,500 kg CO2 per household for 2000. Note that fossil fuel energy reduction through onsite renewables such as solar panels will reduce this practice; however the energy mix of the national grid is not included here. We assume old houses have slightly higher emissions (5700kg), and can be lowered by one third through refurbishment (Boardman *et al.*, 2005), (3800kg), and new houses can be as low as one third (1900kg). We define the practice axis as CO2 emissions from household energy use, and set the endpoints at 0 emissions (an ideal) up to 7500 kg CO2/year as a maximum, see Table 2 for agent assigned practices.

Table 1: Energy usage in old, refurbished and new houses. Data are from the *40% House* research (Boardman *et al.*, 2005), except where noted. all in kWh/year.

	space heating	appliances	water heating	total energy
total old inefficient house	14,600 (average pre-1996 dwelling)	3,000 (1998 average household)	5,000 (1998 average household)	22600
total old refurbished house	9,000 (refurbished pre-1996 dwelling)	~ 1,800 (our assumption: almost as new house)	~ 4,200 (our assumption: median value)	~15,000
total new efficient house	2,000 (average post 1996 dwelling)	1,680 (predicted 2050 household)	3,400 (predicted 2050 household)	7080

Table 2: Practice 1 - direct CO2 emissions from home energy use, in kgCO2 per household per year

	point on axis	emissions kgCO2/year	notes
0 point	0	0	Ideal of zero emissions
100 point	100	7500	Above current average
regime	75	5625	Slightly above current average
niche 1	30	2250	40% of regime, using 40% house (Boardman *et al.*, 2005) example: reduced demand through efficient appliances, water saving mechanisms, and increased use of renewables.
niche 2	20	1500	lower than niche 1, through deeper change to the built environment which could lead to lower energy demand both directly in the home and more broadly in the community.
niche 3	10	750	lower than niche 2 through deeper behaviour change (reducing demand) and localisation of supplies.
niche 4	50	3750	improvement from regime due to alleviating fuel poverty through efficiency and insulation measures and community facilitated energy reduction measures

3.2.ii.Density

This practice is at the residential area (community) level. The density of the residential (urban) built environment varies from low density urban sprawl to densely built high rises, with sustainability implications in services and transport as well as (green belt) land management. It is the most commonly used measure of urban compactness, and the UK government favours the metric of *dwellings per hectare* (DETR, 1998). The importance of higher density for sustainability is explained by the Urban Task Force, which argues that: ‘As density levels are increased – even to the moderate levels of 40 to 60 dwellings per hectare – the land take diminishes rapidly. More people are close enough to communal facilities to walk and an efficient bus service can be made viable. Moreover, the critical mass of development contributes to the informal vitality of the streets and public places that attracts people to city centres and urban neighbourhoods as well as contributing to energy efficiency' (UTF, 1999).

Table 3: Practice 2 - density, in dwellings per hectare (not just built up area)

	point on axis	density in dwellings per hectare	Notes
0 point	0	0	Unobtainable 0 point, even with complete sprawl
100 point	100	100	Using FoE estimate (FoE, 2004) and new dwellings in London
regime	30	30	Assuming continued rise as new dwellings are built in high density in most areas.
niche 1	30	30	As regime
niche 2	60	60	Rethinking built environment – BedZED as rough guide
niche 3	60	60	As niche 2
niche 4	45	45	Half way between regime and radical niches

Burton (2002) looks at measurements of urban compactness in UK towns and cities, their relative use and how they relate to sustainability. She has data for 25 cities and towns of medium size (80,000-220,000), mostly from 1991-1995. She distinguishes between density of a *built-up area*, which excludes open land such as parks, school playing fields etc., but includes private gardens, and a *residential built-up area*, which excludes commercial and industrial areas. She found built-up areas varied from an average of 11.7 dwellings per hectare (dph) in Scunthorpe to 26.2 in Southampton, rising to 12.1 and 27.2, respectively, for the built-up residential area. DEFRA (2006) lists the density of *newly built* dwellings in England as fairly constant between 1993 and 2001, at an average of 25 new dwellings per hectare. Recently, however, density has increased and in 2005 the figure was 42 new dwellings per hectare (provisional estimate). For London, dwelling density rose from 48 new dwellings per hectare in 1993 to 56 in 2000. After a drop in 2001, density rose to 102 new dwellings per hectare in 2005 (provisional estimate). BedZED has 92 homes on 1.6 hectares (57.5 dph) including a large green open space with space for allotment gardens, and yet every home has either a conservatory, and/or a private rooftop garden on top of the workspace roofs that can accommodate raised beds. (www.earthfuture.com/community/bedzed.asp) The Urban Task Force recommends increasing the minimum density for new residential developments to 40 dph (UTF, 1999), while Friends of the Earth suggests new developments should always be above 25 dph, and urban sustainability in the UK could require 50 or more dph in some areas (e.g., FoE, 2004). We set our density practice as dwelling per hectare, see Table 3 for values assigned to each agent.

3.2.iii.Mixed-use zoning

This practice is also at the community level, and relates to the proximity of amenities, services and workplaces to homes. In her study of urban compactness measures, Burton (2002) looks at *accessibility* of seven 'key facilities': newsagent; restaurant / cafe; takeaway; food store; bank / building society; chemist; doctors' surgery. One of her measures is the number of postcodes in the towns which have all 7 key facilities, and finds a large variation, from 10% in Grimsby and Southampton, to 60% in Hastings. The great variation suggests potential for change as development, urban renewal and community action change cities and town; the facilities listed can change relatively fast (shops opening, closing and relocating can be faster than new developments being built).

We therefore chose this indicator as one of our practices. Our practice ranges from a zero point of ~10% of postcodes with all 7 key facilities, indicating all facilities are located in the city centre or out of town centres, up to a 100 point of 100% of postcodes with all 7, indicating facilities are found within walking distance of nearly every dwelling, see Table 4 for exact values assigned to each agent.

Table 4: Practice 3 - mixed use measured as percentage of postcodes with all 7 key facilities

	point on axis	postcodes with 7 key facilities	Notes
0 point	0	~10%	Facilities in city centre or out of town centre only
100 point	100	100%	Facilities in walking distance of every dwelling
regime	20	~28%	Close to average of Burton's (2002) 25 towns and cities, which is 27.4%
niche 1	20	~28%	As regime
niche 2	60	~65%	Mix of most facilities locally available, with others by (intensively used) public transport
niche 3	80	~82%	Almost all facilities are community organised and locally available
niche 4	80	~82%	As niche 3

3.2.iv.Public transport and slow modes

Use of public transport and slow modes (walking and cycling) is an important indicator of communities' sustainability both in terms of environmental damage from private vehicles, including air pollution, greenhouse gas emissions and land used for roads, and in terms of social sustainability, including accessibility to non-drivers and community cohesion. A classic study (Appleyard, 1981) found that increased traffic impacts negatively on both individual and community behaviour: residents of higher traffic volume streets are less likely to know their neighbours, and show less concern over their local environment than residents of streets with lower traffic volumes and speeds. Pedestrian-friendly streets create opportunities for people to meet and interact, helping to create community networks. While choice of mode, distance and frequency of travel are a household choice, we look at this as a community level practice due to the significance of transport and traffic at the community level and the (infra)structural dimensions of transport demand.

There are various way to express public transport and slow mode use, including percentage of households within walking distance of a bus stop, or distance travelled by people per year in different modes. The National Transport Survey (DfT, 2006) shows that in 2006 cars accounted for nearly four in five travelled miles, nearly unchanged since 1995/1997, while the *percentage* of trips made by car rose in the same period, primarily due to a decrease in walking. Bus use in London increased, while total bus use elsewhere decreased. DEFRA (2006) shows public transport and taxis in slight decline from 10.3% of trips in 1989-91 to 9% in 2004, and walking and cycling dropping in the same period from 32% of trips to 26% in the same period. Car trips remained fairly constant in number, but rose in percentage terms from 57% to 64%. We use the measure of percentage of trips made by slow modes or public transport (i.e., anything but a car and plane) as our practice, although we are aware of great differences, mainly between metropolitan areas, primarily London, and smaller cities and towns. See Table 5 for value assigned to each agent.

Table 5: Practice 4 - percentage of trips made by public transport and slow modes

	point on axis	% of trips using public transport or slow modes	Notes
0 point	0	0%	No one leaves their house without their car
100 point	100	100%	No private motorised transport
regime	35	35%	Approximately current level
niche 1	35	35%	As regime
niche 2	75	75%	Assumes reshaping of the built environment and public transport infrastructure for reduced car use, increased public transport provision and slow modes.
niche 3	70	70%	Similar to niche 2, but a variety of ideas, some centred around slow modes and reduced demand, others around public transport
niche 4	60	60%	Similar to niche 2, but higher car use enabling mobility for those without sufficient local amenities or public transport

3.2.v.Waste to landfill

As a first attempt at an environment indicator other than CO2 emissions, we use household waste per person going to landfills. This is an indicator of both personal behaviour and institutional waste management such as packaging and recycling policies. In 2002-3, municipal, commercial, industry and construction waste totalled 220 million tonnes. About half of this was from construction and demolition. A further 16% was municipally collected, and included household waste. We look at practice primarily at the household level, although community factors can play a part. Household waste per person increased by 2% between 1999-2000 and 2004-5, and is around 500kg per person per year. The percentage of this recycled or composted has increased to 22% for 2004-5. The amount not recycled, mostly going to landfill, decreased from 2000 to 2005, and is about 400kg per person per year (DEFRA, 2006). We define the practice as kg per person to landfill, with the 0 point the ideal of 0kg per person, and the 100 point at 700kg per person. See Table 6 for agent assigned practices.

Table 6: Practice 5 - waste to landfill, in kg per person per year

	point on axis	landfill waste kg/person/yr	Notes
0 point	0	0	Ideal of no waste
100 point	100	700	Above current average
regime	70	490	Slightly below 2004-5 average, as the regime attempts to mildly reduce landfill use
niche 1	60	420	Slightly lower than regime, mainly as climate change concerns carry over to broader environmental issues, with more recycling facilities and changes to construction and demolition to reduce material throughput
niche 2	40	280	Less waste through localisation and changes to the built environment, including responsible construction and demolition; more committed to all around improvement increases recycling
niche 3	10	70	Significant behaviour change and local problem solving lead to reduced use, increased recycling and reuse, reduced landfill waste.
niche 4	50	245	Local problem solving and community improvements combined with some changes to the built environment

3.2.vi.Social cohesion

Social cohesion refers to strength of communities. The Council of Europe's Directorate General of Social Cohesion (DG III**)** has a mandate which "is fulfilled through the promotion of European standards in the social and health field, the support of ethnic and cultural diversity, and the implementation of social development co-operation." (http://www.coe.int/T/E/Social_cohesion/). While this is a very broadly defined social sustainability indicator, we think it important to include one, and will attempt to relate this to social sustainability indicators from the Egan Review (ODPM, 2004): *percentage of people who feel they 'belong' to the neighbourhood or community* (#5) and *percentage of people who feel a great deal involved in their local community* (#7). We acknowledge that our implementation of this practice is more arbitrary than the other practices we have chosen.

Table 7: Practice 6 – social cohesion

	point on axis (abstract value)	**Notes**
0 point	0	Local communities have little power or cohesion, few people involved
100 point	100	All people involved in their local communities, which are strong and diverse.
regime	20	Centralised decisions leave little room for local involvement
niche 1	20	As regime
niche 2	50	Local solutions to local problems in interpreting government policies and goals strengthens communities
niche 3	80	Community power and local involvement
niche 4	80	As niche 3

3.3.Supporters

The supporter canvas is a collection of ten thousand simple agents, scattered in the practices space. At the start of the simulations, the supporters are scattered in three groups in the practices space: the largest (80%) 'mainstream' group has preferences similar to those of the regime. The 'concerned' group (15%) have higher sustainability preferences, especially on the CO2 and Social Cohesion practices. The 'active' group (5%) have much higher sustainability preferences, similar to those of the two more radical niches (niches 3 and 4). We note that the sizes of these groups are arbitrary at this stage, and leave a better researched division for future work.

The supporters have two actions performed at every timestep of the model: *moving* in the space, as a response to changing landscape, and *choosing* which agent to support, based on their distance from the agent in the practices space, the relative strength of the agent, and the price of supporting it – an abstract price at this stage. In the housing implementation we included a third decision: whether or not to *refurbish* one's house. Unlike the first two, this decision is taken once a year, i.e., once every 12 timesteps.

While the supply of new houses is determined in the model through policies and landscape, and the dynamics of CO2 emissions from both old and new houses involves practices of supported agents, the dynamics of CO2 reducing refurbishment is importantly left to supporters. Their decision is based on their CO2 practice, the current rate of refurbishment, and policy encouragement (subsidies).
Renovation could be improving insulation / appliances to improve CO2 emissions / energy efficiency;

installing renewable energy source such as photovoltaics; or mitigating other environmental impacts, e.g., adopting water saving measures such as grey water recycling.

3.4. Landscape signals

We include several landscape signals in the model. The landscape signals include slow changing world events, paradigms and environmental conditions, as well as policy interventions dictated by central UK government, regional government, or possibly EU directives. Within the model framework the distinction between non-policy/generic and policy signals is somewhat arbitrary, as both are external forcings, and are not, at this stage, linked to any feedbacks within the model.

3.4.i. Generic landscape signals:

Climate change influence on supporters' preferences assumes climate-related events will be more intense and more frequent over the next decades. Public actors will increase provision of low emission houses through new-build, demolition and refurbishment, and might push for high density build as a mitigation policy. Consumers' preferences shift towards lower emission lifestyles including lower emission houses and transport. We arbitrarily model this signal as three bell-shaped curves, each pushing supporters towards lower CO2 preferences. The first such wave is assumed to have started in 2005, peaking at 2010, and lasting approximately one decade.

Demographics affect CO2 emissions and household waste: Both emissions and waste per household are considerably higher per capita for 1 person household than for large (4+) households. INCPEN (2001) gives estimates of 1600kg waste/person/year for single person households, compared with 1000kg for large households, and energy use of 190GJ/person/year for singles, compared with 80GJ in large households. The 40% House study (Boardman *et al.*, 2005) has population figures of 59.2 million in 2002, and projects 66.8 million in most of its scenarios for 2050, including the 40% House Scenario, which we will use here.

To estimate the demographic effect, we make the following assumptions: (1) energy use is a proxy for household CO2 emissions[3] (2) we can approximate the use per person for both waste and energy as a linear function of average household size, and (3) this linear relationship holds until 2050. Using the 40% house figures of 25.6 million households in 2002, with an average household size of 2.31, and their scenario of reduced household size to 2.1 in 2050 (for 66.8 million people this means 31.8 million households), we can estimate projected increase in waste and CO2 emissions. Assuming 'large' households (4+ people) have an average of 5-6 people, this calculation gives an increase from 2002 to 2050 of 28-29% in total household CO2 emissions, and 26-27% in total household waste. We start the model at 2000, so the figures should be slightly increased. For simplicity, we estimate a 30% increase in total household CO2 emissions and waste production due to demographic changes between 2000 and 2050, and use a linear function.

Fuel prices rise as global oil price increases from 2000 to 2050. This shifts supporters' preferences to more energy efficient houses and more use of slow modes, assuming 100% increase in (real terms) household fuel prices from 2000 to 2050. This is modelled as a step function, with three steep increases in price. This is not meant as a quantitative prediction of oil prices, but rather aims to capture the notion that cheap (fossil fuel) energy cannot last forever. Alternative scenarios for this signal are of course possible, but were not explored in this paper.

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[3] Microgeneration installations are considered a form of energy-use reducing refurbishment in this calculation.

Inequality increase: The last two landscape signals are more abstract. We assume that in the market economy socio-economic inequality, as defined by poverty levels and accessibility, will increase unless mitigating actions and policies come into play. This will negatively affect social sustainability indicators, but can be reduced in the model by policies and practices which increase provision of low emission houses and refurbishment (to alleviate fuel poverty), increase mixed-use zones (to increase accessibility), and improve public transport and community cohesion. For simplicity we assume a slow, linear increase in this landscape signal.

Environmental degradation: Similarly to inequality increase, environmental degradation in air quality, ecological systems etc. from increased pressure on land and other resources is assumed to increase, causing pressure for improved land use in planning new-build and existing communities. Again, we assume a linear signal for simplicity, which will shift supporters' preferences slowly towards less landfill use and denser living patterns.

*3.4.ii.*Housing policies:

We include four specific housing policies in the model: the first two may be seen as subsidies or regulations, giving an advantage to agents with certain practices by making them more attractive to supporters. The last two policies affect the housing stock, and do not have feedbacks which affect the agents or supporters. The numeric effects in the model are summarised in Table 8.

- *1. Subsidies to improve CO2 emissions / energy efficiency* in houses. This policy gives an advantage to agents with a low CO2 emissions practice, by lowering their price (and thereby making them more attractive to supporters).
- *2. Subsidies to tackle social inequality*. This policy gives an advantage to agents with good social cohesion practices, by lowering their price.
- *3. Schemes to improve refurbishment and renovation*. This policy increases the probability of supporters refurbishing their homes, and increases the average emissions saved through renovation.
- *4. Increased demolition of energy inefficient houses*. This policy increases the rate of demolition of the most energy inefficient houses. The rate of new-build adjusts accordingly, so more new, energy efficient houses are built. It is worth pointing out other sustainability aspects of demolition: it can harm communities, especially if conducted in a piecemeal fashion rather than as part of an overall renewal plan (Power & Mumford, 1999; SDC, 2007); and whether it is more environmentally beneficial than renovation may depend on how responsible the demolition process is (Weizsäcker *et al.*, 1998). However, in this work we take the simple energy approach detailed in 3.6.ii.

Table 8: quantified policy effects in the model

policy	period of effect	effect in model
1	2010 – 2040	Increased attractiveness for agents with low emissions practice (practice 1). This is captured by lowering effective price† in Equation (1) as follows: (a) if practice 1 < 25 => effective price down 50% (b) if 25 < practice 1 < 40 => effective price down 20%
2	2010 – 2050	Increased attractiveness for agents with good social practices (practice 6). This is captured by lowering effective price† in Equation (1) as follows: (a) if practice 6 > 50 => effective price down 40% (b) if 50 > practice 6 > 40 => effective price down 20%
3	2010 – 2050	Relative improvement in emissions following refurbishment / renovation (*z* in 3.6) is increased by 50%; probability of refurbishment is increased up to fourfold.
4	2010 – 2030	Increased demolition rate by 5,000/year to a maximum of 80,000/year. Without the policy the maximum is 20,000/year, see 3.6.ii.

† We do not imply that the price of the house would be reduced by this percentage, rather this is an attempt to quantify the overall effect of subsidies and other promoting policies on the attractiveness of the paradigm this agent represents.

3.5.Sustainability indicators

Changes in practices can have affects on various sustainability indicators. While the practices themselves, and the relative strengths of the different agents, can tell us a lot about sustainable development, we also include a short list of semi-quantitative indicators in an attempt to evaluate the sustainability impacts of changes in the system. For example, changes to the practice of (direct) energy use from houses may indicate a change in people's preferences and choices, but the total emissions from direct energy use are a combination of behaviour, infrastructure, and the nature of the housing stock. We therefore defined a CO2 emissions indicator for a rough calculation of emissions. Other indicators similarly combine different practices and other parts of the model.

When calculating indicators from practices, we take each *agent's* appropriate practice and its relative strength, rather than *supporters'* practices. This reflects the fact that the practices of the agent one supports are a better expression of a supporter's behaviour than its ideal practices.

3.5.i.CO2 emissions: Emissions-related indicators are common. For example, The Egan Review's sustainability indicator #17 (ODPM, 2004) and *Sustainable development indicators in your pocket* indicator #6 (DEFRA, 2006) both list *Household energy use*, and refer to CO2 emissions. As a first attempt, we include only direct CO2 emissions from households, i.e., appliances, space heating and water heating, although related emissions from house building, daily transport in the community (commuting etc.) and other factors could be included in future work. 'Potential' CO2 emissions from the changing housing stock (3.6) are estimated from the 40% House study (Boardman *et al.*, 2005). Our calculation will be a combination of the potential emissions indicated by the changing housing stock and the household energy use practice, as an indicator of behaviour, calibrated by the demographic changes as defined by the demographics landscape signal. We use the relative strengths of the different agents (regime and niches) and their position on the household energy use practice axis as a proxy for household emissions. The emissions at time *t* are therefore calculated from the average potential emissions from the housing stock, *ave* (see 3.6) and the demographic change *demog* (from 0 to 0.3, see 3.4.i), summed over the agents with their relative strength and emission profile:

(5) $$\textit{total emissions}(t) = \textit{ave}(t)\,(1 + \textit{demog}) \sum_{\textit{agents}} \textit{strength} \times \textit{energy use}\,.$$

3.5.ii.Accessibility: Accessibility captures whether key services and facilities are available nearby, the difficulty of the journey (time, price, convenience), and whether there are options other than a car journey. The Egan Review indicator #34 (ODPM, 2004) looks at the percentage of residents finding it easy to access key local services. We calculate accessibility from three practices: density, zoning and public transport/slow modes. We assume that in areas of high density, mixed-use zoning is enough to provide good accessibility, but lower density areas require a high use of public transport/slow modes. As with emissions, we calculate for the system by the relative strength of each agent as indicators for the infrastructure, institutions and behaviours. The calculation for each agent is:

(6a) low density ($\textit{density} < 35/100$):

$$\textit{accessibility} = 0.1 + 0.4 \times \textit{zoning} + 0.4 \times \textit{transport} \qquad \text{(maximum 0.9)}$$

(6b) medium density ($35/100 \le density < 65/100$):

$$accessibility = 0.3 + 0.4 \times zoning + 0.25 \times transport \quad \text{(maximum 0.95)}$$

(6c) high density ($65/100 \le density$):

$$accessibility = 0.5 + 0.4 \times zoning + 0.1 \times transport \quad \text{(maximum 1)}$$

3.5.iii.Community strength: While we do not include any detailed social interaction modelling in this work, we attempt to assess how various parameters could affect community strength as a social sustainability indicator, in addition to the social cohesion practice. Lower car use (as indicated by the public/slow modes practice) is assumed to contribute to community strength, following studies such as Appleyard (1981) - see 3.2.iv. More recent reports suggest initiatives such as Home Zones can improve communities (DfT, 2005). We also assume mixed-use zoning improves communities, and that very low density limits community strength. Our indicator is calculated again by agent, as 70% social cohesion practice, and 10% each from the practices mixed-use zones, density and public transport/slow modes:

(7) $$community\ strength = \sum_{agents} strength \times (0.7 \times social\ cohesion + 0.1(zoning + density + transport)).$$

Other indicators: While we consider other sustainability impacts, the above listed three indicators were the only ones explicitly calculated in the model. However, we note several other potential indicators from this model, such as land use, where density, travel and waste to landfill would serve as proxies, or 'non-decent' and 'unfit' homes, as used by The Egan Review indicator #26, could be estimated from the changing housing stock as new houses are built and old houses are refurbished.

3.6.Housing stock

Unlike the preceding descriptions of model application, this is a new addition to the model (i.e., since Bergman *et al.*, 2008), added specifically for this case study. We model the changing housing stock as two distinct stocks, using the *40% House* terminology (Boardman *et al.*, 2005): **old houses** are those built prior to 1996, and **new houses** are houses built from 1996 onwards. New houses have much higher efficiency and insulation on average than old ones. In 2000 there were about 23,000,000 households in the UK, most of them old houses and about 600,000 new ones. By 2050, there could be 10,000,000 or more new houses.

We model the two changing housing stocks through the processes of **building**, **demolition** and **refurbishment**. Building applies only to new houses, the other two processes to both stocks, although refurbishment and demolition of new houses will be zero or very low in the early 21st century. As we are interested in CO_2 emissions from the housing stock, we need to model the changing emissions that each of these three processes causes. This can be seen schematically in Figure 2.

We capture the CO_2 emissions by the changing size of the stocks, and the changing average emissions level in each stock. The description below applies to each of the stocks new and old, except for new-build, which is only for new houses.

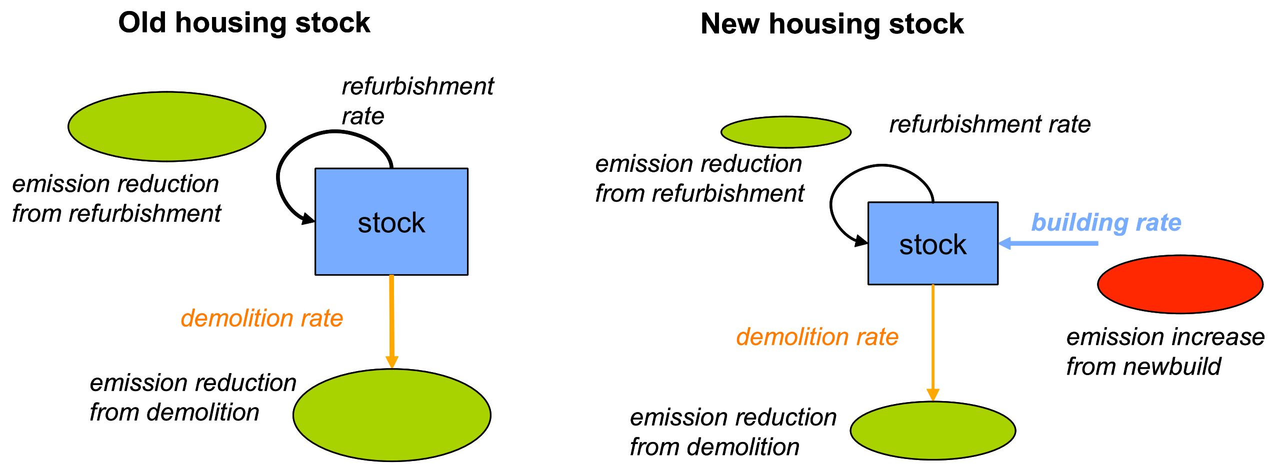

Figure 2: Schematic highlighting changes to emissions from old (left) and new (right) housing stocks through building, refurbishment and demolition. Blue boxes indicate the stocks, green ovals indicate emission reduction, red ovals emission increase, with size qualitatively indicating magnitude. Old building stock is improved through refurbishment, and its size decreased through demolition, both resulting in emission reduction. New building stock has far less refurbishment and demolition, resulting in more modest emission reductions, and a building rate which increases the size of the stock, thereby increasing emissions (unless the new-build is completely carbon neutral).

3.6.i.New-build

We define b as the number of new houses built (per year), and *ave* as the average emissions of the housing stock. Therefore, at time t, we can express the average emissions of the new-build as:

(8) $$ave_b = ave_t(1-x),$$

i.e., houses built at time t are relatively more efficient than the extant stock by x. x is a year upon year improvement, determined by a learning curve, or by supply and demand. The total stock at $t+1$ is:

(9) $$stock_{t+1} = stock_t + b,$$

and the total emissions are given by:

(10) $$stock_{t+1}ave_{t+1} = stock_t ave_t + b \times ave_b .$$

From (8) and (10) we find the improvement in the average emissions from t to $t+1$:

(11) $$ave_{t+1} = \frac{stock_t + b(1-x)}{stock_t + b} ave_t .$$

Different rates of building should be balanced by the demolition rates and the demographic assumptions, to increase the stock by nearly 10,000,000 in 2050. This is roughly 200,000 new houses per year + replacing demolished houses.

3.6.ii.Demolition

Similarly, we define d as the number of houses demolished per year. We assume the houses demolished were of poorer quality than the average. This is expressed as:

(12) $$ave_d = ave_t(1+y),$$

where y is the relative surplus of emissions of demolished houses over the average stock. A similar calculation to the one above gives us:

(13) $$stock_{t+1} = stock_t - d \, ,$$

(14) $$ave_{t+1} = \frac{stock_t + d(1+y)}{stock_t + d} ave_t \, .$$

For old houses, the 40% House scenario explores the effects of increasing demolition from present rates of about 20,000 per year to 80,000 per year in 2016, remaining at that level until 2050, targeting the least efficient houses (high *y*). Different rates should be included in policy options. For new houses, we take $d = 0$ at the beginning of the simulation (year 2000), and assume that no houses are demolished until they are ~30 years old. So, from 2026, as 'new houses' get older, d increases, but at a much lower demolition rate of new houses than old houses, even in 2050.

3.6.iii.Refurbishment

Finally, we look at refurbishment. We define *r* as the number of houses refurbished per year, and *z* as their relative improvement in emissions so that:

(15) $$ave_r = ave_t(1-z) \, .$$

The total stock is unchanged, so we have:

(16) $$stock_{t+1} = stock_t \, ,$$

(17) $$stock_{t+1} ave_{t+1} = (stock_t - r) ave_t + r \times ave_r \, .$$

This gives us:

(18) $$ave_{t+1} = \left(1 - \frac{r}{stock_t} z \right) ave_t \, .$$

On average, refurbished old houses could reduce their net energy demand by up to 1/3 (see Table 1). The 40% House scenario (Boardman *et al.*, 2005) has over 20 million old houses still standing in 2050, almost all of which require some refurbishment to save energy. So *r* could be up to 400,000 houses a year, with *z* up to 0.33, dependent on policies / preferences / practices. For new houses, $r = 0$ in 2000, assuming ~10 years until refurbishment starts, when technologies become widely available or as repairs are needed; *z* will be lower than for old houses.

3.6.iv.All together

Assuming our timestep of one month is short enough to approximate continuous functions, we have, for new and old housing stocks, respectively:

(19) $$ave_{t+1,new} = \frac{stock_{t,new} + b_{t,new}(1 - x_{t,new})}{stock_{t,new} + b_{t,new}} \times \frac{stock_{t,new} + d_{t,new}(1 + y_{t,new})}{stock_{t,new} + d_{t,new}} \times \left(1 - \frac{r_{t,new}}{stock_{t,new}} z_{t,new} \right) \times ave_{t,new}$$

(20) $$ave_{t+1,old} = \frac{stock_{t,old} + d_{t,old}(1 + y_{t,old})}{stock_{t,old} + d_{t,old}} \times \left(1 - \frac{r_{t,old}}{stock_{t,old}} z_{t,old} \right) \times ave_{t,old} \, .$$

4. Model simulations

The agent-based nature of the model leads to results which are not deterministic, and simulation runs using the same starting parameters are never identical, and can sometimes have very different dynamics. The model was run with different policy combinations, repeating each combination at least

20 times. This allowed us to characterise typical simulations for different policies, both in terms of model dynamics (i.e., the agents changing practices, support and strength) and sustainability indicators, and also to analyse the diversity of behaviour.

4.1.Dynamics of agents under different policies

Model runs showed a diversity of results, but with strong commonalities. In the overwhelming majority of runs, the existing, 'business as usual' regime collapses before 2050, regardless of the policy options chosen. This is due to the effect of landscape changes, namely climate change, rising fuel prices, increasing household numbers and decreasing household sizes. However, in most cases, there is no stable regime taking its place at the end of the simulations; rather, there are a number of empowered niche agents (ENAs). Most runs show a collapse of the regime between 2020 and 2030, with niche 1 (energy efficient housing) becoming the strongest agent. However, niche 1 is not strong enough to become a stable regime; towards the end of the run it becomes weaker, and niche 2 (spatial environmental planning) becomes the strongest agent, although not powerful enough to be a regime by 2050. In a small percentage of runs one of the more radical niches (niche 3 or niche 4) becomes the strongest agent. The near certainty of regime change most likely indicates landscape signals and policies are too strong; while the probabilities may not be well predicted, the different scenarios are of interest and may be plausible.

There are nonetheless clear differences in the inter-agent dynamics between the runs with different policy options. Policy 1 gives an advantage to low CO2 emission practices, primarily niches 1 and 2. Policy 2 gives an advantage to practices promoting social sustainability, primarily niches 3 and 4. Policies 3 and 4 directly affected the housing stock, and did not change the agent dynamics.

Figure 3 shows batches of 10 runs for no policy, policy 1, and policies 1 and 2 together. The main differences in dynamics when adding policy 1 are that niche 1 overtakes the regime sooner, and is more likely to become an interim regime, while niche 2 is more likely to be stronger than niche 1 at the end of the run. In other words, policy 1 gives more power to these niches over the regime, and they grow faster.

Adding policy 2 has the effect of making the two alternative niches, 3 and 4, stronger. The runs with both policies show that one or the other of these niches is likely to become an ENA by the end of the run, and in a few runs one of them becomes the most powerful agent, resulting in very different practices from the original regime.

One other dynamic deserves attention: the *absorption* of niche 1 by the regime, which happened in approximately one run in 5 when all policies are used. The absorption mechanism represents a situation where the regime breaks out of the lock-in and adapts to landscape changes by taking on practices of a niche, incorporating some of the niche's norms, paradigms, and perhaps some of its actors, without major disruption. Figure 4 shows an example of such a run. The business-as-usual regime absorbing the energy efficient housing niche is a plausible scenario, whereby mainstream builders and planners incorporate building of more energy efficient houses into their practices, as a reaction (or adaptation) to changes in norms and an increased demand for low energy, low CO2 emission houses. However, it is not clear how likely such a scenario is, i.e., how strong the current lock-in is. Model runs show this absorption occurring around 2010-2012. If the niche is not absorbed by then, it becomes an ENA, too powerful to be absorbed, resulting in the dynamics discussed above.

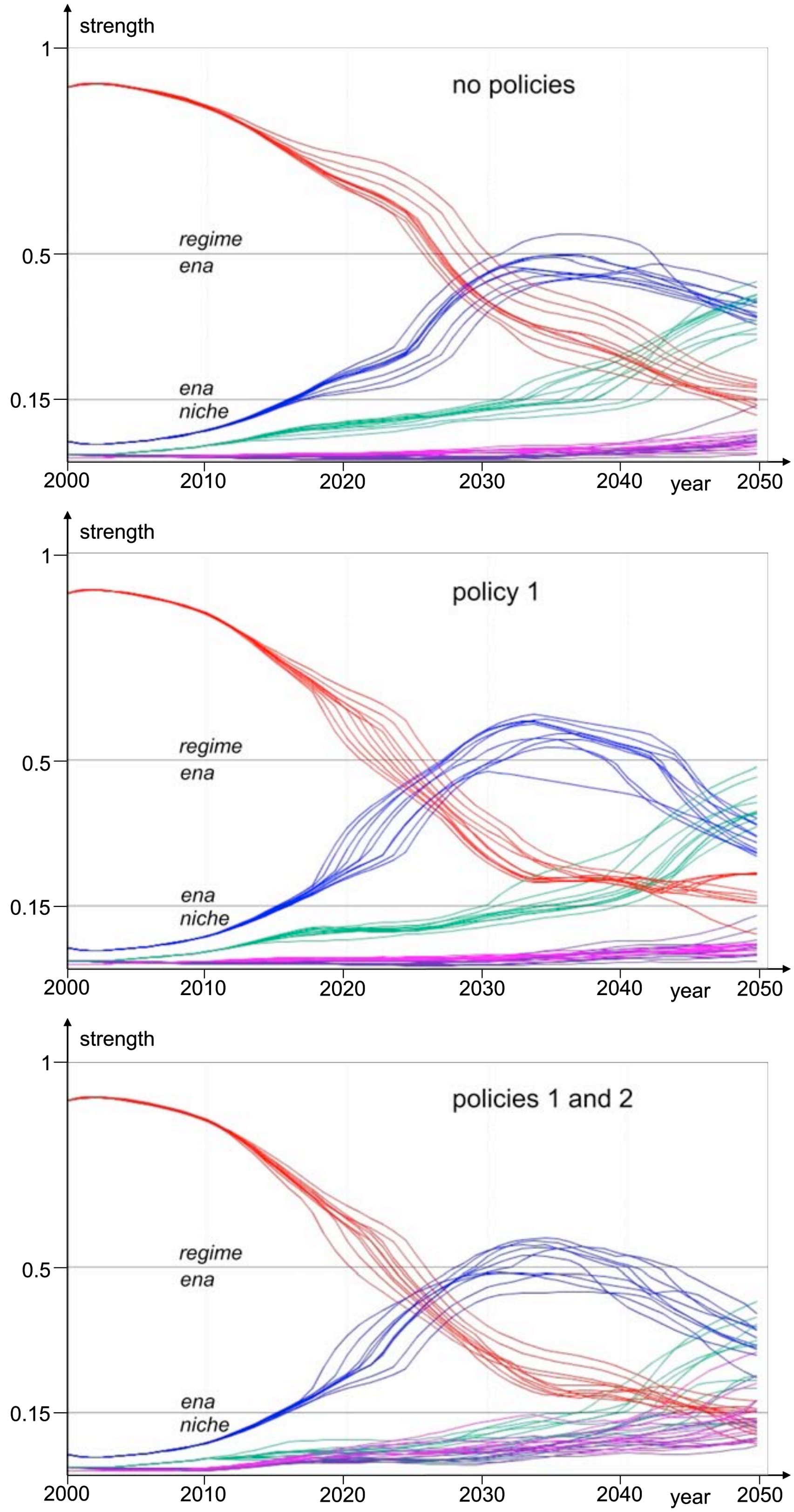

Figure 3: Batch runs of three different policy options: each panel shows agent strength over time in ten runs with one of the policy options: no policy (top), policy 1 only (middle) and policies 1 and 2 (bottom). The x-axis is the year, the y-axis the relative strength of agents, with vertical sections differentiating niches (bottom), ENAs (middle) and regime (top). The agents are: red – business as usual regime; blue: niche 1 – energy efficient houses; green: niche 2 –

spatial environmental planning; pink: niche 3 – alternative (eco-)communities; maroon: niche 4 – community action groups.

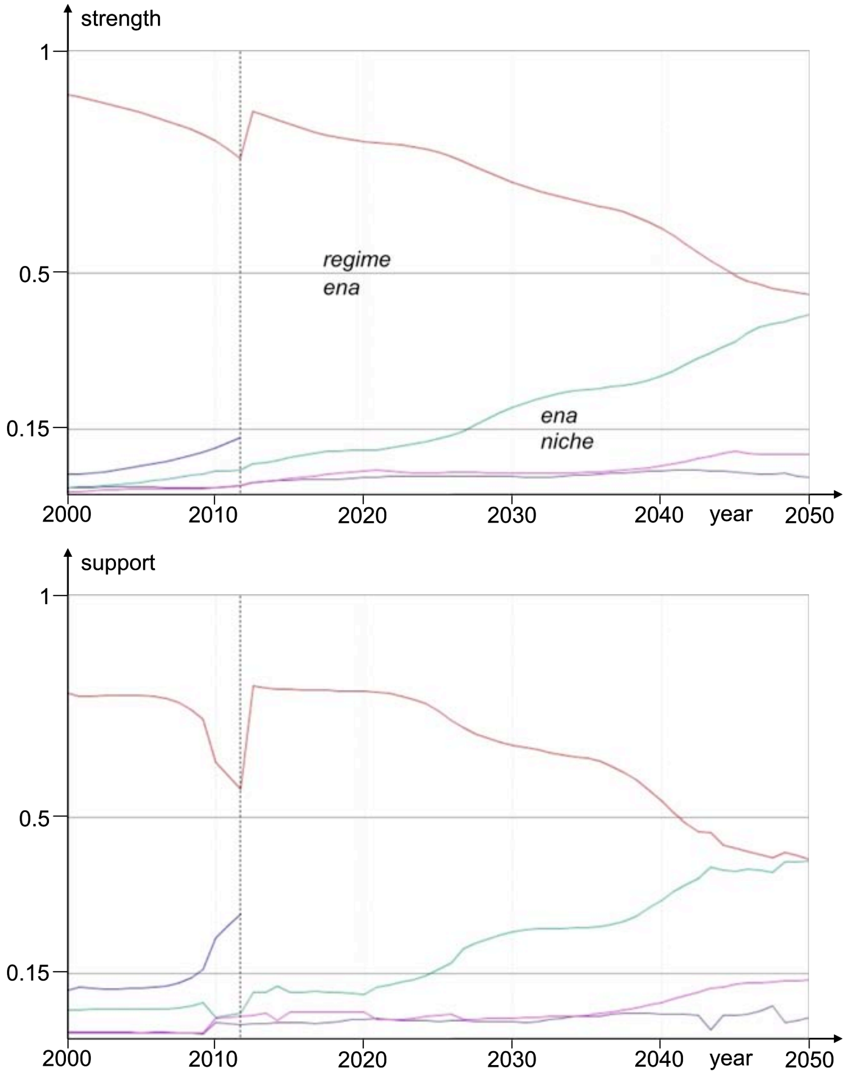

Figure 4: Dynamics of a typical model run with absorption. The y-axis in the top panel is relative strength of agents, as in Figure 3, and the y-axis on the bottom panel is share of support. The dotted vertical line shows the time of absorption. Agent colours as in Figure 3. The support of niche 1 grows, followed by an increase in its strength. The regime protects itself by taking on practices and some norms of the niche, effectively 'absorbing' it. This results in the support and strength of the regime recovering.

4.2.CO2 emission profiles

Model runs show a drop in CO2 emissions from the residential sector, even when no special policy options are chosen. The changing landscape, including climate change and fuel price rise impacts on preferences and norms are in themselves enough to cause increasingly efficient new-build and a rise in demand for refurbishment of old houses, as well as minor shifts in behaviour, for a total of nearly 1/3 emission reduction. However, including the various policy options causes considerably greater emission reduction (see Figure 5). Policy 1, which encourages a wide variety of actors with low CO2 practices, yields an average drop in emissions to 63.1% by 2050. Adding policy 2, which empowers social sustainability actors, slightly improves the results, as these actors generally have better than average CO2 practices as well. Policies 3 and 4, greatly increasing refurbishment rates of energy inefficient houses and demolition of energy inefficient housing, yield an average drop to 54.8%.

Combining all four policies yields an average drop to 51.4% by 2050, nearly 1/2 of 2000 emissions, despite the demographic changes of population rise and household size decrease. This is less than government targets of a 60% emissions reduction, however, our results are only semi-quantitative, and we think the relative success of different model options are more meaningful than the absolute emissions cut. Policy 1 is far more effective when it runs all the way through to 2050; when it is active only for part of the simulation, there is a 'rebound' of rising emissions, as agents with lower CO2 practices lose power.

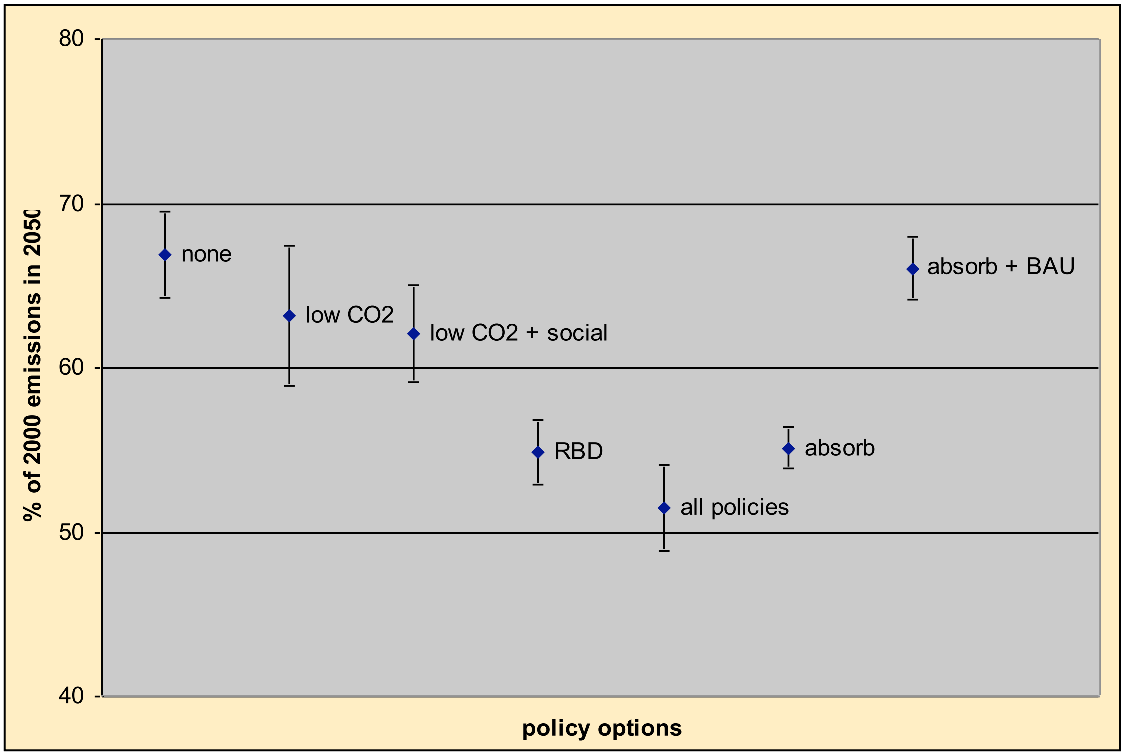

Figure 5 Average reduction in CO2 emissions from the housing sector in 2050 (relative to 2000): the y-axis indicates emissions in 2050 as a percentage of those in 2000 assuming the different policy options listed in 3.4.ii; the error bars show standard deviation from the average. *none* = none of the four policies included; *low CO2* = policy 1 - subsidising agents with lower CO2 practices; *social* = policy 2 - subsidising agents with more socially sustainable practices; *RBD* = policies 3 and 4 - targeting infrastructure by increasing refurbishment, building energy efficient new houses, and demolition of old inefficient houses; *all policies* = all four policies in conjunction; *absorb* = as all policies, in runs where the regime absorbs the energy efficient housing niche; *absorb + BAU* = as absorb, in runs where the original (business-as-usual) regime survived. All based on 20 runs, except *absorb + BAU*, based on seven runs, due to this being an unusual result.

As with model dynamics, here too runs in which the original regime absorbs niche 1 (see 4.1 above) are of interest. In these runs the regime adapts to the changing landscape by taking on some of the practices of niche 1, i.e., building more energy efficient houses. In these runs the regime manages to stay in power longer, but usually collapses in the 2040s. Emission reductions are slightly less successful as other runs with similar policies, e.g., 55.1% drop with all policy options with absorption, compared to 51.4% without. In a small number of runs the original 'business as usual' regime survives to 2050 through adaptation after the absorbing niche 1. Significantly, in these runs the emissions reduction is to 66.1%, similar to the result with no policies activated. In other words, this suggests that if the current building and planning regime maintains its power through the adoption of more energy efficient buildings, and in doing so staves off calls for more radical change to city spatial planning, reduced traffic and increased social sustainability measures, emission cuts would be much worse than if the current regime were replaced.

While the drop in emissions due to the changes in stock (refurbishment, demolition and new-build) is continuous, the overall drop in emissions is more variable, being more rapid when the original regime falls or in times of increased landscape signals, as these times indicate changes in supporters' practices (see Figure 6). This is partly a model artefact, but could realistically indicate periods of more rapid emission reduction and periods of slow reduction or even increase, such as the first several years of the 21st century.

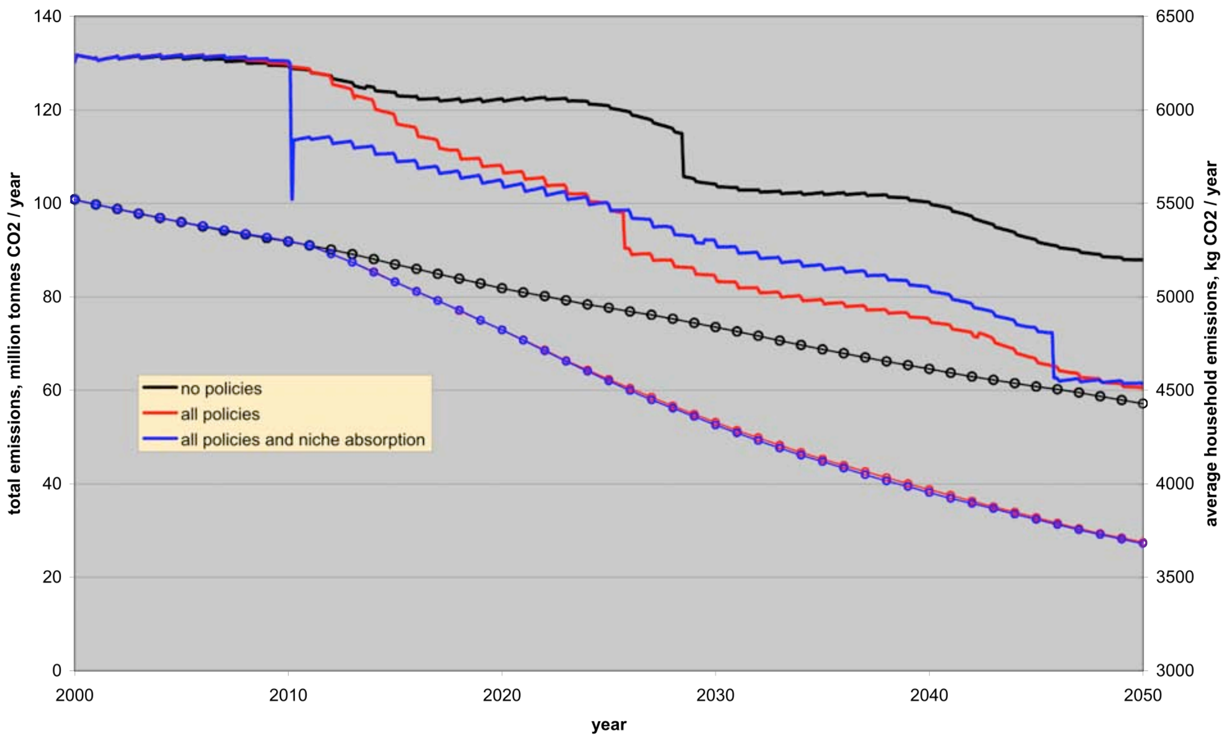

Figure 6: CO2 emission reduction in three typical runs with different policy measures: no policy measures (black), all four policies (red) and all policies runs in which the regime absorbed niche 1 (blue). The x-axis shows the year, the left hand y-axis total emissions per year from the housing sector (solid lines) and the right-hand axis changes to the average household emission, calculated for the housing stock change only, i.e., through refurbishment, demolition and new-build, not including demographic and behavioural changes (lines with circles). The waviness and discontinuities of the total emissions lines are model artefacts: the first is due to the housing stock being updated only once a year, with other parameters changing every month; the second occurs when a regime falls, except the deep discontinuity in the blue line which occurs at the time of niche absorption.

4.3.Other indicators

We analyse two sustainability indicators other than a reduction in CO2 emissions: accessibility of services and facilities, and community strength, as defined in 3.5. For these indicators, we consider our results to be more qualitative than quantitative. Both of these indicators show a significant improvement from 2000 to 2050 in all runs. This is partly due to our choice of landscape signals, and may well indicate that they are overly optimistic in the change in preferences and behaviour they cause. It may also indicate a lack of feedbacks in the model: the *increase in inequality* landscape signal pushes consumers towards higher social cohesion practices, thereby strengthening agents with higher social sustainability practices. However, there is no feedback to reduce the inequality one might assume from the stronger communities which emerge.

Nonetheless, we find it useful to analyse the relative effects of different policy options on these indicators, see Figure 7. The different policy options have overall similar effects on these two indicators. Policy 1, which supports low CO2 emission practices, has little or no effect on community strength and accessibility. Including policy 2 as well, which supports social cohesion, significantly improves the relative community strength. However, there is a very high variability in the final result, especially when both policies are included. This is a result of the more complex and variable dynamics of the runs with both policies included (see 4.1): there is variability both in the *relative strength* of the agents between runs, and also changes in the *practices* of the different agents at the end time of the run. Runs where the radical agents (niches 3 and 4) gain strength show higher social sustainability indicators on average than other runs.

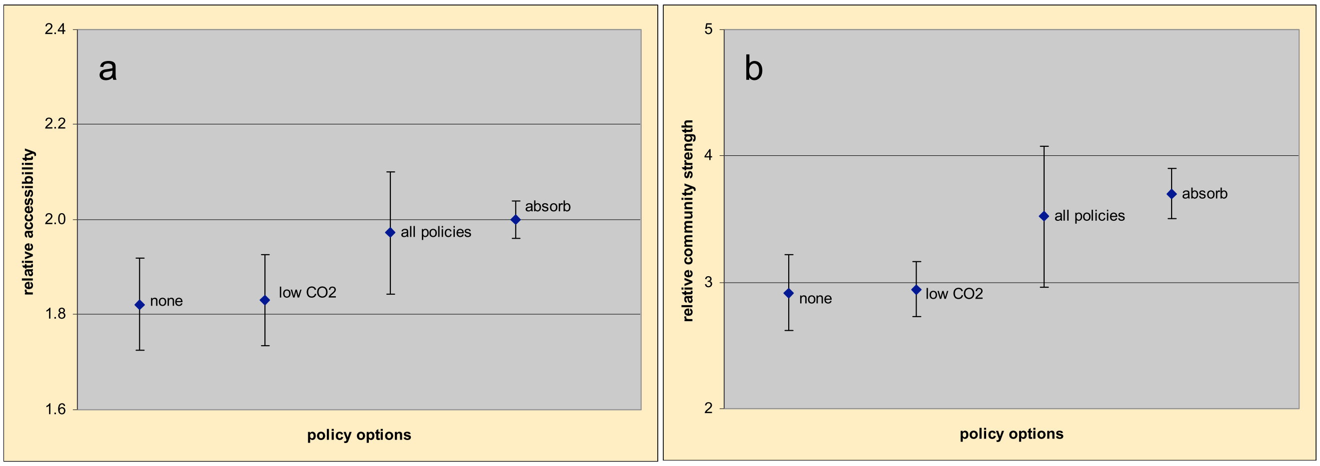

Figure 7 Average improvement in sustainability indicators in 2050 relative to 2000: accessibility (a) and community strength (b) indicators, as defined in 3.5. The y-axis denotes the indicator value in 2050 relative to 2000 assuming different policy options. Policy options as listed in Figure 5; *all policies* and *low CO2 + social* give the same results, as the RBD policies don't affect these indicators. All based on 20 runs.

Runs where the regime absorbs niche 1 show a very low variability, in contrast to other runs with both policies. These runs show slightly higher sustainability indicators on average, and a much lower standard deviation than other runs, especially in accessibility. We attribute the lower variability to the continuity of the regime over most of the simulation in these runs: while there are different outcomes towards the end, for the period 2000-2040+ the same regime is in place (see Figure 4), causing the whole system to follow a more predictable, slow change of practices, and thereby reducing the possible variability.

Unlike the CO2 emission drops, runs where absorption leads to the business-as-usual regime remaining in power until 2050 do not differ significantly from runs where the regime collapses despite niche absorption. This is at least partly due to the fact that the accessibility and community indicators in the model can change faster than the CO2 emission rates, which are linked to the slow turnover rate of the housing stock. Further work is needed to fully develop these indicators.

5. Discussion and conclusions

There is much evidence of unsustainability in the residential sector in the UK. Analysing this sector using transitions theory shows evidence of lock-in, i.e., the system is entrenched in current unsustainable practices through economic, social and normative inertia. Transition theory suggests that a more sustainable sector can only be reached via systemic change, or transition. We use a model to capture some of the dynamics in this sector. For example, systemic lock-in is captured by making the regime slow changing and difficult to depose, the latter a result of its attractiveness to supporters, which is itself a result of being powerful.

Our model simulations suggest that the current planning and construction regime is untenable in the face of change over the coming decades. These results are the outcome of model assumptions about landscape change, specifically: assuming a stronger effect of climate change on public opinion as its effects manifest more strongly, significant increases in real fuel prices for households, and the continued trend of an increase in household numbers and a decrease in household size. In the model, change is led by landscape change shifting supporters' preferences, and possibly a shift in their support. This forces the agent, and specifically the regime, to adapt or lose support and ultimately power. However, these dynamics should not be misconstrued as all change being consumer-led. The shift of preferences and support expresses not only consumer support and public opinion, but more broadly cultural trends, political climate, incentives and economic investments. The model is limited in this respect in that it cannot distinguish cultural or public opinion-led change from political or economic-led change.

The two most common scenarios portrayed in the model runs showed a collapse of the current house building and planning regime, earlier if it does not adapt to the changing nature of the sector, and later if it adapts by absorbing some of the practices of more energy efficient and environmentally-friendly alternative builders and planners. The early collapse scenario is followed by practices of planning and building energy efficient, low emission houses becoming the norm. However, this new paradigm does not last, as changing landscape conditions make these minor adjustments insufficient; the more thorough re-planning of urban spatial environment then becomes the norm, with new actors becoming more powerful. The absorption and later collapse scenario shows the adaptation of the regime to be temporarily successful, but similarly insufficient in the long run. Another noteworthy scenario is the current regime surviving through to 2050 after successful adaptation which included absorption. This is arguably the business-as-usual scenario towards which we are heading due to the lack of sufficient pressure for radical change; the fact that it occurs in only a small percentage of model runs could indicate that model assumptions and dynamics make such change too likely. Overall, the system is not completely predictable, with occasional runs resulting in more radical agents coming into power.

Our simulations show a reduction of 1/3 to 1/2 in direct CO_2 emissions in the residential sector, depending on policies adopted. This is despite a population increase and decrease in household size, indicating reductions of up to ~60% for individual households. The agent dynamics discussed above suggest that building more energy efficient houses is only a temporary measure, and more changes are necessary to ensure a significant and ongoing reduction in emissions. To maximise reductions, a combination of policies was found to have the best effect. On the one hand, increased renovation of energy inefficient houses, along with targeted demolition of poor houses (policies 3 and 4) are needed to improve the housing stock. On the other hand, support through legislation, regulations or subsidies of actors with low CO_2 policies is needed (policy 1), as this supplies the complimentary measures of changing citizens' support, which could be expressed as choosing lower CO_2 appliances, lower emission behaviour, and increased renovation. Measures outside the house were not included in the CO_2 emission calculation: a more complete calculation would include effects of traffic levels, mixed zoning, and other factors.

Results suggest that if the current regime were to persevere until 2050 (through absorption and adaptation), even with change of practices to support more energy efficient houses, this would actually impede significant CO_2 reductions, as the small changes the regime makes to stay in power prevent deeper infrastructural changes at the systems level. The business-as-usual agent did not completely disappear in any of the runs, indicating that some of the current practices are likely to continue despite radical changes to the system.

Some runs showed no regime at 2050, with two or more vying empowered niches. This implies widespread parallel, competing processes: some builders, planners, local authorities and other actors would support and act under a spatial environmental planning paradigm (for example), with some institutional, infrastructural and governmental support, while other actors would continue with business-as-usual practices similar to the current situation, with their own infrastructure and institutions. Such a period might offer people a real choice between radically different developments, neighbourhoods, or even towns. However, none of the alternatives would be as readily accessible and complete as a regime. While such a transitional period is certainly possible, it seems unlikely that a period of no regime would persist for a long time in the UK housing sector, assuming political stability.

The socio-economic sustainability indicators are not as developed in this work as the emissions calculations. Nonetheless, a few conclusions can be reached. Policies aimed solely at lowering CO2 emissions did not perform as well at these sustainability measures as did the inclusion of policies supporting actors with strong social sustainability (policy 2). The latter improved our community strength indicator, as well as the accessibility indicator. This would suggest that such policies are highly desirable: they not only improve social and economic sustainability, but can contribute to lower CO2 emissions through changes to the broader community level and built environment. A deeper reduction in emissions requires infrastructural and normative changes which can be encouraged by these policies. Conversely, policies aimed solely at lowering CO2 cannot guarantee sustainability in other areas, and are limited in the emission reductions they offer through lack of broader change.

Further development of this case study could include more quantification of the model, specifically for social sustainability indicators and CO2 emissions in the residential sector outside the house. Another possibility would be division into regions or city and town sizes, for a more detailed analysis. Ultimately, we believe this type of model could prove a useful tool for policymakers to investigate different policy options and their potential impact on different aspects of sustainable development in the residential sector in the UK.

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