Technological Forecasting & Social Change 151 (2020) 119665

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

Understanding transition pathways by bridging modelling, transition and practice-based studies: Editorial introduction to the special issue

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ABSTRACT

This paper presents an introduction to and overview of the papers in this Special Issue of *Technological Forecasting & Social Change* on 'Transition Pathways' is presented. Each of these papers are an output of the PATHWAYS project (EC FP7-funded, 2013–2017) which looked into ways to integrate alternative approaches for analysing sustainability transitions. Methods to bridge across scenario-modelling, socio-technical transition, and practice-based action research approaches (Turnheim et al. 2015; Geels et al., 2016) were implemented in eight empirical and modelling studies reported here. A variety of approaches to bridging emerged in practice, with differing methodological strategies employed, analysing transitions processes across different sectors, at a range of scales, and separately, comparatively or in a fully integrated way. This paper suggests a framework for understanding different approaches to bridging and shows how policy- and decision-making can be enriched by theoretically- and empirically-informed bridging approaches to transitions analysis.

1. Introduction

Addressing persistent environmental problems like climate change or biodiversity loss requires transitions to new kinds of energy, mobility, housing, and agricultural and food systems (EEA, 2016; IPCC, 2014). These sustainability transitions involve not just technological reconfigurations, but also changes in consumer practices, policies, cultural norms and meanings, infrastructures and business models (Markard et al., 2012). In other words, they involve complex social processes involving multiple actors acting across scales in a mostly uncoordinated way which are not easy to describe or govern (Kuzemko et al., 2016; Sovacool, 2017).

Moreover, multiple pathways towards achieving sustainability goals can be envisioned. Each of these pathways is associated with different interests and value systems of specific actors and imply a variety of cultural and political commitments. Reductions in greenhouse gas emissions, for example, can be achieved with different combinations of renewable energy technologies, nuclear power, substantial demand reduction, negative emission technologies, and changes in lifestyle (Creutzig et al., 2018; Grubler et al., 2018; Van Vuuren et al., 2018). Clearly, different social groups (business, citizens, the media, the law, Government) will have different attitudes and preferences with respect to these options.

A high level of uncertainty adds to this social, political and technological complexity. Uncertainty is associated with many dimensions of transitions (social, cultural, political, technical, organisational) and can influence both *changes in speed* through setbacks or accelerations (Davidescu et al., 2018; Roberts et al., 2018) or *changes in direction* due to unintended consequences, unexpected challenges, learning, or changing ideologies and coalitions (Olsson et al., 2006). These two characteristics have led to a vibrant debate about transition pathways (Geels et al., 2016b; Marletto, 2014; Moradi and Vagnoni, 2018; Rosenbloom, 2017; Rosenbloom et al., 2018; Turnheim et al., 2015).

Transitions are studied by different approaches. Each of these approaches addresses different features of transitions and develops different representations and ideas about the unfolding of transitions at a societal scale. Below, we discuss three important strands of research.

Quantitative system models, which are concerned with techno-economic and behavioural options to achieve specific sustainability targets (such as deep reductions in global carbon emissions), have many strengths (Van Vuuren and Hof, 2018): 1) they enable systematic future-oriented assessments of a range of options and pathways, 2) they allow systematic explorations of alternative pathways by varying the settings of parameters (e.g. cost, performance, preferences, policy instruments) in different scenarios, 3) they include an analysis of interactions between techno-economic systems, and 4) they assess sustainability *outcomes* of different scenarios in relation to future policy targets. But they also have limitations (Turnheim et al., 2015), including an oversimplification of social realities, a limited attention for actors and behaviours (struggles, beliefs, strategies), a stylised account

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https://doi.org/10.1016/j.techfore.2019.05.023

Available online 03 June 2019

of institutions, a strong preference for economic mechanisms, while portraying transitions as emerging smoothly over time (which downplays non-linearities, twists and turns). The balance of strengths and weaknesses varies across types of model (e.g. techno-economic, integrated assessment, system dynamic, network, agent-based, complex systems).

Socio-technical transition analysis, which does conceptually-informed historical analysis of technologies embedded in social relations and processes (Farla et al., 2012; Geels et al., 2017), is strong in terms of: 1) analysing techno-economic and socio-political struggles between niche-innovations and path-dependent socio-technical regimes (Hess, 2016; Smith, 2007), 2) attention to multiple actors and kinds of agency (sense-making, debates, struggles, learning, coalition-building), 3) analysis of institutions and 'rules of the game' (Fuenfschilling and Truffer, 2014), and 4) acknowledgement of contexts, contingencies, twists and turns. Weaknesses of the socio-technical approach include their limited assessment of future *outcomes* including the achievement of future targets, a lack of systematic quantification, the emphasis on context-specificity over generalization, and the focus on policy strategies rather than policy instruments (Turnheim et al., 2015).

Practice-based action research, which does in-depth analyses of on-the-ground initiatives and local transition projects (Bulkeley et al., 2016; Seyfang and Haxeltine, 2012) also has several strengths: 1) it addresses concrete socio-technical experiments at the local level, which encompass learning-by-doing by actors in real-life contexts, 2) it evaluates actors (project developers, local authorities, citizens, local businesses, community groups) and their concerns, interests, strategies and interactions, and 3) it provides in-depth assessments of bottom-up projects to pick up 'weak signals' of impending groundswells of change. While practice-based action research offers detailed insights about actors' experiences, interpretations and problem-solving, it also has weaknesses, including limited attention to wider structural contexts, a short-term orientation, and challenges to generalization because of the contingency and messiness of experimental and local contexts.

Because these approaches have complementary strengths and weaknesses, Turnheim et al. (2015: 249) suggest that 'bridging' between them may enable "…a more multi-dimensional evaluation of transitions as they unfold, informing governance decisions and practices". Geels et al. (2016a: 581) similarly suggest that the "…three analytical approaches offer different kinds of knowledge that together may underpin a multi-faceted transition approach in polycentric governance systems" and that their "…combination would enable a governance approach that accommodates both goal-oriented directionality and emergent experimentation and learning".

The papers in this Special Issue set out conceptual, methodological and empirical contributions to this debate, focusing in particular on combinations of methods for exploring transition pathways. Each of the papers is an output of the PATHWAYS project (EC FP7-funded, 2013–2016, www.pathways-project.eu). A variety of approaches to bridging emerged through the project, as different teams sought to put bridging into practice, drawing on some of the groundwork reported in Turnheim et al. (2015) and Geels et al. (2016a). Differing methodological strategies were employed, transitions processes were analysed across different sectors, and at a range of scales, and either separately, comparatively or in a fully-integrated way. In this way, the collection of papers represents a series of experiments with different foci, set-ups and approaches to methodological and theoretical integration.

In this introductory paper, we summarise the eight substantive papers, review what we have learnt about the practice of bridging across a series of coordinated studies, reflect on how well these papers deal with the key challenges identified in Turnheim et al. (2015) and then draw some first conclusions about the value of bridging analysis for policy and governance. Although the evidence of these studies is quite limited, we do believe that we have achieved a 'proof of concept' for bridging analysis. We have been able to demonstrate through these studies that certain key needs for decision-makers and governors can be provided from bridging studies. These needs relate to the generation of more realistic near-real time assessments of transitions-in-flight, the provision of a more fine-grained analysis of key trade-offs at any one time, and a perspective on which of a range of policy and governance interventions may be effective. We believe that further work needs to be done to extend and refine the methodological hybridisation, which the PATHWAYS project has demonstrated, across a wider range of topics and places.

2. Bridging approaches in the PATHWAYS project

Proposals for bridging approaches leading to more comprehensive analyses of transition pathways have been made previously but have remained quite abstract (but see Foxon et al., 2013 for some concrete examples, Li et al., 2015, McDowall, 2014, Trutnevyte et al., 2014). Our aim in the PATHWAYS project was to take a next step by exploring and substantiating these promises with concrete and empirical studies that bridge multiple approaches. Each of these papers study transition pathways in a variety of domains (heating, mobility, electricity, nature conservation) and in different countries and settings (UK, Germany, Sweden, Netherlands, Europe).

All the papers bridge analytical approaches, but they do so in different ways. Bridging was largely based on using similar concepts (a 'shared conceptual space'). The term 'transition' itself needed to be defined in such a way that it could be used across all the three approaches and in different contexts. This required focusing on its essence: the patterns of changes in socio-technical systems unfolding over time that lead to new ways of achieving specific societal functions (Turnheim et al., 2015). To provide a simple analytical frame for all the studies reported here, we made a decision to make a distinction between futures that involved changes primarily of technologies (technological substitution) or changes across a broader regime of actors and their interaction (regime change). These two archetypical transitions could be elaborated in the different domains but also be used to bridge across different approaches. In modelling studies, for instance, the two archetypical transitions could be used as scenario narratives determining key model assumptions of technology innovation, preferences and lifestyle changes. In socio-technological studies, the same archetypes could be used to describe processes in contemporary systems.

Based on these insights, De Cian et al. (this issue) analyse how model-based scenarios can be enriched by a deeper engagement with socio-technical transition studies, initiative-based learning, and applied economics, focusing on the role of actors, decision-making, and institutions in each of these approaches. They conclude that more realistic model-based scenario analysis can arise through model refinements oriented towards a more detailed approach in terms of institutions and actor heterogeneity and behaviour, as well as through integration across different analytical and disciplinary approaches. Both would imply a lower priority for optimisation while encouraging scenario assumptions that offer a wider variety of outcomes.

Focusing on European low-carbon transition scenarios in electricity, transport and heating, van Sluisveld et al. (this issue) draw on case studies of emerging socio-technical niches to make assumptions for scenarios used in the TIMER/IMAGE model. They classify a range of niches according to their momentum and allocate them across the two archetypal scenarios (technological substitution or regime change) developed for PATHWAYS. In this way the study bridges between qualitative socio-technical analysis and quantitative system models: a) it translates *empirical findings* about niche-momentum and system inertia to *calibrate model parameters*, and b) it uses the two storylines to focus on the consequences of a substitution scenario versus a more complete socio-technical regime transformation.

By looking at low-carbon transition pathways in EU electricity systems consistent with a target of limiting global temperature increase to 2 °C, Hof et al. (submitted for publication) also model a technological substitution pathway and a broader regime change pathway, calibrating scenarios on the basis of socio-technical analyses of historical case studies in the UK and Germany. The study uses two global Integrated Assessment Models (IAMs, IMAGE and WITCH) to develop global and European scenarios and link these to a detailed European electricity system model (Enertile) to look into country-specific outcomes. The UK revealed itself to be closer to technological substitution while Germany is better typified as a broader regime change – with both countries delivering substantial changes in carbon emissions. The bridging between the modelling approaches achieves two analytical advances. First, the more detailed national sectoral models provide a reality check on global IAM assumptions and results. This provides more insight into boundary conditions for changes in the mix of electricity systems to achieve deep emissions reductions. Second, the global IAMs put national scenarios in a broader perspective with respect to technical and environmental constraints, such as biomass availability.

Taking low-carbon electricity transitions as their central question, Rogge et al. (this issue) and Geels et al. (this issue) develop *socio-technical scenarios* (STSc) elaborating the two archetypal scenarios for Germany and the UK. Both studies implement iterative dialogue processes between socio-technical transitions theory and quantitative system models. Starting with existing models (here the results of the IMAGE and WITCH integrated assessment models with the Enertile electricity sector model), they first produce baseline scenarios for electricity systems. In a first dialogue step model parameters are adjusted to accommodate the two socio-technical transition pathways introduced above (technological substitution and broader regime change). In a second dialogue step, these future-oriented scenarios (which assume particular diffusion curves for low-carbon technologies) are confronted with socio-technical analyses of contemporary dynamics of the same low-carbon technologies, which leads to the identification of particular 'socio-political bottlenecks'. A third dialogue step consists of developing future-oriented socio-technical storylines, which describe how these bottlenecks can be overcome through particular socio-technical change mechanisms (e.g. learning processes, changing coalitions, public debates, institutional change). The resulting socio-technical scenarios describe goal-oriented transition pathways with greater realism that address contentious issues like social acceptance, political feasibility, and policy mixes.

Taking as its system of interest passenger transport in the Netherlands, Köhler et al. (this issue) use an iterative bridging approach between an agent-based model (MATISSE) and more qualitative analysis of socio-technical niches and regimes, also through a series of steps. The first bridging step is that the multi-level perspective is built into MATISSE's model structure. A second step is that empirical findings from niche- and regime analyses of Dutch passenger transport are used to calibrate model parameters. A third step is formed by a dialogue that confronts the outcomes of exploratory model runs with empirical assessments of current niche momentum and regime inertia. This dialogue leads to the identification of possible branching points and to new model runs with iteratively-revised parameters. The fourth bridging step is the joint development of quantitative scenarios outcomes and qualitative socio-technical storylines that underpin the quantitative pathways and describe the main branching points.

Focusing on space heating in Sweden, Nilsson et al. (this issue) proposes a framework that bridges all three approaches (models, socio-technical analysis and practice-based research) to develop rich and multi-faceted scenarios (in terms of actors) that also have quantitative pathways. They apply a quantitative energy systems model of residential heating in Sweden to characterize technical components and energy use. They use socio-technical analysis to describe promising niche-innovations, the actors and institutions related to the existing energy system, and exogenous landscape trends (which act as drivers in their scenarios). In addition, they employ local action studies to determine the attitudes of people about specific niche-innovations and how they may perceive interventions and policies. Integrating across these three approaches, they develop both quantitative transition pathways (to 2050) and underpinning narrative descriptions that explain how future systems transitions may unfold (in terms of actors, policies, and attitudes).

Finally, by looking at agricultural nature conservation in The Netherlands, Zwartkruis et al. (this issue) use the three analytical approaches as different *lenses* on the same problem, each offering complementary suggestions to policymakers. Since the three lenses have different objects of interest, they highlight different issues. IAMs indicate what kinds of transition pathways could be consistent with the Sustainable Development Goals and European biodiversity targets. Socio-technical analysis provides insights into the causes of inertia and path-dependency of the contemporary Dutch land-use regime (which prevent transitions), which regime cracks exist, and which niche-innovations could potentially contribute to more sustainable pathways (if the momentum of identified niches can be increased). The analysis of local change initiatives then provides more detailed insights about real-world opportunities and struggles with concrete implementation of agricultural nature conservation.

3. Bridging in practice: what did we learn?

Having set out an argument for bridging between three different approaches to the understanding and analysis of transition pathways (Turnheim et al., 2015), the papers in this Special Issue report on the experience of seeking to implement this perspective. In the 2015 paper we proposed a framework of procedures for an iterative two-way interaction between three approaches. The aim of this sequential, iterative process of interaction was to enrich and calibrate separate streams of analysis with the aim of generating a more complete, theoretically- and empirically-informed account of transitions (see Fig. 1).

To enable a dialogue between approaches, a process of mutual phenomenological adjustment needs to take place – what van Sluisveld et al. (this issue) call 'a shared conceptual space'. This includes the nature of the empirical domains to be analysed (such as the scale and temporalities of analysis), the metrics and data to be transferred and compared, and the specific governance problems to be investigated (for instance, the shaping of technological innovation compared to regulating behavioural change). In this process of setting common conceptual and methodological frames, much work needs to be done in 'opening the black box' on the assumptions, analytical procedures and data intrinsic to each approach. The set-ups of the analytical approaches are themselves re-examined and there may be a need for additional translation of scales, metrics and problems in order to enable a two-way flow of information and insights. The more intensive and detailed this alignment, which may be repeated at each step of the recursive interaction envisaged by the bridging approach, the more resource-intensive and time-consuming it will be. New conceptual frameworks – boundary objects – may be needed to achieve the translation and to order the articulation of methodological approaches. In the papers reported here we see new concepts emerge, including archetypal transition narratives and socio-political bottlenecks. Bridging therefore has costs and one of the questions to be answered is whether the additional effort and complexity involved is justified by the new insight and reliability generated for policymakers and others as a result.

The evidence from the papers published here shows that there are a variety of ways to give expression to the bridging approach in analysing transitions processes. In the PATHWAYS project we sought to experiment with a range of approaches to bridging, giving room to each individual study to resolve the question of interaction and integration of methods, data and insights in their own way. Some significant differences in approach have emerged which relate to the 'style' of analysis which is carried out. The approaches to bridging which have emerged may be described as *comparative* (see Zwartkruis et al., this issue), *procedural* (see De Cian et al., this issue; Geels et al., this issue; Hof et al., submitted for publication; Rogge et al., this issue; van Sluisveld

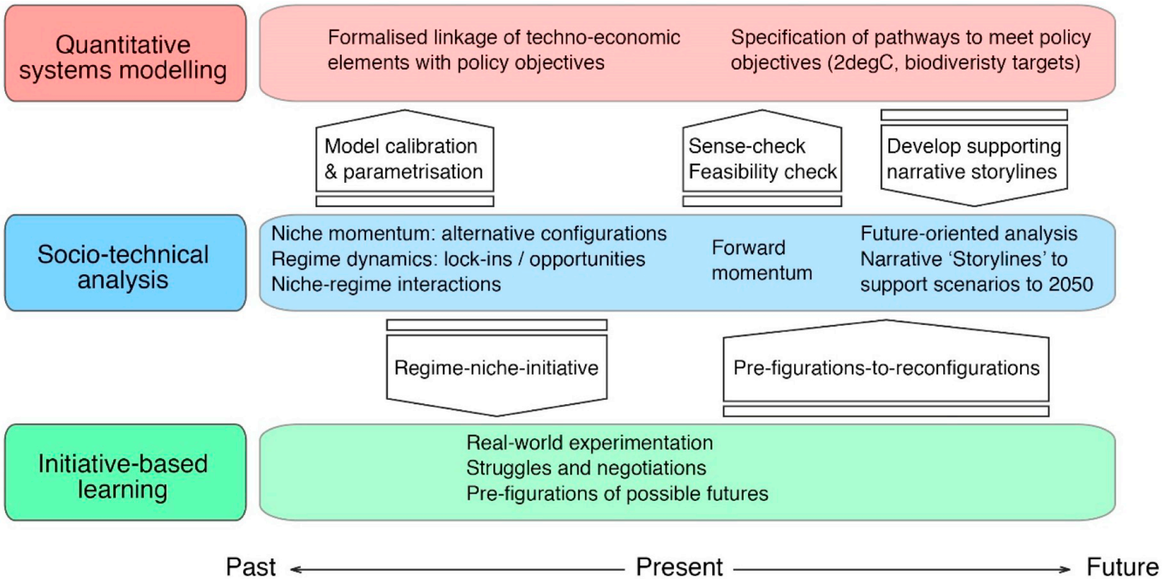

Fig. 1. Linkages between approaches for exploring transition pathways (Turnheim et al., 2015: 249).

et al., this issue), or *integrative* (see Köhler et al., this issue; Nilsson et al., this issue).

A comparative approach to bridging is distinguished mainly by a less intensive degree of interaction between different methods. For instance, Zwartkruis et al. (this issue) take the outputs of analysis from one set of methods and uses these sequentially to inform analysis in another. In this way, modelling results inform socio-technical analysis and initiative-based analysis to generate insights for policy. Each approach contextualises and constrains the next in a 'single pass-through' analysis, providing a more layered set of insights for policy. Instead of aiming for a fully integrated chain of analysis with iterations, the authors aim for a pragmatic, policy-oriented combination of insights from the three lenses. In this way it is driven by a set of clear policy questions: What global and European transition pathways are needed to meet bio-diversity targets? What are current barriers and opportunities in one country? And which policy options may help implement change on the ground?

A greater level of methodological interaction can be found in the procedural approach to bridging which has been taken in several papers. A detailed engagement between integrated assessment models, socio-technical analysis, practice-based learning, together with insights from institutional economics, is described in De Cian et al. (this issue). The paper argues that bridging is challenging because it involves a deep-seated recasting of conceptions about actor heterogeneity, their behaviour and institutions (defined here with reference to democratic decision-making, good governance and corruption) in techno-economic modelling frameworks. This kind of approach forces the models to adopt non-optimal approaches, adding to their complexity but, so they argue, also to their reliability as representations of the world and, by implication, their usefulness for decision-makers.

van Sluisveld et al. (this issue) show how socio-technical analysis can inform integrated models in analysing new and emergent directions of change, using shared concepts such as niche momentum and transition narratives. The innovation in this study is to associate specific emerging socio-technical niches with one or other transition narrative and to give them a weighting based on qualitative case studies of these niches. This approach offers a powerful new way of specifying the modelling of scenarios, at global, regional and more local levels. The modelling exercise by Hof et al., submitted for publication builds on this, providing the frame and the opportunity to develop a more open and experimental model inter-comparison study. It provides an important insight: the differences in the energy mix of electricity generation vary more between different storylines than between models. This implies that considering insights from socio-technical transition studies can have strong implications on scenario outcomes.

Taking a different approach to procedural interaction, Geels et al. (this issue) and Rogge et al. (this issue) designed socio-technical scenarios for the electricity domain of respectively the UK and Germany, each using a sequential analytical approach. The STSc concept is novel since it provides a conceptual structure allowing detailed and historically-informed socio-technical analysis of the electricity domain at the regional level to inform a sectoral model of a system at the national level. This model is, in turn, constrained by global integrated models of emissions providing a fully-articulated, structured link between qualitative case studies of niches and momentum in socio-technical systems with a quantitative modelling of global emissions.

While Rogge et al. explore how 'socio-technical tensions' unfold over future time for Germany, Geels et al. introduce 'socio-political bottlenecks' to describe key strategic and policy choices under each of the two pathways. The key insights here are that the nature of the trade-offs is inherent to different transitions pathways and that a combination of methods is needed for these to be fully identified and specified. A greater granularity and specificity about the tensions and trade-offs, which is of great interest to policy- and decision-makers, is revealed through the integration of analytical approaches. Such detail is less evident when employing one analytical approach by itself – partly because they are resolved through the technical rules of optimisation. The technical, economic and behavioural details of the pathways are given greater complexity and depth.

Finally, in an integrative approach to bridging, as in Köhler et al. (this issue), the multi-level socio-technical perspective is used to structure the MATISSE agent-based modelling approach from the ground-up. In this case, the two approaches are embedded in each other and can be seen as being integrated. The three future scenarios developed in this study include one technological substitution scenario and two system-change or reconfiguration scenarios – a variation from the other studies reported here. Each of these three transitions pathways is assessed using the concepts of niche momentum and regime stability, feeding through to the parameterisation of agent behaviour in the model. In this approach, given the integration of concepts and methods, there is no further need for define new boundary objects.

Nilsson et al. (this issue) also represent a more integrated approach, but include additionally an integration of insights from practice-based action research (the local action in the Sustainable Hökarängen project in Stockholm). A key insight from this paper is its inclusion of a full range of technological and behavioural changes in both the supply and the demand for space heating, including an analysis of the willingness of householders to adopt demand-side measures, many of which are behavioural or cultural. Demand and emissions reductions potentials and presented with a more informed view of the potential for behavioural change.

Beyond these variations in the approaches used to achieve bridging, there are also other significant differences in these studies. There is variation in the objectives of the analysis, broadly whether the analysis is primarily concerned with providing insight (for example van Sluisveld et al., De Cian et al., Hof et al., Köhler et al.) or whether the aim is to make contributions to policy and governance (for example, Zwartkruis et al., Rogge et al. and Geels et al.). Integration between the approaches (modelling, socio-technical analysis, action learning) may be achieved within a single study, or step-wise in follow-on studies, as in the case of van Sluisveld et al. and Hof et al. This suggests that we might envisage sequences of studies, with not all the bridging steps being implemented within a single study. All the studies noted the resource- and time-intensity of this style of integrated research. Such resources may not always be available. There are also variations in the scope of approaches which are covered by analysis, ranging from the interaction of two approaches (for example, Rogge et al.) or three (for example, Zwartkruis et al.). Each of the initiatives involves the bringing into interaction of concepts, results and analytical procedures. But the scope, intensity and reciprocity of interaction vary.

In addition to these methodological variations, the studies also demonstrate a variety of spatial and governance scales of analysis and a range of sectors that are addressed. One of the main promises of methodological bridging is that it offers a means of linking in a structured and theoretically-informed way the analysis of objects of interest as a very local scale with analysis of national, regional and global scale. The ‘weak signals’ manifest in emerging niche experiments and niches may then be traced through a plausible global assessment, which avoids the stasis and conservatism of many integrated models which may be unable to reproduce observable socio-technical dynamics. It is important not to overstate this promise. The problems of forecasting, for all the well-known reasons, remain. But at least it should be possible, through the flexible and creative use of bridging approaches, to explore the consequences and trade-offs associated with small but promising innovations and shifts, instead of having to wait for them to be observable in broader systems changes.

The sheer variety of ways in which the challenge of comparing, combining and integrating approaches has been addressed in this collection of papers suggests that bridging may be a family of analytical procedures. There will be shallower and deeper ways of achieving bridging, and the specific approach taken in any given case will be determined by the resources available and the benefits expected from deeper integration. We can anticipate that bridging will be generative of multiple experiments in methodological hybridisation.

4. Bridging in practice: responding to the five key challenges

In the Turnheim et al. (2015) paper, we outlined five key challenges which, we argued, needed to be addressed by analytical approaches to inform policies to support transitions to sustainability. These related to i) scale and temporality, ii) complexity and uncertainty, iii) innovation and inertia, iv) the normative goals of transitions, and v) the varying perspectives on the governance of transitions.

On *scale* and *temporality*, the studies presented here provide analysis, frequently integrated in a single study, of processes at a wide range of scales, ranging from the local to the global. In several of the studies, the global context is provided by the boundary conditions set by the IAMs – a useful template in which the socio-technical, policy and behavioural dynamics of systems at a more granular scale can be analysed and understood. The time-scales investigated are also quite broad, but these appear to be more constrained by the temporalities intrinsic to the climate policy debate, with defined periods of decades (to 2030, to 2050, for instance) becoming the temporal framing for most of these studies.

On the challenge of *complexity* and *uncertainty*, the primary methodological response in all these studies has been to introduce additional layering to the analysis, as well as the introduction of boundary conditions informed by analysis from complementary approaches. The layering, such as the introduction of analysis of socio-technical niches in Sluisveld et al., is a demonstration of the enrichment of IAM approaches, by broadening the range of options considered. By adding evidenced constraints to the analysis, for instance by including ideas about institutional and behavioural dynamics to models as suggested by De Cian et al. (this issue), a greater degree of realism is added to the analysis. This realism adds complexity but may also be seen as adding to the handling of uncertainty in complex, long-term societal transition processes.

On the challenge of *innovation* and *inertia*, the studies respond in a variety of ways. For the modelling studies which have integrated the results of socio-technical case studies of niches (van Sluisveld et al., Hof et al., Geels et al., Köhler et al.) the analysis includes a greater variety of socio-technical options, enriching and consolidating the basis for scenario studies. Likewise, the inclusion of considerations related to the co-evolution of markets, regulation, infrastructure and behaviours with technologies, enables a richer concept of innovation. Four of the studies (van Sluisveld et al., Hof et al., Geels et al. and Koehler et al.) pay explicit attention to niche or regime inertia or momentum. This suggests that this remains a feature of socio-technical systems which remains difficult to codify in more formal, modelling analysis.

On addressing the *normative prescription* challenge, which relates to the emergence of new normative frameworks around new socio-technical system, there is little evidence in these studies. While there is some commentary on historical changes in norms and standards in Geels et al., in general this challenge is absent in the consideration of these studies.

Finally, regarding *governance*, there is also a lack of very specific results. Most of the studies are concerned with offering broad guidance for policymakers, but there is little that is specific and no substantive discussion about appropriate modes of governance, or the scales at which it may be achieved. The development of a multi-perspective approach to governing sustainability transitions thus form an important topic for future research. One of the implications of the ‘second best’ outcomes from the modelling studies may also be that the standard assumptions about the imposition of an environmental tax to achieve outcomes are relaxed. But this too remains an area for further attention.

5. Lessons for governance and policy

A key claim of the original Turnheim et al. (2015) and Geels et al. (2016a) papers was that policy- and other decision-makers, including investors, civil society organisations and citizens and consumers, would benefit from having more reliable and informed assessments of sustainability transitions as they unfold. While integrated modelling assessments have played a significant role in international and national policy-making, this has primarily been in helping to set broad and long-term targets for policies and strategies. Socio-technical analysis has been far less influential in policy-making and strategy-setting, although the OECD (2015), EEA (2018), and IPCC (2018) have adopted it as ‘big picture’ framework to inform their strategic thinking about the complexity of transitions. Practice-based initiatives have played a role as demonstrations of ideas, although their broader impact may have been constrained by the specificities of the context in which they have emerged and operated.

Policy- and decision-makers interested in transition processes are looking for more than long-term targets, stylised facts and exemplars. In order to understand, respond to and govern transitions as they happen, they need additional information that may be provided by more holistic analysis. First, they need real-time assessments of the state of a system in transition, including the interactions between the technical, institutional, social, political and normative dimensions of a transition. Second, they need a clear understanding of the critical trade-offs, enablers and constraints on a transition at any given moment in the evolution of a transition. Third, they are interested in effective policy and governance interventions for shaping transitions – in response to prevailing trade-offs, enablers and constraints – at any given moment. Finally, they would like to know what the costs, benefits and risks of any given series of interventions may be, including unintended and second-order effects. They would like to understand who the winners and the losers are and what measures may be needed to deal with these distributional effects, at different scales.

The evidence from the papers in this Special Issue suggests that combined, bridging analysis of sustainability transitions may provide ways of providing these things. Several papers, including van Sluisveld et al., Rogge et al. and Geels et al., provide a perspective on the real-time status of transitions processes and a realistic analysis of the key issues at stake at the moment of their analysis. Similarly, many of the papers are concerned with identifying trade-offs and constraints on transitions in the making, including Hof et al., Nilsson et al., and Köhler et al. These papers include assessments of a range of transition domains (electricity, agriculture and nature, and mobility) and across different scales, implying the range of policy audiences that might be addressed on this crucial question. On the third of the desiderata – policy and governance interventions – many of the papers suggest where key interventions may be most needed – to sustain niche momentum, for instance – while all papers include some scenario analysis in which policy choices, conflicts and differing policy styles are explored. Several papers, such as Köhler et al. and Zwartkruis et al., provide a more detailed account and analysis of specific policy measures. On the final measure, social and other impacts of these measures, this collection of papers tends to say less. This may also be because it was not one of the explicit aims of the project. However, further analysis of the existing case studies, scenario studies and modelling results would likely provide insights into distributional issues.

Although this Special Issue reports the results of a small number of experiments with a new bridging approach to transitions analysis, we believe this collection demonstrates both the analytical value of this approach, as well as the potential value to policy- and decision-making. This is also shown by the influence the PATHWAYS research has had on the thinking of the European Environment Agency (EEA, 2018, 2016) which provides strategic advice to the European Commission and European Parliament. The further development of bridging approaches, by bold and creative methodological and empirical experimentation, and by engaging policy-makers themselves in the co-production of transitions understanding, seems necessary and potentially influential in achieving the radical changes which these assessments seek to shed light on and to bring to life.

Acknowledgements

We gratefully acknowledge support from the European Union's Seventh Framework Programme (FP7/2007–2013) under grant agreement no. 603942 (PATHWAYS).

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