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Perspectives

Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the Multi-Level Perspective

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ABSTRACT

This paper firstly assesses the usefulness of Christensen's disruptive innovation framework for low-carbon system change, identifying three conceptual limitations with regard to the unit of analysis (products rather than systems), limited multi-dimensionality, and a simplistic ('point source') conception of change. Secondly, it shows that the Multi-Level Perspective (MLP) offers a more comprehensive framework on all three dimensions. Thirdly, it reviews progress in socio-technical transition research and the MLP on these three dimensions and identifies new challenges, including 'whole system' reconfiguration, multi-dimensional struggles, bi-directional niche-regime interactions, and an alignment conception of change. To address these challenges, transition research should further deepen and broaden its engagement with the social sciences.

1. Introduction

Effective mitigation of climate change will require transitions towards low-carbon electricity, heat, agro-food, mobility and other systems. Since existing systems are locked-in and path dependent, these transitions will involve disruptions of the status quo and transformational changes in technology, user practices, markets, business models, policy, infrastructure and cultural meanings [1–3].

It is therefore timely that this Special Section in ERSS aims to assess the usefulness of Christensen's disruptive innovation framework [4] for energy system transformations. My contribution to this debate has three goals. Firstly, Section 2 acknowledges some useful insights of Christensen's framework, but also identifies several important shortcomings with regard to broader system transformation. These include two definitional limitations and three conceptual problems, which relate to units of analysis, limited multi-dimensionality, and a 'point source' view of change. Focusing on the three conceptual issues, the second goal is to demonstrate that the Multi-Level Perspective (MLP) usefully foregrounds relevant aspects of big phenomena like low-carbon transitions. Thirdly, again focusing on the three conceptual issues, the paper aims to take stock of progress in transitions research and the MLP in recent years, identify new challenges, and suggest directions for future research. The second and third goals are addressed together in Sections 3–5, which are organized along the three conceptual issues. Each of these sections first indicates why the MLP offers broader understandings than Christensen's framework, then offers empirical examples, and then discusses new challenges and conceptual elaborations. Section 6 concludes.

2. Strengths and weaknesses of the disruption innovation framework

Christensen [4] made important contributions to the long-standing debate in innovation management about new entrants, incumbents and industry structures. He argued that disruptive innovations enable new entrants to 'attack from below' and overthrow incumbent firms. Christensen thus has a particular understanding of disruption, focused mainly on the competitive effects of innovations on existing firms and industry structures. His framework was not developed to address systemic effects or broader transformations, so my comments below are not about the intrinsic merits of the framework, but about their usefulness for low-carbon transitions.

Christensen's disruptive innovation framework offers several useful insights for low-carbon transitions (although similar ideas can also be found elsewhere). First, it suggests that incumbent firms tend to focus their innovation efforts on sustaining technologies (which improve performance along established criteria), while new entrants tend to develop disruptive technologies (which offer different value propositions). Second, it proposes that disruptive technologies emerge in small peripheral niches, where early adopters are attracted by the

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technology's new functionalities. Third, incumbent firms may initially overlook or under-estimate disruptive technologies (because of established beliefs) or are not interested in them, because the limited return-on-investments associated with small markets do not fit with existing business models. Fourth, price/performance improvements may enable disruptive technologies to enter larger markets, out-compete existing technologies and overthrow incumbent firms.

Nevertheless, Christensen's framework also has limitations that constrain its usefulness for low-carbon system transformation.[1] One definitional limitation is that Christensen's *disruptive* innovation concept would only draw attention to a sub-set of low-carbon innovations (namely those that introduce new functionalities or value propositions). It would thus exclude *sustaining* low-carbon technologies that meet existing performance standards with less carbon emissions (e.g. electric vehicles, wind turbines, light emitting diodes). Another definitional limitation is that Christensen has a somewhat idiosyncratic understanding of disruptive innovation as being cheaper than existing technologies, underpinning his view on 'attacks from below' (disruptive innovations first entering lower ends of the market and then migrating upwards). While this may apply to a sub-set of innovations, it unhelpfully excludes innovations that are initially more expensive and first enter the high or specialized end of the market. Utterback and Acee [5] give many historical examples. Solar-PV or Tesla's electric vehicles are contemporary low-carbon examples.

Christensen's framework also has several conceptual limitations for system transition. Firstly, it focuses on products or components (like hard disk drives or micro-processors) rather than comprehensive systems. It also focuses on *single* innovations, whereas system transformation is likely to entail interactions between multiple innovations. Secondly, it focuses on price/performance competition in markets, and ignores social, political, cultural and infrastructural dimensions. Consequently, it does not consider that changes in the selection environment (carbon taxes, subsidies, performance standards, regulations) may be important drivers of low-carbon transformation. Thirdly, the framework has a 'point source' approach to change, which understands disruption as being caused by (heroic) innovators conquering the world. While this approach is common in innovation management, it overlooks the possibility that major change and transitions may occur when new technologies *align* with broader ongoing processes such as political struggles, societal debates, and strategic games. For each conceptual limitation, the next three sections show how the MLP offers broader understandings, provide low-carbon transition examples, and identify new research challenges for transition research and the MLP.

3. Socio-technical systems and system reconfiguration

3.1. Broader MLP-understanding

Compared to Christensen's disruptive innovation approach, the Multi-Level Perspective (MLP) broadens the unit of analysis from technological products to socio-technical systems that provide societal functions such as mobility, heat, housing and sustenance. These systems consist of an interdependent and co-evolving mix of technologies, supply chains, infrastructures, markets, regulations, user practices and cultural meanings [6]. Sociotechnical systems develop over many decades, and the alignment of these different elements leads to path dependence and resistance to change. Existing systems are maintained, defended and incrementally improved by incumbent actors, whose actions are guided by 'socio-technical regimes', the semi-coherent set of rules and institutions [7].

The MLP argues that sociotechnical transitions come about through interacting processes within and between the incumbent regime, radical niche-innovations and the sociotechnical landscape [8–10]. Niche-innovations are emerging social or technical innovations that differ radically from the prevailing sociotechnical system and regime, but are able to gain a foothold in particular applications, geographical areas, or with the help of targeted policy support [11]. The sociotechnical landscape refers to broader contextual developments that influence the sociotechnical regime and over which regime actors have little or no influence. Landscape developments comprise both slow-changing trends (e.g. demographics, ideology, spatial structures, geopolitics) and exogenous shocks (e.g. wars, economic crises, major accidents, political upheavals).

The MLP suggests that transitions come about through the alignment of processes within and between the three levels (Fig. 1). In a nutshell, radical innovations emerge in peripheral niches in phase 1, and stabilize and enter small market niches in phase 2. Breakthrough in phase 3 depends on niche-*internal* drivers such as price/performance improvements, scale and learning economies, the development of complementary technologies and infrastructures, positive cultural discourses, and support from powerful actors. But diffusion also depends on *external* windows of opportunity, due to regime destabilisation because of landscape pressures or persistent internal problems. Regime transformation occurs in phase 4, including adjustments in infrastructures, policies, lifestyles and views on normality.

While the MLP positions many of Christensen's insights in a broader framework, many applications implicitly maintain the focus on *singular* innovations (which is also visible in the single bottom-up graph in Fig. 1). The focus on single innovations (like solar-PV, wind turbines, biogas, electric vehicles) also permeates the Strategic Niche Management and Technological Innovation System literatures. While niche-innovations are important, this singular focus falls short of foundational interests in *system* innovation [1,2].

3.2. Empirical examples of low-carbon system reconfiguration

The current unfolding of low-carbon transitions suggests, however, that system change may also occur through interactions between *multiple* innovations. Low-carbon transitions in electricity, for instance, depend not only on radical innovations like renewables (wind, solar-PV, bio-energy, geo-thermal), but also on hybridization between niche-innovations and regimes (coal-with-CCS, coal-with-biomass) and on complementary innovations in electricity networks and demand, e.g. network expansion (to increase capacity, connect remote renewables and link to neighbouring systems); smarter grids (to enhance flexibility and grid management); energy storage (e.g. batteries, flywheels, compressed air, pumped hydro); demand response (e.g. new tariffs, smart meters and intelligent loads); and new business models and market arrangements (such as capacity markets to ensure system security). Together these innovations may transform the entire electricity system.

Similarly, low-carbon system transitions in mobility could go beyond green cars (biofuels, hybrids, plug-in hybrid, full-electric, fuel cell) and also address broader changes in the personal mobility system such as new business models (car sharing, car-pooling, Uber), changing user practices (e.g. modal shift towards trains, trams, buses, cycling or tele-conferencing or tele-work, which reduces the need to travel), integration of Information and Communication Technologies in self-driving cars, dynamic traffic management, intelligent transport systems. More broadly, mobility can be reconfigured through linkages between systems. Urban planning and transport systems, for instance, can be integrated via transit-oriented development (building mixed-use areas around public transport stops), compact cities, and intermodal transport, which facilitates mode-switching with seamless transfer facilities, smart cards, and aligned time-tables [13].

[1] In this paper, I use the terms 'transformation' and 'transition' interchangeably to refer to substantial change (depth) in energy, mobility, agro-food systems across multiple dimensions (scope).

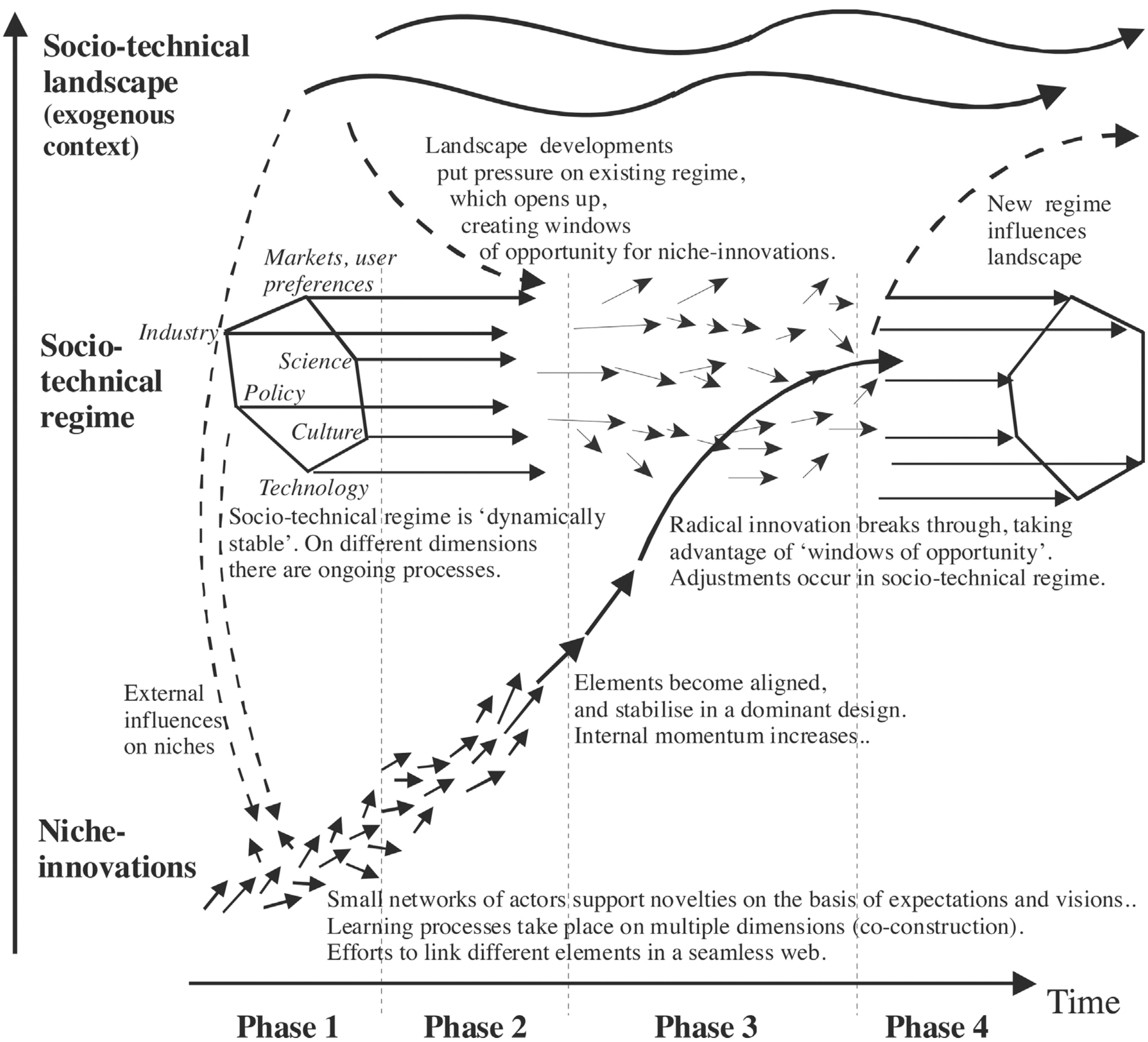

Fig. 1. Multi-level perspective on sociotechnical transitions [12]: adjusted from [86].

3.3. Conceptual elaborations and challenges

The conceptual implication of the above examples is that transition scholars should consider complementing their analytical focus on 'singular disruption' with greater attention for 'multiple innovations and system reconfiguration' [14]. Addressing system reconfiguration may also require some reconceptualization of the MLP to pay more attention to different kinds of change mechanisms:

- Interactions between niche-innovations, e.g. positive alignments (leading to 'new combinations') or competition (for resources, consumers or regulations).
- Adoption of niche-innovations(s) within existing systems (through add-on, hybridisation, or modular component substitution), which may have knock-on effects and trigger further 'innovation cascades' [15].
- Interactions between multiple systems is also important for reconfiguration processes [16–20].

The broader point is that investigation of system reconfiguration creates opportunities for developing a broader repertoire of change mechanisms. In political science, Thelen [21] introduced new change mechanisms (layering, drift, conversion, displacement, erosion) to understand institutional change, which aimed to beyond the established dichotomy of incremental adjustment or (external) disruption. I suggest there are similar opportunities with regard to socio-technical transitions, where we can complement the Schumpeterian dichotomy of incremental and radical change with a broader repertoire of change mechanisms.

Some of these reconfiguration mechanisms are gradual, not rapid and discontinuous. This means that transition scholars could benefit from making a clearer distinction between the *speed* of change (disruptive or gradual) and the *outcome* of change (large or small change in socio-technical systems). It is not true that large change and performance improvement can only be achieved through disruptive, revolutionary change, as transition scholars often assume. A multitude of successive gradual changes can also have transformative effects. In this regard, it is useful to heed ([85]: 337) Don Quixote inspired warning to the transitions community: "One sometimes gets the idea that the change that really matters is truly dramatic change, the overturning of big systems. (…) Yet we should take care here. Our concern should be solving societal problems not tilting at 'systems'."

An additional implication is that transition scholars could benefit from moving beyond the Schumpeterian dichotomy, in which new entrants overthrow locked-in incumbents. Additional patterns include: a) alliances between incumbents and new entrants [22], b) incumbents developing niche-innovations, possibly followed by strategic reorientation [23–25], c) niche-involvement of incumbent actors from different sectors [26], e.g. ICT companies moving into renewables or self-driving cars.

4. From techno-economic to multi-dimensional approaches

4.1. Broader MLP-understanding

While Christensen's framework focuses on technical and business dimensions, the MLP also accommodates consumption, cultural, and socio-political dimensions. Although co-evolution has always been a core concept in the MLP, this is even more important for low-carbon transitions, which are goal-oriented or 'purposive' in the sense of addressing the *problem* of climate change. This makes them different from historical transitions which were largely 'emergent', with entrepreneurs exploiting the commercial *opportunities* offered by new technology [27].

Because climate protection is a public good, private actors (e.g. firms, consumers) have limited incentives to address it owing to free-rider problems and prisoner's dilemmas. This means that public policy must play a central role in supporting the emergence and deployment of low-carbon innovations and changing the economic frame conditions (via taxes, subsidies, regulations, standards) that incentivize firms, consumers and other actors. However, substantial policy changes involve political struggles and public debate because: "[w]hatever can be done through the State will depend upon generating widespread political support from citizens within the context of democratic rights and freedoms" ([28]: 91).

Additionally, cultural repertoires and discursive struggles are important for low-carbon transitions, because they shape the interpretations and meanings of radical innovations and existing technologies; influence consumer preferences and the social acceptance of innovations; and affect public and policy debates by providing the categories, metaphors and storylines through which issues are discussed [29–31].

These considerations reinforce the point that low-carbon transitions are multi-dimensional and involve co-evolutionary interactions between technology, firms, markets, user practices, cultural meanings, and institutions.

4.2. Empirical examples of problematic societal embedding

The importance of public engagement, social acceptance and political feasibility is often overlooked in technocratic government strategies and model-based scenarios, which focus on techno-economic dimensions to identify least-cost pathways [32]. In the UK, which is characterized by closed policy networks and top-down policy style, this neglect has led to many problems, which are undermining the low-carbon transition.

- Onshore wind experienced local protests and permit problems, leading to negative public discourses and a political backlash, culminating in a post-2020 moratorium.
- Shale gas experienced public controversies after it was pushed through without sufficient consultation.
- Energy-saving measures in homes were scrapped in 2015, after the Green Deal flagship policy (introduced in 2013) spectacularly failed, because it was overly complicated and poorly designed, leading to limited uptake.
- The 2006 zero-carbon homes target, which stipulated that all new homes should be carbon-neutral by 2016, was scrapped in 2015, because of resistance by major housebuilders and limited consumer interest.
- The smart meter roll-out is experiencing delays, because of controversies over standards, privacy concerns, and distribution of benefits (between energy companies and consumers).

4.3. Conceptual elaborations and challenges

Conceptually, this means that we should analyse socio-technical transitions as *multi-dimensional struggles* between niche-innovations and existing regimes. These struggles include: economic competition between old and new technologies; business struggles between new entrants and incumbents; political struggles over adjustments in regulations, standards, subsidies and taxes; discursive struggles over problem framings and social acceptance; and struggles between new user practices and mainstream ones.

The struggles are being explored in recent debates about niche-regime interactions, focusing on socio-political 'empowerment' strategies by niche advocates [33,34,87], alliances between niche and regime actors to draw in more resources [35], activities by intermediary actors or boundary spanners [36,37], alliances between niche-organizations and political parties, incumbents from other sectors, or social movements [26].

While productive and highly relevant, this literature is biased in two ways: it privileges the viewpoint of niche advocates and focuses mainly on socio-political and discursive dimensions. A more comprehensive understanding of niche-regime interactions should also accommodate the actions from incumbent regime actors (see Rosenbloom et al. [38] for a more symmetric approach) and address techno-economic and business dimensions.

A further challenge is to deepen the conceptualization of crucial dimensions and societal groups in socio-technical transitions. Because the MLP is a middle range theory [39],[2] it could benefit from crossovers with theories in the broader social sciences. The last few years have seen great strides in this direction, which have enriched the MLP in many ways.

- In response to calls to better address *political* dimensions, scholars have linked the MLP to Sabatier's advocacy coalition framework [40], Kingdon's multiple streams framework [41], political economy [42,43], and political coalition theories [44,26].
- To better address the role of *culture and wider publics*, scholars have enriched the MLP with ideas from discourse theory and narrative approaches [45,30,46,38,31].
- To further elaborate the role of *firms and organizations*, scholars have started to import ideas from organizational and business literatures on technological competence and capabilities [23], technology management [24], institutional theory [7] and disruptive innovation [23,47,48]. Some scholars provide broad reviews that additionally address the behavioural theory of the firm, resource dependence theory, organizational ecology, and resource-based view [49], as well as economic positioning, corporate political strategy, discursive strategy, issue management, sense-making [50,51].
- With regard to *consumers and households*, scholars have begun exploring crossovers between the MLP and practice theory [52–54,14], which share processual orientations and interests in routines, rules, habits, conventions. Crossovers to traditional adoption approaches [55] or socio-psychological theories [56] are under-explored, perhaps because of an excessive fear of using reified analytical categories. But dismissing the role of consumer attitudes or cost-benefit calculation [57] unnecessarily limits the analytical repertoire.

[2] Merton [77] introduced the notion of 'middle range theories' as a middle way between abstracted 'grand theories' that provide general outlooks or worldviews (e.g. rational choice theory or structural-functionalism) and low-level empirical propositions and abstracted empiricism (aimed only at data-collection and number crunching). Middle range theories focus on particular topics, make explicit efforts to combine concepts in frameworks, and search for abstracted patterns and explanatory mechanisms that help explain concrete cases or instantiations of the focal topic [39]. Middle-range theories thus also differ from critical theories (which critique dominant narratives, 'uncover' hidden interests and power structures, emancipate silenced voices, or pose normative questions).

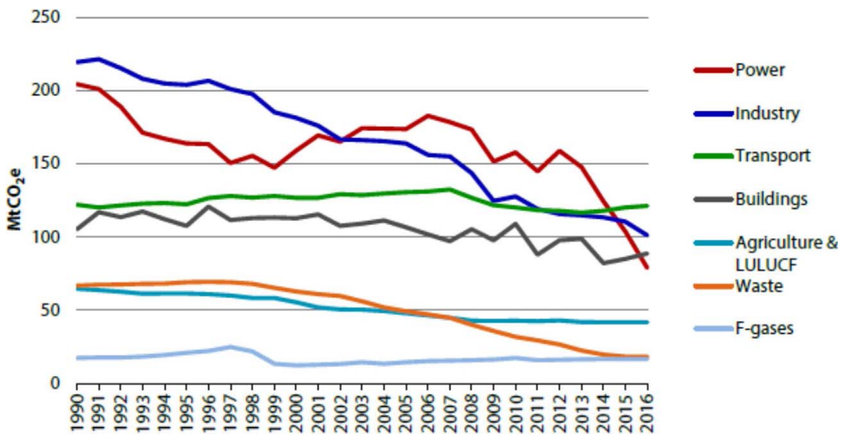

Fig. 2. UK greenhouse gas emissions by sector, 1990–2016 ([62]: 26).

This overview shows that scholars have begun to deepen the understanding of particular dimensions in transitions and the MLP, mobilizing ideas from various mainstream social science disciplines. While this holds much promise, a potential risk is disciplinary fragmentation, which could give transitions research a 'donut shape', with an empty middle surrounded by specialized research on particular social groups (policymakers, firms, consumers). To alleviate this risk and keep generating interesting research questions, it is important to not lose sight of co-evolution and multi-dimensionality in socio-technical transitions.

5. From 'point source' to alignment dynamics

5.1. Broader MLP-understanding

Christensen and other innovation management scholars typically adopt a 'point source' approach to disruption, in which innovators pioneer new technologies, conquer the world, and cause social change. Existing contexts are typically seen as 'barriers' to be overcome. This 'bottom-up' emphasis also permeates the Strategic Niche Management and Technological Innovation System literatures. While this kind of change pattern does sometimes occur, the MLP was specifically developed to also accommodate broader patterns, in which niche-innovations diffuse because they *align* with ongoing processes at landscape- or regime-levels [9].

The MLP thus draws on history and sociology of technology, where processual, contextual explanations are common. Mokyr [58], for instance, emphasizes that "The new invention has to be born into a socially sympathetic environment" (p. 292) and that "Macro-inventions are seeds sown by individual inventors in a social soil. (.) But the environment into which these seeds are sown is, of course, the main determinant of whether they will sprout" (p. 299). So, if radical innovations face mis-matches with economic, socio-cultural or political contexts, they may remain stuck in peripheral niches, hidden 'below the surface'.

Since low-carbon transitions are problem-oriented, transition scholars should not only analyse innovation dynamics, but also 'issue dynamics' because increasing socio-political concerns about climate change can lead to changes in regime-level institutions and selection environments. Societal problems or 'issues' have their own dynamics in terms of problem definition and socio-political mobilization as conceptualized, for instance, in the issue lifecycle literature [59,50]. Low-carbon transitions require stronger 'solution' *and* problem dynamics, and their successful alignment, which is not an easy process, as the examples below show.

5.2. Empirical examples of (mis)alignment

In the UK, for instance, public attention for climate change strongly increased between 2004 and 2008, creating an important impulse for the 2008 Climate Change Act, but subsequently decreased because of the financial-economic crisis. This major landscape shock, and its political translation into austerity and cutbacks, shifted public attention to different topics. The content of public discourse also changed, as policymakers increasingly emphasised the costs of green policies. In 2015, the Conservative government scrapped or weakened a dozen green policies (e.g. feed-in-tariffs, zero carbon homes target, CCS subsidy, Green Deal). Socio-political regime developments in the UK thus became less favourable for many low-carbon innovations [60].

There are also positive developments, however, that provide windows of opportunity. Coal is losing legitimacy in parts of the world, because it is increasingly framed as dirty, unhealthy and old-fashioned, and because oil and gas companies are distancing themselves from coal, leading to cracks in the previously 'closed front' of fossil fuel industries. The UK has committed to phasing out coal-fired power plants by 2025 and several other countries (Netherlands, France, Canada, Finland, Austria) also move in this direction, providing space for low-carbon alternatives, including renewables.

The automobile regime also experiences tensions that provide opportunities for electrified cars and other alternatives. Local air pollution problems, for instance, led some cities to introduce low-emission zones and call for bans on diesel cars. Scandals like 'diesel gate' and the gaming of emission tests (leading to 40% discrepancies between laboratory tests and real-world driving conditions) have tarnished the reputation of companies and the legitimacy of the industry at large. In response, Volkswagen announced stronger commitments to electric vehicles, while Volvo announced that it will cease production of conventional vehicles by 2019. Governments in France, UK and Norway announced bans on the sale of new diesel and petrol cars (from 2040, 2040 and 2025 respectively), while other countries (Netherlands, Germany) are discussing similar policies. While a shift to electrified cars may not represent a comprehensive system change, the examples indicate that low-carbon transitions are not just driven by endogenous dynamics, but also by alignments with regime and landscape developments.

Despite these 'glimmers of hope', low-carbon transitions are progressing slowly, except for renewable electricity [61]. Also in the UK emission reductions since 2012 mostly occurred in the electricity sector (Fig. 2), primarily because of diminished coal-burning. In transport and buildings, however, emissions have increased in recent years, while emission reductions in industry mostly relate to plant closures or offshoring.

5.3. Conceptual elaborations and challenges

One conceptual challenge for transition research is thus to broaden the analysis from niche-innovations towards better understanding

	Micro level	Meso level	Macro level
Identifiable configurations that work (artefact in context)	Artifacts (tangible arrangements, immutable mobiles), 'machines'	Technical systems	Mumfordian megamachine
Merge into	Scripts, technical fixes	(Technical) regimes	Sociotechnical landscape
Seamless webs	Artifacts as channels of social/historical forces	Sectoral structures and strategic games	Patterns in transformations of society

Fig. 3. Different views on socio-technical complexity ([8]: 339).

alignments with regime developments, including degrees of lock-in, tensions, destabilisation, and incumbent reorientation [63–67].

More generally, the understanding of alignment and co-evolution of technology and society could benefit from greater awareness of disciplinary differences. The social sciences are "highly balkanized and tribal" ([68]: 7), with most disciplines focusing on particular 'spheres' or social groups (economy, politics, consumption, business, culture). But technology and socio-technical systems (in mobility, agro-food, energy) do not neatly fit in disciplinary boxes and, in fact, span all of them. Consequently, social science disciplines have different understandings of technology and socio-technical systems, and highlight different dimensions. In this respect, I want to draw attention to a little-noticed figure in Rip and Kemp [8], which aims to position different disciplinary views in a 3 × 3 table (Fig. 3). The horizontal axis refers to increasing *scope* of configurations (from specific innovations to entire societies). The vertical axis, which draws heavily on STS jargon, represents different ontological views on the *characteristics* of socio-technical configurations (from discrete technical entities to heterogeneous networks, relations and alignment processes). Fig. 3 thus positions different views on socio-technical complexity.

- 'Identifiable configurations' refers to positions that view technology as a central and stand-alone category. At the micro-level, this position privileges artefacts and the engineers/innovators/entrepreneurs who introduce novelty (e.g. [4]), which subsequently change society (a linear, technological determinist view). At the meso-level, systems are analysed in terms of technical components (cars, engines, roads, fuel infrastructure, global oil flows). At the macro-level, the philosopher Mumford [69] critically described societies as 'mega-machines', in which people are cogs in the wheels of global energy, materials and information flows, including associated bureaucracies. Contemporary incarnations of this macro-level approach are Earth System Models [70], socio-metabolic transition approaches [71] or energy flow Sankey diagrams [72].
- The 'seamless web' position emphasizes that technologies are malleable and embedded in social networks and that their meanings and development are socially shaped [73,74]. At the micro-level, technology then appears as channel or weapon in situated social struggles.[3] At the meso-level, technological diffusion appears as shaped by interactions between collective groups and strategic moves and counter-moves.[4] At the macro-level, technological development is understood as embedded in long-term societal trends.[5]
- The middle ('socio-technical') approach aims to bridge both views, attributing (varying) causal influence to both technology and social groups. At the micro-level, artefacts may have embedded 'scripts' that shape action. At the meso-level, deep-structural regime rules and technological trajectories constrain action. At the macro-level, Rip and Kemp [8] write about "the material landscape of society" (p. 362), including infrastructures, urban structures, and "material culture" (p. 388), including broad consumption patterns and modernist values, that provide 'gradients of force' that make some actions easier than others.

One implication of Fig. 3 is that no single discipline is sufficient to understand heterogeneous entities like socio-technical systems. Economists, engineers, and management scholars tend to focus on tangible dimensions, often leading to technological determinist or 'point source' understandings of change. Historians, sociologists and political scientists offer more contextual 'alignment' views, although these vary in kinds of contexts (social networks, organizational fields, institutions, structures, regimes) and degrees of constraints on agency.

Another implication is that different disciplines may interpret the MLP-levels in varying ways, focusing on different *characteristics* of socio-technical configurations. Perhaps this helps explain why many scholars find the MLP useful, and why applications in the literature range from rather 'mechanical' to deeply processual. Additionally, slippage may occur in the operationalization of different concepts between different cells. For instance, while Rip and Kemp [8] conceptualized socio-technical landscape as material backdrop and sedimented *longue durée*, others (including myself) often use it as a garbage can concept for gradual societal transformations and rapid shocks.

Thirdly, if we assume that various disciplines highlight relevant parts of socio-technical complexity, Fig. 3 reinforces the importance of making multi-level analyses of transitions, including alignments. Unfortunately, "contemporary social scientists are strongly predisposed to focus on aspects of causal processes and outcomes that unfold very rapidly" ([68]: 13). An excessive focus on short-term actions and micro-level strategies may thus lead scholars to ignore meso- and macro-level developments. Pierson [75] warns that this may lead to flawed

[3] American local authorities, for instance, adopted busses as part of a long-standing conflict with electric tram companies, who were monopolists in urban transit [78]. Dutch traders, shipping agents and stevedore firms adopted pneumatic grain unloaders in the Rotterdam port to break the power of dockworkers and labor unions [79]. Less voluntaristically, one can also think of the role of social media in the Arab Spring. Another example is White's [80] suggestion that the stirrup played an important role in the medieval shift to feudalism, because it enabled heavy cavalry and horse-mounded shock combat, which advantaged knights.

[4] Nye [81], for instance, describes how the integration of electricity in factories, urban transportation, homes, and rural areas progressed through interactions between factory owners, workers, city authorities, housewives, farmers, etc.

[5] Beniger [82], for example, suggests that the post-war information revolution was a response to coordination problems arising from earlier revolutions, particularly mass production and accelerated trade and transport flows. Hughes [83] and Misa [84] represent other efforts in interpreting long-term socio-technical patterns.

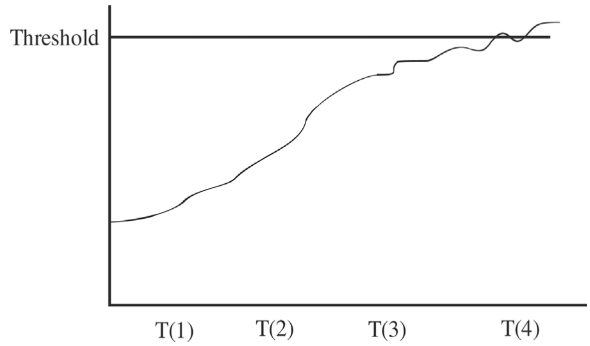

Fig. 4. Longitudinal developments creating conditions for trigger events ([75]: 186).

explanations of large-scale change, which over-emphasize the importance of specific actions or trigger events (T4 in Fig. 4), while ignoring the less dramatic, preceding processes leading up to particular thresholds, thus creating the right conditions (as also emphasized by Mokyr above and the MLP).

6. Conclusion

For low-carbon transitions and system change, the MLP offers a more comprehensive framework than Christensen's disruptive innovation theory. The MLP has become a cumulative, collective research program, which has made great progress in recent years with regard to understanding the multi-dimensionality of socio-technical systems, niche-regime interaction, and more differentiated relations between new entrants and incumbents. The mobilization and incorporation of insights from various social sciences has also deepened the understanding of roles and actions of particular social groups (firms, policymakers, consumers, wider publics).

The paper has also identified several research challenges, where the transitions community could fruitfully do more work. First, we should broaden our analytical attention from singular niche-innovations (which permeate the literature) to 'whole system' change. This may involve changes in conceptual imagery (from 'point source' disruption to gradual system reconfiguration) and broader research designs, which analyze multiple niche-innovations and their relations to ongoing dynamics in existing systems and regimes. That, in turn, may require more attention for change mechanisms like add-on, hybridisation, modular component substitution, knock-on effects, innovation cascades, multi-regime interaction.

Second, we should better understand regime developments. Existing regimes can provide formidable barriers for low-carbon transitions. Incumbent actors can resist, delay or derail low-carbon transitions, but they can also accelerate them if they reorient their strategies and resources towards niche-innovations. The analysis of niche-to-regime dynamics (as in the niche empowerment literature) should thus be complemented with regime-to-niche dynamics, including incumbent resistance or reorientation. Additionally, we need more nuanced conceptualizations and assessments of degrees of lock-in, tensions, cracks, and destabilisation.

Third, we need greater acknowledgement that socio-technical systems are a special unit of analysis, which spans the social sciences and can be studied through different lenses and at different levels. The recent trend towards deepening our understanding of particular dimensions and societal groups is tremendously fruitful, because disciplinary theories offer more specific causal mechanisms. But, as a community, we should complement this with broad analyses of co-evolution, alignment, multi-dimensionality and 'whole systems'.

Together, these challenges provide a stimulating and exciting agenda for future transitions research that could broaden its scope, strengthen relations with disciplinary social sciences, and deepen awareness of its unique characteristics in terms of research topic and explanatory style.

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