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Review

Reducing energy demand through low carbon innovation: A sociotechnical transitions perspective and thirteen research debates

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ABSTRACT

Improvements in energy efficiency and reductions in energy demand are expected to contribute more than half of the reduction in global carbon emissions over the next few decades. These unprecedented reductions require transformations in the systems that provide energy services. However, the dominant analytical perspectives, grounded in neoclassical economics and social psychology, focus upon marginal changes and provide only limited guidance on how such transformations may occur and how they can be shaped. We argue that a socio-technical transitions perspective is more suited to address the complexity of the challenges involved. This perspective understands energy services as being provided through large-scale, capital intensive and long-lived infrastructures that co-evolve with technologies, institutions, skills, knowledge and behaviours to create broader 'sociotechnical systems'. To provide guidance for research in this area, this paper identifies and describes thirteen *debates* in socio-technical transitions research, organized under the headings of emergence, diffusion and impact, as well as more synthetic cross-cutting issues.

1. Introduction

Improvements in energy efficiency and reductions in energy demand are widely expected to contribute more than half of the reduction in global carbon emissions over the next few decades [1]. To provide a reasonable (66%) chance of limiting global temperature increases to below 2 °C, global energy-related carbon emissions must peak by 2020 and fall by more than 70% in the next 35 years. As an illustration, this implies a tripling of the annual rate of energy efficiency improvement, retrofitting the entire building stock, generating 95% of electricity from low-carbon sources by 2050 and shifting almost entirely towards electric cars [2]. The rate and scale of change required is best described as revolutionary: there are few historical precedents and existing policy initiatives have achieved only incremental progress towards those ends [3].

Major reductions in energy demand will require the widespread uptake of technical and social innovations. The paper focuses on ***demand-side low-carbon innovations***, which refer to new technologies, organisational arrangements and modes of behaviour (or social practices) that are expected to improve energy efficiency and/or reduce energy demand. This broad definition encompasses both incremental and radical innovations relevant to all energy using sectors. Fig. 1[1] provides some relevant examples, broadly classified by their degree of technical or social novelty.

To date, most policy efforts have focused upon technically and socially incremental options (in the bottom left quadrant of Fig. 1). While these are important in the short term, they face diminishing returns in the long term, since their potential for further diffusion is limited. Hence, more substantial demand reductions are likely to require more radical innovations that are presently at an earlier stage of emergence and require larger changes to existing sociotechnical systems.

The two dominant approaches that have, so far, underpinned most policy efforts (neo-classical economics and social psychology) have strengths, but also important limitations for understanding both the emergence and diffusion of radical innovations and the associated system transformations [4]. Neoclassical economics considers energy or carbon prices to be the critical variable in reducing energy demand, supported where appropriate by policies to reduce economic barriers to energy efficiency, such as split incentives, asymmetric information, high transaction costs and difficulties in accessing finance [5–8].

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[1] Radical innovation need not only refer to 'new to the world' innovations, like 3D-printing. Radical innovation can also refer to 'new to the city' (e.g. district heating, light-rail) or 'new to the organization' (e.g. tele-conferencing).

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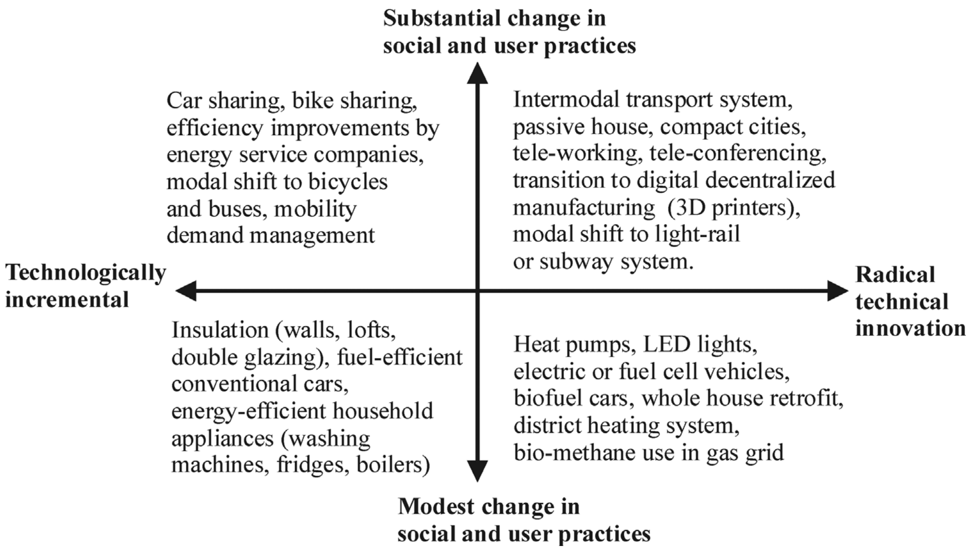

Fig. 1. Variety of low carbon innovations with different degrees of social and technical novelty.

Neoclassical economics also provides a rationale for supporting new, energy efficient technologies at different stages of the 'innovation chain', but offers only limited insights into either the process of innovation or the most effective means of policy support.

These recommendations have at least three drawbacks. First, for most consumers energy efficiency represents a secondary and largely invisible attribute of goods and services, thereby muting the response to economic incentives. Factors such as comfort, practicality and convenience commonly play a larger role in energy-related decisions, with energy consumption being dominated by habitual behaviour shaped by social norms [9,10]. Second, carbon pricing is politically unpopular and energy efficiency remains a low political priority, resulting in a policy mix that is frequently weak and ineffective [11]. Third, neoclassical economics assumes rational decision-making by firms and individuals and tends to pay limited attention to the broader, non-economic determinants of decision-making [12].

Insights from behavioural economics and social psychology provide deeper insights into the cognitive, emotional and affective influences on relevant choices and routines and suggest ways to 'nudge' people and organisations towards more energy efficient choices and routines [13–15]. But social-psychological research focuses overwhelmingly upon individual consumers and under-appreciates the importance of interactions with other actors, organisational decision-making and economic and social contexts. More fundamentally, both economic and social psychology have an individualist orientation that underrates the significance of the collective and structural factors that shape behaviour, guide innovation and enable and constrain individual choice.

Thus, the dominant perspectives on reducing energy demand have a number of limitations and these limitations are reflected in the partial focus and relative ineffectiveness of the current policy mix. Given this, we propose a broader socio-technical perspective that more fully addresses the complexity of the challenges involved as well as integrates relevant insights from various social science disciplines.

A socio-technical transitions perspective is more appropriate for two reasons. First, energy services such as heating and mobility are provided through large-scale, capital intensive and long-lived infrastructures that *co-evolve* with associated technologies, institutions, skills, knowledge and behaviours to create broader 'sociotechnical systems' [16–22]. These systems are termed 'sociotechnical' since they involve multiple, interlinked social and technical elements, such as technologies, markets, industries, policies, infrastructures, user practices and societal discourses. Second, a transitions perspective acknowledges specificities of the kinds of change processes involved. Sociotechnical systems have considerable inertia, making it difficult for radically different (and more sustainable) technologies and behaviours to become established – such as electric mobility or mass transit schemes. Hence, reducing energy demand involves more than improving individual technologies or changing individual behaviours, but instead requires interlinked and potentially far-reaching changes in the systems themselves – or 'sociotechnical transitions'. These transitions are typically complex, protracted and path dependent and the outcomes are difficult to predict. A socio-technical transitions perspective acknowledges these characteristics, while neo-classical economics and social psychology do not.

The socio-technical transitions perspective has received much attention in recent years [3,22–25]. In fact, authors have made so many and diverse contributions in recent years that there is a risk of not seeing the forest for the trees. Our key contribution is therefore to inductively identify and describe thirteen key debates within this literature that are relevant for energy demand reduction. Our aim is to construct a research map useful for guiding future research.

We have organized our discussion along three research themes: emergence, diffusion and impact. Although this is suggestive of a linear model of innovation, we think the distinction is useful since each theme encompasses very different analytical topics. *Emergence* and *diffusion* of radical demand-side low carbon innovations refer to different phases in decades-long transition processes (although the boundaries between them may be fuzzy). *Impact* refers to the ultimate effect of low carbon innovations on energy demand. Acknowledging complexities, we also identify crosscutting debates that span the three themes. The focus throughout is on theoretical and conceptual issues rather than specific empirical topics. Many of the debates are relevant to research on 'sociotechnical transitions' in general as well as to research on energy demand in particular.

The paper proceeds as follows. Section 2 briefly introduces the sociotechnical transitions perspective on low carbon innovation and contrasts this with more mainstream approaches to understanding innovation. Section 3 then explores the *emergence* of low carbon innovations from a sociotechnical perspective and identifies five debates on which further research is required. Section 4 briefly conceptualizes the *diffusion* of low carbon innovations and identifies three pressing debates. Section 5 addresses the *impact* of low-carbon innovations on energy demand and identifies three further debates. Section 6 then highlights two cross-cutting debates that span all three themes, while Section 7 concludes.

2. The sociotechnical transitions perspective

Numerous frameworks identify themselves as being 'sociotechnical', with scores more focusing broadly on the interactions between science, technology, and society. One review identified no less than 96 distinct frameworks or theories focusing across the domains of technological change, sociotechnical transformation, sustainability transitions, or the diffusion, acceptance, and use of new technologies [26]. Nonetheless, there are some key distinctions that set our sociotechnical transitions perspective apart from others, which we examine here.

2.1. Assumptions with regard to innovation

The sociotechnical approach differs from more conventional models of innovation, which often equate innovation only with new technology. The simplest 'linear' model of innovation assumes that technological development proceeds according to its own, internal logic, largely separated from society, and that once introduced in society, it 'causes' social changes. This model envisions science and technology as an assembly line that begins with basic research, follows with development and marketing of a given technology, and ends with the product being purchased by consumers. Fischer [27] characterized this as a "billiard-ball" model, in which technological development rolls in from outside, and impacts elements of society, which in turn impact one another.

A more sophisticated model sees innovation as arising from an *innovation system*, defined as a "network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies" [28]. This model highlights the interactions and feedback loops between the different phases of R&D, development, demonstration, market formation and diffusion. Innovation is viewed as a collective activity involving many actors and knowledge feedbacks and is strongly influenced by institutional settings [28]. Within policy and scholarly debate around low-carbon transitions, this challenge has increasingly been framed in terms of 'pathways' towards change [29–31].

The sociotechnical approach takes this further and focuses upon how innovation processes are often about creating new *sociotechnical systems* through the co-construction of multiple elements [32–34]. In addition to technological changes, this involves changes in infrastructures, markets, regulations, user practices and so on. The successful development of bike-sharing, for example, is about modal shifts from cars to cycling, shifting from individual ownership to sharing, developing robust bicycles, establishing an infrastructure of docking stations and easy payment facilities, establishing new business models, building political support, ensuring effective maintenance and repair, and disseminating positive discourses about cycling more generally.

The 'co-construction' of user practices and technology [34–36]. is particularly relevant for our interest in reducing energy demand. On the one hand, technologies are adjusted (in smaller and larger steps) to fit better with the user environment. On the other hand, the user environment (user practices, behavioral routines, infrastructures, policies, etc.) is adjusted to accommodate the new technologies. In this way, technologies, environments and user practices *co-evolve*, as Fig. 2 depicts.

More generally, the sociotechnical approach is concerned with the *interactions* between various actors in the development and diffusion of innovations. These may include researchers, designers, engineers, firms, consumers, policymakers, urban planners, intermediaries and the media. A sociotechnical analysis pays attention to interpretations, interests, decisions, resource allocations, learning processes, and power struggles among these actors. Innovation is understood as arising from actions and interactions in social contexts, rather than from an intrinsic technical or economic logic (e.g. the 'best' technology wins).

Within the sociology of technology, there are different kinds of socio-technical approaches that share some of the above characteristics,

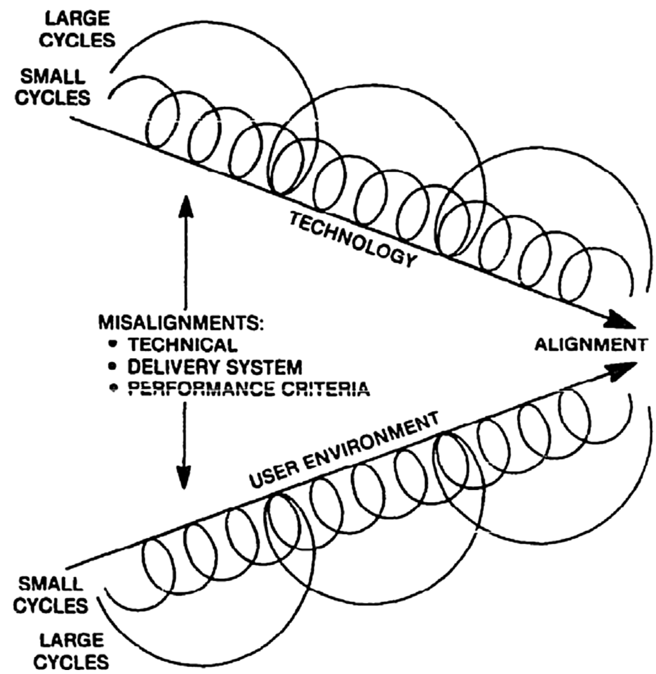

Fig. 2. Co-construction of technology and user environment ([37]: 251).

but differ in other ways. The Social Construction of Technology (SCOT) approach [38], for instance, focuses on the *meanings* of technologies and how these emerge from competing interpretations in relevant social groups. SCOT consequently downplays the importance of economic considerations such as finance and market competition. SCOT-studies tend to focus on the emergence and stabilisation of artefacts, but pay less attention to diffusion, impact or replacement of existing systems. The Large Technical System (LTS) approach [39,16] focuses on a particular kind of technology: large-scale, integrated infrastructures. LTS-scholars address emergence, diffusion and societal transformation, but also pay less attention to replacement of existing systems. Their emphasis on 'system builders' also has heroic, voluntarist connotations, often with a supply-side orientation. Actor-Network Theory (ANT) [40] is a radical approach that adopts a 'flat ontology', which means it understands coordination as emerging from circulations and translations between local practices [41]. It thus challenges the traditional social science emphasis on institutions and social structures as coordinating forces. ANT also challenges traditional views on actors by endowing artefacts (including electrons, scallops, assault rifles, and doorstops) with agency, because they hold socio-technical networks together. While provocative, ANT's translational focus makes it impractical for investigating decades-long transition processes as its methodological recipe to 'follow the actors' is difficult to put into practice.

To understand transitions, we suggest that the Multi-Level Perspective (MLP) [42,43,18] is the most suited socio-technical approach. The MLP combines ideas from SCOT (on social networks and interpretations) with evolutionary economics (which acknowledges economic dimensions and struggles between radical innovations and existing systems). The MLP thus spans foundational social science dichotomies [44]: agency and structure; stability and change; ideational and material dimensions.

2.2. Transitions in sociotechnical systems

Substantial reductions in energy demand require *transitions* towards new or durably reconfigured sociotechnical systems in heating, lighting, motive power and mobility. Promising low carbon innovations are the seeds for such transitions, but many of them are currently small in terms of market share and amount of investment and face uphill struggles against existing sociotechnical systems.[2] One implication is that current policy interventions (which revolve around cost structures, information provision and regulation) may be insufficient to bring about non-marginal change. A second implication is that low carbon innovations should not be studied in isolation, but in the context of their compatibility with and struggles against existing sociotechnical systems. One framework to understand these issues is the Multi-Level Perspective (ML), which we briefly describe to contextualize our later discussion.

The MLP distinguishes three analytical levels [42,43,45].

1. The incumbent *sociotechnical system* refers to the interdependent mix of technologies, industries, supply chains, consumption patterns, policies, and infrastructures. These tangible system elements are reproduced by actors and social groups, whose perceptions and actions are shaped by rules and institutions, such as shared meanings, heuristics, rules of thumb, routines and social norms. These more intangible elements are referred to as the sociotechnical *regime*. Innovation in existing systems is mostly incremental and path dependent, aimed at elaborating existing capabilities, because of various lock-in effects [17]. These include sunk investments (in skills, factories, and infrastructures), economies of scale, increasing returns to adoption, favourable regulations, cognitive routines, social norms and behavioural patterns. These reinforcing factors act to create stability in the incumbent system.
2. *Niche innovations* refer to novelties that deviate on one or more dimensions from existing systems. The novelty may be a new behavioural practice (e.g. car sharing), a new technology (e.g. battery-electric vehicles), a new business model (e.g. energy service companies), or a combination of these. Because radical novelties initially have poor price/performance characteristics, they cannot immediately compete with existing systems (e.g. electric vehicles or heat pumps). Particular applications, geographical areas, markets or subsidized programs therefore act as 'incubation rooms' – called 'niches' – which protect novelties against mainstream market selection [46,47]. In these niches, radical innovations are initially often developed by small networks of dedicated actors, often outsiders or fringe actors [48].
3. The *sociotechnical landscape* forms an exogenous environment beyond the direct influence of niche and regime actors, but acting upon them in various ways. This may be through gradual changes, such as changes in cultural preferences, demographics, and macro-political developments, or through short-term shocks such as macro-economic recessions and oil shocks.

Transitions come about through processes within and between the three analytical levels that vary over time. In the *emergence* phase, niche actors engage with radical innovations (e.g. by improving technologies, opening up markets, finding customers, attracting investment, lobbying policymakers for support), but this does not automatically lead to sociotechnical transitions because existing systems are stabilized by multiple lock-in mechanisms. In the *diffusion* phase, niche innovations build up internal momentum (through various mechanisms, discussed below), while changes at the landscape level create pressure on the regime. The subsequent destabilisation of the regime creates windows of opportunity for niche innovations to diffuse. The wider breakthrough of niche innovations leads to broader system transformation, which generates *impacts*.

This brief description indicates that the MLP provides a big picture understanding of transitions. The next three sections draw upon this framework to further assess the processes through which low carbon innovations *emerge* and *diffuse*, together with their *impacts* on energy demand. In each case, we first provide a general *conceptualisation* of the relevant theme (emergence, diffusion, impact) and then highlight several *research debates* within this theme. These are largely theoretical debates that need to be connected to empirical questions.

3. Emergence of low carbon innovations

Research on *emergence* does not focus on the initial invention of new ideas (e.g. from scientific research), but on the early introduction of these ideas and their concrete embodiment into society. Confusingly, the word 'innovation' is often used as a synonym for emergence, and to distinguish early introduction from 'diffusion'. The distinction between emergence and diffusion is often fuzzy and gradual, but the former involves much greater emphasis on plurality, experimentation, testing, demonstration and collective learning.

The introduction of innovations tends to be difficult because the supportive sociotechnical contexts that allow innovations to thrive – e.g. networks of institutions, formalised and tacit knowledge, social norms and expectations, design standards, financial resources, and so forth – have yet to be established. A common manifestation of the absence of supportive contexts for innovations is the so-called 'valley of death' [49] between research or demonstration projects on the one hand and full-blown market commercialisation on the other. Many novelties fail to cross this chasm or take a very long time to do so. As a result, it is difficult to mobilise sufficient financial resources and/or policy support for development and subsequent diffusion.

According to the sociotechnical transitions literature [46–52], the creation of 'protective spaces' is a useful and important means of encouraging emerging innovations because they shield those innovations from the pressures imposed by the existing system and give them time to mature. Such protective spaces allow actors associated with innovations to address and reduce a wide range of uncertainties, including:

1. *Techno-economic uncertainties*: There may be competing technical configurations (electric vehicles, for instance, may use lead acid batteries, nickel metal hydride batteries, lithium ion batteries, and zinc air batteries), each with different advantages and disadvantages.
2. *Finance and investment related uncertainties*: Often it is difficult not only to obtain the funding that is necessary for technical development and practical experimentation, but also to evaluate the rationality of investments in innovations. To attract funding, product champions often make positive promises [53,54] and even expert analysts in technical areas often suffer from 'appraisal optimism' [55–57].
3. *Cognitive uncertainties*: Actors developing niche innovations often have different views and perceptions about technical specifications, consumer preferences, infrastructure requirements, future costs, and so forth [58]. This 'interpretive flexibility' [38] gives rise to debates, disagreements, discursive struggles and competing visions [59,60].
4. Social uncertainties: The networks of actors developing niche-innovations are often unstable and fluid. Actors may enter into partnerships for a few years, but then leave if difficulties arise or funding runs out [61]. Start-up or spin-off firms may be attracted by new opportunities, but then may also exit when economic ventures fail (as they often do in early phases).

To address these uncertainties, the literature on 'strategic niche management' (SNM) distinguishes three core processes in the development of niche-innovations (see [51], for a summary):

- *Articulation of expectations and visions*: Expectations are considered crucial for niche development because they provide direction to

[2] The UK heating system, for instance, is dominated by individual boilers (95% of households), most of which are linked to the national gas infrastructure (80% of households) [175]. So, low carbon heating innovations that rely upon different energy carriers (e.g. heat pumps) or require different infrastructures (e.g. district heating) face considerable difficulties in becoming established.

learning processes, attract attention, and legitimate (continuing) protection and nurturing [53,54,62];

- *Building of social networks*: This process is important to create a constituency behind an innovation, to facilitate interactions between relevant stakeholders, and to provide the necessary resources (e.g. venture capital, people, and expertise) for further development and subsequent diffusion [46];
- *Learning processes* along multiple dimensions [63], including: technical aspects and design specifications; markets and user preferences; cultural and symbolic meaning; infrastructure and maintenance networks; production, supply chains and distribution networks; regulations and government policy; and societal and environmental effects.

Niches can be said to gain momentum if: first, visions and expectations become more precise and more broadly accepted; second, the alignment of various learning processes results in shared expectations and a 'dominant design'; and third, networks increase in size, including the participation of powerful actors that add legitimacy and expand resources [51]. These processes of *stabilisation*, growing *acceptance and support* and *community building* tend to occur over sequences of concrete demonstration projects, experiences and trials (see [50], for one conceptualisation of these processes).

Having summarised and characterised the niche-innovation literature, we now identify five research debates that are relevant to the emergence of low carbon innovations.

3.1. The relative role of outsiders and incumbents

One debate that has attracted significant attention is the composition of social networks and the question of which actors drive the innovation. Specifically, what are the roles of new entrants relative to actors *within* the incumbent regime such as electric utilities and car manufacturers? The early SNM literature and the grassroots innovation approach [64,65] suggested that start-ups, civil society organisations and grassroots innovators tend to pioneer radical niche innovations because they are less 'locked in' and willing to think 'out of the box'. Incumbent actors, in contrast, were thought to focus on incremental innovations that fit easier with existing capabilities, capital investments and interests.

Recent work has questioned this simple dichotomy, identifying many instances where incumbent actors develop radical niche innovations [66–70]. New entrants may also collaborate with incumbents in order to draw on their financial resources, technical capabilities and political connections. This may accelerate emergence but almost inevitably entails some 'mainstreaming' and weakening of the radical aspects of the innovation [71]. While this may enhance the scalability of innovations – i.e. the potential for growth and wider diffusion – the risk is also that their critical edge and potential to bring about 'deep' changes to contemporary society are lost.

3.2. The scalability of niche-innovations

A second debate concerns the scalability of niche-innovations. Some innovations (like bike-sharing) may be scaled up through successively larger demonstration projects [72,50]. But others (like bike co-operatives or urban gardening projects) may be more difficult to scale-up and hence remain relatively small – catering to the needs of a specific (local) user segment. This raises questions for policy. A focus on efficiency and effectiveness may result in a greater support for scalable innovations that hold the promise of significant reductions in energy consumption, including electric vehicles and urban light rail. Yet, less scalable innovations may provide significant wider and/or not necessarily easily quantifiable benefits. For instance, bicycle cooperatives can fulfil an important role in the maintenance of individually and publicly owned bikes and, like urban gardening projects, assist in the (re)integration of disadvantaged youth, ex-convicts, etc. into working life and mainstream society [73]. This may make support for innovations with limited scalability worthwhile and raises hitherto largely unaddressed questions for SNM and multi-level thinking: is up-scaling of niches the only way through which regime shifts can come about?

3.3. Place and geography

A third debate concerns the significance of place and geography for sustainability transitions [74–76]. While the sociotechnical literature is strong on temporal issues, it has paid less attention to spatial questions such as: Why do innovations emerge more often in some than in other places? Why do transitions unfold faster in certain locations than in others? What is the role of local and regional institutions, policies and forms of governance in the emergence and diffusion of innovations? Much of the recent thinking on the geography of sustainability transitions focuses on cities and urban networks [68,77–80]. This is largely because cities now house the majority of the world's population; urbanisation is continuing apace [81]; cities have long been the cradle of innovations and creativity [82,83]; and economic and state restructuring under neoliberal capitalism have enhanced the economic and political significance of cities [84,85]. Research on the role of place, cities and urban networks can advance understanding of how interactions within and across niche innovations, and indeed niche innovations themselves, are constituted by assemblages of regulation, funding, discourses, the pre-existing material fabric (e.g. buildings, physical infrastructures, technical artefacts), collective values and customs that are both place-specific and networked across localities. This deepens insight into the locational 'stickiness' (e.g. why have all attempts to create congestion charge schemes in the UK beyond London failed?) and spatial politics of niche innovations, and hence their scalability and potential transferability.

3.4. The economic and business dimensions of niche innovations

A fourth debate is the need to further articulate the business and economic dimensions of niche-innovations. Reflecting their sociological origins, SNM studies have tended to focus disproportionately on socio-cognitive dimensions, such as visions, social networks and learning processes. This could be fruitfully complemented with more economic research on the development and evolution of new business models (e.g. energy service companies, bike/car sharing) and the role of (private and public) funding mechanisms [86–89]. The latter is especially important since funding is a major constraint on the emergence of innovation in sectors such as domestic buildings and urban transport [68]. Insights from political economy can also be utilised to analyse how powerful actors influence funding streams [90]. Another important economic issue is how investments in emerging (technological) innovations may generate broader economic benefits, such as 'green jobs'. Promises of such benefits form a key part of societal debates around such innovations (e.g. underpinning the creation of the Office for Low Emission Vehicles), even though there are many uncertainties about the size of these benefits and to whom they accrue [91].

3.5. Changing user practices

A fifth debate concerns changes in user practices in relation to niche innovations. This topic has not been studied in great depth in the SNM literature, which has focused more on new technologies and services than on their consumption and end-use [92,93]. Further development of the role of users in niche-innovation can draw on insights from various literatures. For example, the literature on domestication [94–96] emphasizes the creative agency of consumers who do not just *buy* new technologies but also embed them in their daily lives. This requires cognitive work (learning about the artefact and developing new competencies), symbolic work (articulation of new interpretive categories, symbols, and beliefs that guide 'sense-making' of new technologies) and practical work (adjustment of user routines to match the new technology). Similarly, the literature on user innovation [97–99] suggests that users play active roles in the development of new uses of technologies that were not foreseen by producers. Furthermore, interactions between supply and demand may be facilitated by intermediary actors (e.g. consumer organizations, patient representatives, organizations, marketing and testing agencies, retailers, auto clubs, salespeople) and by institutional loci where users, mediators and producers can meet to negotiate and align technical design choices and user preferences [99–104].

4. Diffusion of low carbon innovations

The widespread *diffusion* of low carbon innovations is necessary to achieve energy demand reduction on a substantial scale. However, large-scale diffusion in mass markets often means head-on competition with incumbent sociotechnical systems, which are stabilised through the alignment of existing technologies with the business, policy, user and societal contexts. Therefore, the diffusion low carbon innovations does not happen in an 'empty' world, but in the context of existing systems that provide barriers and active resistance [105]. Another problem is that many low carbon innovations are not intrinsically attractive to the majority of consumers since they are often (initially) more expensive and perform less well on key dimensions. Much of the recent policy interest in low carbon innovation is driven by public good concerns (e.g. sustainability, climate change) rather than by private interests, which implies that diffusion is unlikely to be driven solely by economic mechanisms. Policy support, cultural discourses and social pressures are therefore likely to be important factors as well, which means that a multi-dimensional approach is required.

The MLP conceptualises diffusion as entailing two interacting developments: 1) the creation of *endogenous momentum* of niche-innovations; and 2) the *embedding* of niche-innovations in wider contexts and environments. Both developments can be seen as process of *co-construction* and *alignment*.

Endogenous momentum arises gradually from the same processes that drive the emergence of innovations, namely: developing larger social networks with greater legitimacy and resources; aligning learning processes on multiple dimensions (technical, market, infrastructural, social political, cultural) resulting in a 'dominant design'; and forming clear and widely accepted visions of the future of the innovation. The gradual shift from the *emergence* phase to the *diffusion* phase is characterized by a *reversal* in which the innovation shifts from initial flexibility (when it is fluid and socially shaped) to 'dynamic rigidity' [106]. Hughes [16] describes the emerging *momentum* of new systems in terms of an increasing 'mass' of technical and organizational components,[3] emerging directionality and system goals, and an increasing rate of perceptible growth. Thus, endogenous momentum is driven my multiple and reinforcing causal mechanisms including: expansion of social networks and bandwagon effects; positive discourses and visions; learning by doing; increasing returns to scale; network externalities; strategic games between firms (e.g. 'jockeying for position'); and increasing support from policymakers who see the innovation as a way of solving particular problems.

The diffusion of low carbon innovations also requires *embedding* within policy, social, business and user environments [107]. This external fit may be difficult to foresee, as Rosenberg ([108]: 14) noted more than forty years ago: "the prediction of how a given invention will fit into the social system, the uses to which it will be put, and the alterations it will generate, are all extraordinarily difficult intellectual exercises". Achieving this fit may be especially difficult for more radical niche-innovations that often face a 'mismatch' [109] with the existing sociotechnical system. The process of societal embedding is conceptualised as a co-construction process that entails mutual adjustments between the innovation and wider contexts: "Technology adoption is an active process, with elements of innovation in itself. (…) Behaviours, organization and society have to re-arrange themselves to adopt, and adapt to, the novelty. Both the technology and social context change in a process that can be seen as co-evolution" ([42]: 389). The degree of adjustment is a question for research, where one extreme is that the innovation is adjusted to fit in existing contexts and another extreme is that the contexts are adjusted to accommodate the innovation.[4]

The distinctive contribution of a sociotechnical approach to diffusion is to study the interaction between endogenous mechanisms and external embedding. Although adoption decisions by individual consumers remain important, the sociotechnical perspective focuses upon the activities of a broader range of actors. Within this literature, we highlight three debates that are relevant to the diffusion of low carbon innovations.

4.1. How does the MLP relate to existing diffusion models

First, a general debate is how the MLP-based view on diffusion relates to existing diffusion models that have been developed in the economic, sociological, geographical, and psychological literatures [110–113]. We suggest that these existing models may be grouped into three broad families, namely: *adoption* models, *socio-technical* (or co-construction) models, and *spatial* models (Box 1).[5] The MLP currently draws primarily upon the socio-technical (co-construction) models. A conceptual research challenge is therefore to consider if and how the socio-technical[6] perspective can be enriched with insights from the adoption and spatial models. A second question is how relevant the various diffusion models are for different types of low carbon innovation and if their salience varies over time[7].

4.2. Diffusion of systemic innovations

Second, there is a debate regarding the diffusion of *systemic* innovations (which often, but not necessarily, have an infrastructural component). The adoption models, which are the dominant approach in diffusion research, can be criticized for focusing on discrete artefacts or products such as televisions, computers, and consumer goods. The diffusion of *systems* or "systems of systems" [116] poses particular challenges, which have not yet been systematically addressed ([117]: 160; [118]). Lyytinen and Damsgaard [119], for example, note six specific shortcomings in the diffusion literature with regard to systems.[8]

Future research could therefore fruitfully investigate how systems

[3] "The large mass of a technological system arises especially from the organizations and people committed by various interests to the system. Manufacturing corporations, public and private utilities, industrial and government research laboratories, investment and banking houses, sections of technical and industrial societies, departments in educational institutions and regulatory bodies add greatly to the momentum of modern electric light and power systems" ([16]: 76–77).

[4] Smith and Raven [52] proposed a dichotomy, characterizing the first extreme as a 'fit-and-conform' pattern and the second extreme as a 'stretch-and-transform' pattern.

[5] While spatial models can be subsumed under both adoption and co-construction headings, we separate them out because they focus on geo-graphical temporal dimensions (whereas most other models focus only on temporal questions).

[6] ANT has overlaps with the relational geography models, discussed below, which suggests that space is created by the extension of socio-technical networks and relations.

[7] Early electricity systems, for instance, emerged within cities, and were subsequently linked into provincial systems, and later into national systems that spanned entire countries.

[8] (a) Systems are not discrete packages, but develop during the diffusion process, (b) the diffusion environment is not homogenous, but consists of different arenas or niches, (c) diffusion rates do not result from push or pull factors, but from co-evolutionary learning and interaction, (d) consumer preferences and innovation characteristics are not given beforehand, but articulated during the diffusion process, (e) instead of a single diffusion curve, there may be multiple diffusion processes for different application domains, (f) time-scales are not short (months, years), as assumed in many adoption models, but long (years, decades), which requires a processual approach.

Box 1
Three families of diffusion models.

I) Adoption models focus on decisions by individual (and sometimes collective) adopters, in their capacity as 'buyers'. The literature contains various specific models, highlighting different causal mechanisms. Examples include: (a) *Epidemic models* that focus on the spread of information through a population, often through face-to-face personal contacts; (b) *Socio-psychological models* that suggest that the propensity to adopt an innovation depends upon people's attitudes, beliefs, and norms [114] or on their orientation towards novelty, leading to characterizations such as early adopters, early majority, late majority and laggards [110]; (c) *Rational choice models* that focus upon rational cost-benefit calculations and barriers to adoption (e.g. split incentives, uncertainty about payoffs) and the socio-economic characteristics (income, profession, status) that shape the thresholds at which it becomes rational for people to adopt; (d) *Characteristics of innovations models* which focus upon how the features of innovations themselves stimulate or hinder adoption, including relative advantage compared to existing technologies, compatibility with existing values and needs, complexity, trial-ability, and observability [110]; and finally (e) *Increasing return to adoption models* that identify positive feedbacks which improve price/performance characteristics as a technology diffuses, e.g. learning by using, network externalities, scale economies in production, informational increasing returns, technological interrelatedness [115].

II) Socio-technical (or co-construction) models fall into two groups. First, *endogenous models* assume that environments or contexts are actively co-constructed with the innovation. Actor-network theory (ANT), for instance, conceptualises diffusion as a process of creating sociotechnical networks and linkages in which new artefacts can function. Latour ([40]: 108) criticises adoption models for conceptualising diffusion as an autonomous process in which "black boxes are effortlessly gliding through space as a result of their own impetus". Instead, ANT suggests that "the spread in space and time of black boxes is paid for by a fantastic increase in the number of elements to be tied together" ([40]: 108). Latour criticises adoption models for neglecting the 'work' that is required to make diffusion possible. "Thousands of people are at work, hundreds of thousands of new actors are mobilised" (p. 135). Geels and Deuten [72] further develop some ANT-ideas into a *circulation and replication* model of knowledge diffusion, which suggests that experiences with an innovation in one location need to be abstracted and codified into general lessons (e.g. 'best practice' guidelines, design heuristics), which can then 'travel' to other locations, where their application requires adjustments to accommodate local specificities. The diffusion of knowledge can thus be understood as a process of 'disembedding, travel and re-embedding' that requires various actors and socio-cognitive activities. The LTS-approach understands diffusion as a process of physically *building systems* and 'seamless webs', which includes system environments [39]. LTS-scholars emphasize the role of 'system builders' in diffusion, which tends to be understood as a process of upscaling, expansion, and linking smaller systems into larger ones [16].

Second, *contextual co-construction models* focus on the *societal embedding* of innovations into pre-existing environments [108,42,107]. These societal embedding processes may entail: (a) cultural embedding and discursive activities that link new technologies to broader narratives [59]; (b) regulatory embedding, including political struggles over adjustments in existing standards, subsidy programs or regulations; (c) changes in the business environment, including business models, supply chains, skills and labour markets,; and (d) appropriation and domestication activities in user environments [94,95], including symbolic work, cognitive work, and practical work.

III) Spatial models also come in two forms that overlap with the adoption and co-construction models. *Spatial-analytic models* analyse how innovations diffuse through space, which tends to be understood as objectively given and absolute. In particular, they investigate how and why certain geographical locations adopt earlier or later [111] as a consequence of spatial, demographic, economic or industrial characteristics. *Relational geography models*, in contrast, assume that space is not objectively 'given' but emerges from social relations. These models focus on the co-construction of space and the diffusion of innovations. Spatial diffusion is thus explained through social relations, networks and activities [85].

such as district heating or trams diffuse across space and over time. Understanding this under-addressed topic is likely to require novel conceptual work. One additional puzzle is that not all systems need to follow a 'point-source dynamic' (as in S-curves), with change starting small and then diffusing. Some new systems may grow out of old systems. Intermodal or integrated transport systems, for instance, first require sufficiently developed train, bus, tram and/or bike systems that can then subsequently be linked together (e.g. through intermodal ticketing, flexible interlinked timetables, high-frequency services and smart-phone apps). Another puzzle is that existing systems may be reconfigured through the adoption of *multiple* innovations, which together lead to wider changes. Car-based systems, for instance, can be reconfigured through self-driving cars, congestion charges, on-board navigation tools, dynamic road management, and electric vehicles providing back-up capacity for electricity grids (via power stored in batteries). So, rather than following the diffusion of *single* technologies (as diffusion theory still does), one could shift the unit of analysis and ask how *multiple* innovations can reconfigure existing systems [120].

4.3. Accelerated diffusion and low carbon transition

Third, there is a more general debate on how diffusion can be accelerated, which is especially relevant to low carbon transitions and the time-sensitive problem of climate change [121,116,122]. The mainstream climate mitigation literature [123,124] has identified a range of options where strengthened policies could help accelerate low-carbon transitions, such as R&D subsidies, feed-in tariffs, carbon pricing, performance standards and removing fossil fuel subsidies. While useful and important, these studies are instrumentalist, focused on analyses *for* policymakers, not on analyses *of* policy, power, or politics [25].

This is problematic because scholars emphasise that the acceleration of low-carbon transitions is a deeply *political* challenge. The German Advisory Council on Global Change ([125]: 1), for instance, states that while technical and policy instruments for low-carbon transitions are well-developed, it is "a political task to overcome the barriers of such a transformation, and to accelerate the change". To understand such deliberate acceleration it is too simple to focus on 'political will' or ask policymakers to show courage (e.g. [126,127]), because such a voluntarist orientation overstates the importance of politicians' own volition. We therefore agree with Meadowcroft's [128] that it is important to better understand the "*political conditions* required to bring [low-carbon policy instruments] into play" (S16; our emphasis). Conditions for accelerated diffusion may derive from external shocks and crises that change socio-political priorities and create a sense of urgency to accelerate deployment [129,121]. Pressure for stronger policies may also come from changes in public opinion or from companies that see commercial opportunities in low-carbon innovations [130,131]. Diffusion may also be accelerated by incumbent firms reorienting themselves towards radical innovations, thereby making financial resources, technical capabilities and marketing expertise available [66,67,132]. Such reorientation is not easy, and often requires both pressures (e.g. negative cultural discourse, threat of regulation) and economic opportunities (e.g. potential new markets, attractive incentives).

5. Impact of low carbon innovations

Comprehending the *impacts* of low carbon innovations on energy demand is central to public policy: energy efficiency improvements are considered to be the most promising, fastest, cheapest and safest means to mitigate climate change, as well as providing broader benefits, such as improved energy security, reduced fuel poverty, and increased economic productivity [176]. However, compared to the large body of work on emergence and diffusion, the analysis of the impacts of low carbon innovations has received much less attention from sociotechnical researchers. Authors often emphasise the limitations of linear, deterministic approaches to projecting impacts; the frequency with which expectations of impacts are confounded by real-world experience [56,57]; and the challenges associated with both anticipating impacts *ex ante* and measuring them *ex-post* [133].

Quantification of impacts is difficult within complex social systems, but may nevertheless be feasible for more incremental kinds of innovation within restricted spatial and temporal boundaries, e.g. the adoption of condensing boilers and the retrofitting of loft and cavity wall insulation [134,135]. In these examples, sufficient data exists for the historical impacts of these changes to be measured and the relevant systems are sufficiently stable for the future impacts to be modelled.

But establishing the historical or potential future impact of more radical innovations over longer periods of time presents much greater difficulties. For example, commonly used modelling tools may not capture all of the relevant mechanisms [133]; there may be no basis for assigning values or ranges to relevant parameters; and certain types of outcomes may be difficult or impossible to anticipate. The impacts of any change within a complex system are necessarily mediated through multiple interdependencies, time-delayed feedback loops, path dependencies, and threshold effects. More fundamentally, the basic concept of 'impact' is problematic from a sociotechnical perspective, because of its connotations with technological determinism – with technology impacting on society in a linear and straightforward fashion [136,137].

Hence, for radical and systemic innovations it is difficult to establish causality, assess historical impacts and project future 'impacts'. While historical analysis can provide rich descriptions of the co-evolutionary processes involved, the primary lesson is the contingent nature of impacts and our limited ability to anticipate them in advance. In this context, authors in the sociotechnical tradition have focused more upon transition processes than on the ultimate impacts of those transitions.

Against this background, we identify three important research debates that are relevant to the impacts of low carbon innovations.

5.1. Rebound effects

First, there is a critical debate on the rebound effects from low carbon innovations and the extent to which these may undermine the anticipated benefits of low carbon innovations [138]. Such effects result from a number of mechanisms operating at different levels, across geographical scales and over different time periods, but only some of these are amenable to quantification. Moreover, attention to date has focused almost exclusively upon economic mechanisms to the neglect of other co-determinants. As an illustration, consider the following example from transport systems: a) fuel-efficient cars make travel cheaper, so people may choose to drive further and/or more often, thereby offsetting some of the energy savings; b) joint decisions by consumers and producers may channel the benefits of improved technology into larger and more powerful cars, rather than more fuel-efficient cars; c) drivers may use the savings on fuel bills to buy other goods and services which necessarily require energy to provide; d) the energy embodied in new technologies (e.g. light-weight materials) may offset some of the energy savings, especially when product lifetimes are short; e) reductions in fuel demand translate into lower fuel prices which encourages increased fuel consumption, together with changes in incomes, prices, investments and industrial structures throughout the economy; and f) more fuel-efficient vehicles deepen the lock-in to the sociotechnical system of car-based transportation, with associated and reinforcing changes in infrastructure, institutions, regulations, supply chains and social practices.

Rebound is therefore an emergent property of a complex system. A growing body of research is exploring mechanisms *a-b*, and to a lesser extent mechanisms *c-e* in transport and other areas (e.g., [139–141]), but this research excludes non-economic mechanisms, tends to be confined to the short to medium term and stops short of assessing the impacts of broader changes in the relevant systems. Nevertheless, such studies indicate significant departures from anticipated impacts. There is a need to apply the relevant techniques to other innovations, contexts, datasets and time periods, and to extend the analysis to include broader psychological, social, institutional and other factors that either offset, reinforce or contribute additional rebounds – for example, the phenomena of 'moral licensing' [142,143]. However, methods for studying the longer term impacts of sociotechnical transitions need much more development, along with methods for evaluating the claim that ongoing transitions are necessarily more sustainable.

5.2. Analyzing impact scenarios

Second, there is an important set of debates about the construction of impact scenarios including the economic, social and political influences on those scenarios and the societal impacts of the scenarios themselves. Scenarios of both technology diffusion and energy consumption are regularly produced by multiple public and private institutions and it would be useful to examine and compare their underlying assumptions, the processes through which they are constructed, their historical (in)accuracy and the perils and pitfalls that result [144,145]. For example, Gross et al. [55] show how reliance on 'learning curves' for forecasting the future cost of electricity generation technologies has led to over-optimistic estimates, exacerbated by the tendency of analysts towards 'appraisal optimism'. The latter may be an endemic feature of technology appraisals owing to the powerful incentives to raise expectations in order to attract finance and social support [146]. Economic, political and institutional influences can shape the choice of data, methodologies and assumptions within impact studies and the results can legitimise political decisions [177,147,56,57]. Exploring this dimension of impact can enhance awareness of how difficult it is to assess future developments, especially for innovations with substantial transformative potential, and how the process of commissioning, creating and communicating those assessments can influence the developments themselves.

5.3. Modelling tools for sociotechnical transitions

Third, there is an important debate on the use of quantitative modelling tools for forecasting future impacts and the feasibility of modelling broader sociotechnical transitions. The economic and policy analysis literature is replete with model-based projections of future transitions and energy-related impacts. While many traditional modelling tools struggle to accommodate the non-linear, disruptive characteristics of socio-technical transitions [133], relevant quantitative techniques can offer useful insights in appropriate circumstances, provided their limitations are acknowledged. Examples include understanding the impacts of specific innovations within circumscribed spatial and temporal boundaries, or clarifying the long-run relationships between aggregate measures of productivity, consumption and growth.

Until recently, the sociotechnical approach has mostly been used for qualitative explorations of future transitions via sociotechnical scenarios and related techniques [178,148]. As with the historical studies, these primarily focus upon the *process* of future transitions rather than their *impacts*. In light of both the complexity of the processes involved and our limited ability to anticipate future impacts, most sociotechnical researchers have avoided formal modelling and quantification.

In recent years, however, a productive research stream has started to explore combinations of socio-technical and quantitative modelling approaches [149,29,69,70]. Some researchers use new techniques, such as agent-based models or stochastic system dynamics, to simulate socio-technical transitions [150–152]. Other scholars have explored future energy transitions through recursive interactions and 'dialogue' between quantitative models and qualitative socio-technical storylines [153–156]. These bridging attempts form an important new research stream that aims to combine quantitative rigour with processual socio-technical insights.

6. Cross-cutting sociotechnical debates

The relational and co-constructionist nature of a sociotechnical approach can blur the boundaries between emergence, diffusion and impact. We identify two more synthetic cross-cutting debates that span the different themes.

6.1. The co-construction of impacts

The first cross-cutting debate is how impacts of low carbon innovations are co-constructed by choices in the earlier processes of emergence and diffusion. It is easy to use this co-construction notion to criticize 'traditional' impact studies (for being too linear or 'technological determinist'), but more difficult to develop a deeper understanding of relevant processes and mechanisms. There are some starting points in sociological theories of innovation, but these need to be further developed, especially for more radical and systemic low carbon innovation.

Actor-network theorists, for instance, have argued that designers build a 'script' into new technologies, which shapes later behaviour in a non-deterministic manner [157]. So the impacts that manifest themselves in later periods are already (partly) constructed in early design and emergence phases. By the time that the in-built impacts become apparent, it is too late or too difficult to make design changes. This problem is sometimes called the 'Collingridge dilemma' [158], and it has inspired some scholars [159,160] to develop 'Constructive Technology Assessment'. CTA emphasizes not only the importance of early thinking about future impacts, but also feeding the views about possible effects back into design decisions in the emergence phase of technologies (which is arguably important for 3D-printing now).

Social historians [137,27] suggest that impacts arise from the way new technologies are *societally embedded* via specific policies, infrastructures, markets, and societal debates [107]. So, the same innovation (e.g. tele-working, bike-sharing, car-sharing, district heating) can have different impacts in different countries or localities, depending on choices during societal embedding processes.

This idea can be further exemplified by exploring social justice impacts. The material and social transformations associated with the emergence, diffusion and impact of new innovations are imbued with contestations over what is *just*, *equitable*, and *right*. Thus, there is a need for studies that explore questions of ethics and justice across these stages, including concern for where, how and with whom new technologies are socially embedded. Without a focus on justice, an energy efficiency revolution may fail to acknowledge the burden of not having enough energy, where some individuals lack access, are challenged by under-consumption and poverty, and may face health burdens and shortened lives as a consequence of restricted energy choices [161,162].

6.2. Policy, politics and governance

A second cross-cutting debate concerns the role of policy and governance in shaping the emergence, diffusion and impacts of low carbon innovations. Three topics are of particular interest. The first is the importance of the *policy mix* and the synergies and conflict between different instruments. In line with the systemic approach to innovation and impact taken throughout this article, we also take a systemic view of policies and policymaking. As Kern et al. [11] identify, much of the 'policy advice' literature still focuses on individual policy instruments, pairwise instrument interactions or intended policy mixes, neglecting the analysis of complex, real-world mixes, their development over time, and their consistency and coherency. We agree with Sovacool [163] and Kivimaa and Kern [164] about the need for comprehensive policies rather than individual, isolated mechanisms that tend to operate in a non-predictable and non-synergetic matter. As an example, Givoni et al.'s [165] exploration of the transport sector illustrates that the deliberate and careful combination of mutually supportive policy packages may result in more effective and efficient outcomes through increasing public and political acceptability and the likelihood of implementation. It is important therefore to look at the 'whole system' of policy instruments, to identify positive and negative interactions between policies, and to investigate how these hinder or stimulate the emergence, diffusion and impact of low carbon innovations.

The second topic is the pervasive role of *politics* in the emergence and diffusion of low carbon innovations. Early transitions thinking was criticised for being too technocratic, with a failure to fully acknowledge the role of politics and conflict [166,93]. Since then a research stream on the 'politics of transitions' has started to incorporate political science theories into socio-technical perspectives, e.g. Sabatier's advocacy coalition framework [167], Kingdon's multiple streams framework [168], political economy [105,169], and political coalition theories [170], with the aim of better understanding the conflicts and power struggles associated with the emergence and diffusion of low carbon innovations. Consequently, policymaking is not seen as a purely rational process, but as a political process involving multiple stakeholders and social groups (e.g. firms, advisory bodies, consumer representatives, NGOs). So, we perceive policymakers as part of socio-technical systems rather than as steering them from outside ('cockpit view'). The interactions within governance networks entail agenda-setting, discussions, negotiations, as well as disagreements and conflicts that relate to different views, interests and positions.

A third topic is *multi-level governance*, which refers to interactions between supra-national, national and local policies and policymakers. This issue is particularly important for low carbon innovations, many of which are not only implemented but also increasingly configured and governed locally (e.g. tram-systems, cycling schemes, district heating systems, building retrofits). In Europe, such local processes are shaped by local policy makers (and their resources, capabilities, and political responsibilities), operating in the context of national and European framework policies such as targets, regulations and subsidy schemes [171]. This literature usefully contextualizes some of the voluntarist tendencies of the urban transitions literature, discussed in Section 3. Schwanen [68] also shows how successes in the implementation of urban transport innovations in UK cities are dependent on national and EU level support. Bulkeley and Betsill [172] therefore advocate multi-level governance approaches in research on the role of urban planning for climate change protection, thereby blurring the boundaries between global goals and local actions in the presence of the nation-state. Alignments and tensions between supranational, national and local policies are therefore critical in shaping the success (or failure) of low carbon innovations.

Table 1
Key research debates with regard to sociotechnical transitions and low carbon innovation.

Theme	Research debate
Emergence	• the relative role of outsiders and incumbents in the emergence of low carbon innovations • the scalability of niche-innovations • the significance of place and geography for the emergence of low carbon innovations • the contribution of economic factors to the emergence of low carbon innovations • the change in user practices associated with low carbon innovations
Diffusion	• the relationship between the MLP and existing diffusion models • the differences between the diffusion of systemic innovations and the diffusion of individual artefacts • the processes through which diffusion can be accelerated
Impacts	• the rebound effects from low carbon innovations • the construction of impact scenarios • the usefulness of quantitative modelling tools for understanding impacts and sociotechnical transitions
Cross-cutting	• the co-construction of impacts • the role of policy and politics in shaping emergence, diffusion and impacts

7. Conclusion and implications

This article has identified and described thirteen research debates in the socio-technical transitions literature. The focus throughout has been on theoretical and conceptual issues rather than specific empirical topics. With this in mind, we offer three broader conclusions.

First, the dominant economic and psychological approaches to understanding energy efficiency and demand reduction only provide a partial picture which is reflected in the limitations of the current policy mix and its focus upon incremental change. Radical reductions in energy demand require more far-reaching transitions in the systems that provide energy services. Policies to encourage this must in turn be informed by a deeper understanding of the actors, innovations, and causal processes involved.

Second, a sociotechnical approach on low carbon innovation offers such an understanding. This perspective focuses upon how radical innovation is about creating new sociotechnical systems through the coconstruction of multiple elements. Informed by detailed case studies, this interdisciplinary perspective sheds new light on how sociotechnical systems evolve, stabilise and transform through the alignment of developments on multiple levels. The themes of emergence, diffusion and impacts are useful heuristic devices through which to understand the sociotechnical transitions that are required for drastic reductions in energy demand. In each case we have described the sociotechnical conceptualisation of the research theme and identified several research debates within the theme. These debates are summarised in Table 1.

Third, a sociotechnical approach exposes several important characteristics about low carbon innovation and transitions, namely:

1. *Radical low carbon innovation involves systemic change*: This extends beyond purely technical developments to include changes in consumer practices, business models and organisational arrangements. A sociotechnical transitions approach links multiple innovations and transforms broader sociotechnical systems.
2. *Radical low carbon innovation involves cultural change*: Low carbon innovations are typically less ‘sexy’ then energy supply innovations, and garner less interest from policymakers and the wider public [173]. Most people have little interest in demand reduction and the economic incentive to save energy is often weak. An energy efficiency and demand ‘revolution’ will therefore require dedicated campaigns to create a sense of urgency and excitement about low carbon innovations. To alter cultural preferences, such campaigns need to go beyond information provision and aim to create positive discourses and increase competencies and confidence among (potential) users.
3. *Radical low carbon innovation involves new policies and political struggles*: Since many of the benefits of low carbon innovation can be considered a public good, incentives may be weak in the absence of collective action. The development and adoption of low carbon innovations will therefore require sustained and effective policies to create appropriate incentives and support. The development and implementation of such policies entail political struggles because actors have different understandings and interests, which give rise to disagreements and conflicts. Managing low carbon transitions is therefore not only a techno-managerial challenge (based on targets, policies and expert knowledge), but also a broader political project that involves the building of support coalitions that include businesses and civil society.
4. *Radical low carbon innovation involves pervasive uncertainty:* The technical potential, cost, consumer demand and social acceptance of new innovations are highly uncertain in their early stages of development, which means that the process of radical innovation is more open-ended than for incremental innovations. Such uncertainty carries governance challenges. Policy approaches facing deep uncertainty must protect against and/or prepare for unforeseeable developments, whether it is through resistance (planning for the worst possible case or future situation), resilience (making sure you can recover quickly), or adaptation (changes to policy under changing conditions) [174]. Such uncertainty can be hedged in part by learning by firms, consumers and policymakers. Social interactions and network building (e.g. supply and distribution chains, intermediary actors) and the articulation of positive visions all play a crucial role. This uncertainty extends to the impacts of low carbon innovations on energy demand and other variables, where unanticipated and unintended outcomes are the norm.

Essentially, low carbon innovation demands we not only rethink the promise of both technology and behavioural change, but our assumptions concerning systems, culture, politics, and uncertainty as well.

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