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Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges

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ABSTRACT

The paper sets out a proposal for bridging and linking three approaches to the analysis of transitions to sustainable and low-carbon societies: quantitative systems modelling; socio-technical transition analysis; and initiative-based learning. We argue that each of these approaches presents a partial and incomplete picture, which has implications for the quality and usefulness of the insights they can deliver for policy and practice. A framework for bridging these different approaches promises to enrich each of the approaches, while providing the basis for a more robust and complete analysis of *sustainable transitions pathways* that serves better to address questions and dilemmas faced by decision-makers and practitioners. We elaborate five key challenges for the analysis and governance of transitions pathways, and compare the three approaches in relation to each of these. We suggest an integration strategy based on alignment, bridging, and iteration, arguing that a structured dialogue between practitioners of different approaches is needed. In practical terms, such a dialogue would be organised around three areas of joint knowledge production: defining common analytical or governance problems to be tackled through integration; establishing shared concepts (boundary objects); and establishing operational bridging devices (data and metrics, pathways evaluation and their delivery). Such processes could include experts and societal partners. We draw conclusions about future research perspectives and the role of analysis in transitions governance.

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1. Introduction

Global environmental and sustainability challenges, including climate change and biodiversity loss, are among the great problems of our time. Limiting global warming to 2 °C, improving resource efficiency, and halting the loss of biodiversity, while improving human well-being, requires radical departures at global, national and local scales from current resource-intensive and high-emission development trajectories (Kriegler et al., 2015, 2014; Tavoni et al., 2015; van Vuuren et al., 2015). Such a departure requires ambitious socio-technical transformations in domains such as energy, mobility and food domains, locally and globally. Governments have made political commitments to such transitions and are seeking to foster them, while business and consumer-citizens have also expressed interest in enacting transformative initiatives and behaviours. However, the scale, scope and urgency of the transitions required are considerable, while deliberately managing such processes is a huge challenge, even for large and powerful actors like governments and global businesses.

The international community and many countries have made policy commitments for decarbonisation and sustainability transitions (UNFCC, 2011; UN, 2012). The European Union, for instance, has set an ambitious target to reduce carbon emissions by at least 80 percent by 2050 (European Commission, 2011a; European Commission, 2014), to manage resources sustainably and to halt biodiversity loss by 2020 (European Commission,

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2011b). The Chinese and United States governments jointly announced in 2014 post-2020 targets on climate change, with China intending to peak its CO_2 emissions by around 2030, while the United States announced reductions of 26–28% below 2005 by 2025 (White House, 2014).

For climate change, the national targets to date do not add up to meet the internationally agreed aim to keep the increase of global mean temperature to less than 2 °C (UNEP, 2014). Moreover, current policies are often not sufficient to meet the announced targets (Roelfsema et al., 2014; Wiseman et al., 2013; Wise et al., 2014; Tittensor et al., 2014). This is due to a combination of economic, political, social and cultural factors.

In addition to the societal challenge, there is also a serious analytical challenge. While there is a need to improve understanding of transitions processes in order to better inform policy, it should be noted that such transformations involving technological, economic, social and ecological change are complex. Therefore, there are major limits to the capacity to project and to govern transitions-in-the-making. A practical approach will involve the ability to capture analytically as robustly as possible the current state of transitions processes, through an assessment of the current scale, scope, and momentum of transitions, and an analysis of adjustments that would be needed to achieve longer-term targets. Effective governance of transitions needs to be appreciative of complexity, uncertainty, emergence and asymmetries of power, it needs to mobilise deep analysis and timely data, and involve a broad variety of actors in processes of learning, experimentation and adaptive adjustment as new facts and perspectives become available.

Sustainability transitions have become the object of increasingly refined academic debates across a wide range of disciplines (Markard et al., 2012; Söderholm et al., 2011; Shove and Walker, 2010), but – besides notable examples mobilised in Section 4.2 – remain tied to relatively isolated analytical approaches. This fragmentation is an obstacle to analytical advance and therefore a constraint on the capacity to govern transitions effectively. There is a need to take advantage of the multiplicity of analytical perspectives on the critical shaping factors and opportunities for accelerating change. We need better ways of evaluating sustainability transitions pathways: where do we stand? Where we are heading? And, how we can get there?

In this article, we employ the notion of *transitions pathways* (Geels and Schot, 2007) to capture the idea that transitions are not determined and linear, but rather involve context-dependent evolutionary processes with emergent properties. Transitions pathways can be seen as analytical constructions that vary across approaches – whether mobilised to denote specific modelling scenarios inspired by socio-technical transitions studies (Foxon et al., 2010; Foxon et al., 2013) or in relation to principles for informed governance that situates experimentation within broader sequences of transformative change (Wise et al., 2014). *Transitions pathways* allow us better to sense and apprehend unfolding transition processes and opportunities for intervention. We define transitions pathways as *patterns of changes in socio-technical systems unfolding over time that lead to new ways of achieving specific societal functions*. Transitions pathways involve varying degrees of reconfiguration across technologies, supporting infrastructures, business models and production systems, as well as the preferences and behaviour of consumers.

We address the challenge of sustainability transitions by exploring the potential for integration across three analytical approaches. We here refer to the following broadly defined perspectives: *quantitative systems modelling* provides a future-oriented perspective on transitions and focuses on techno-economic and behavioural options to achieve specific sustainability or low-carbon targets. *Socio-technical transition analysis* provides a historically informed perspective on transitions and focuses on the interaction of technical, institutional, and socio-political change processes. *Initiative-based learning* provides a situated micro-perspective on local-scale projects, and focuses on the role and interplay of actors such as citizens, businesses, civil society organisations and (local) government in developing, legitimising and scaling up innovative sustainability solutions in practice.

We recognise that there are other literatures concerned with social, economic and political transformations, but have chosen to focus on those contributions that focus on the co-evolution of social and technological innovation processes to address sustainability challenges. For instance, we have not considered complexity or socio-ecological approaches (Leach et al., 2010; Pielke et al., 2012), which may further inform on changes to the environment, the complexity of adaptive human behaviours. We further note that distinctions between literatures are bound to bear some element of arbitrariness. Our main aim in drawing boundaries between approaches is to point-up distinctions as a basis for enabling integration.

We argue that current and prospective sustainability transitions can be more robustly analysed in their variety and complexity by drawing on the respective strengths of these three analytical approaches – an opportunity to bring different kinds of information to bear on transitions assessments and the governance of underlying mechanisms. We believe that a dialogue is needed between approaches, and suggest an integration strategy based on alignment, bridging, and iterations thereof.

In the next section we outline key analytical problems for the evaluation of sustainability transitions. This is followed by a detailed overview of the three approaches and their strengths and weaknesses. We then discuss how the identified analytical problems may be handled through more integrated approaches, before proposing strategies for analytical integration. Finally, we draw conclusions about future research perspectives and the role of analysis in transitions governance.

2. Shaping sustainability transitions: five analytical challenges and related governance implications

Central to the analysis and governance of transitions pathways is the appreciation of a process of change in interacting social, technical, institutional and ecological systems. Not only are these *socio-technical-ecological configurations* complicated to describe and understand, a useful analysis of transformational change must capture new problems and phenomena emerging through the process of reconfiguration. A system undergoing transformation is never fully ordered and stabilised, and so requires a continuing readjustment in the categories and metrics used to describe and analyse it.

Sustainability transitions present a number of challenges due to (1) the multiple scales, geographies and temporalities of transformational processes, (2) uncertainties associated with radical innovation and the limits of prediction, (3) the interplay between the inertia of existing socio-technical systems and the emergence of novelty, (4) the problem of shaping innovation in relation to multiple social objectives and public goods, and (5) contested perspectives about the governance of complex processes of social, economic and technical change. Actively shaping sustainability 'transitions in the making' needs analytical approaches that take such difficulties and related challenges into account.

2.1. Scales, geographies and temporality

Socio-technical transitions involve change unfolding over extended periods of time (decades) and spanning different scales (territorial, jurisdictional, organisational, cultural) (Wiseman et al., 2013). There is no single (spatial or temporal) vantage point from which socio-technical transitions can be comprehensively analysed or steered (Hodson and Marvin, 2012). One response, as in quantitative systems modelling, is to span extremely broad spatial and temporal scales in a geographically-explicit way (Kareiva et al., 2005). Another, as in the multi-level perspective (MLP) is to remain scale invariant and apply structuration as the key dimension (Geels, 2004), across stylised levels where socio-technical phenomena are played out (niches, regimes and landscapes). Transitions involve reconfigurations across levels in nested systems composed of complex bundles of phenomena (Geels et al., 2015).

In more quantitative studies, analytical tools exists that describe relevant processes at different levels of scale – but such tools will always be bounded by the need to avoid too much complexity. In practice, there are a number of implications for transition governance. First, while (technological) innovation theory typically makes distinctions between innovation and diffusion, in the study of sustainability transitions we are concerned with the reconfiguration of socio-technical systems. Diffusion of new technologies alone, assumed to be within a given socio-technical configuration, may not be sufficient to describe a process of transition. Rather, we are concerned with the re-design and re-ordering of a system, a phase-change in which new actors, relationships, logics, norms and performance criteria will emerge. In general, analysis has been directed to understanding the emergence of novelty at local scales (Späth and Rohracher, 2012), but it clearly needs to able to capture transition processes (as reconfigurations) across scales, understanding nestedness and dependencies. For instance, in the case of electric vehicles, the urban scale presents many advantages to overcome the initial hurdle of charging infrastructure rollout (the 'chicken-and-egg' problem) and range anxiety. For an electric mobility transition beyond urban pockets, such interventions need to be complemented with national/transnational perspectives and attention to global regime dynamics (Orsato et al., 2012; Nykvist and Nilsson, 2015). Multi-level governance frameworks offer a clear entrance point for integration around issues spanning different jurisdictions (Nilsson et al., 2012). It is also essential to enable stronger coupling between on the one hand top-down visions and goal-setting, and on the other hand the bottom-up emergence of novelty (Hara et al., 2012).

Second, transitions in the making are not always eventful; perceiving progress towards long-term objectives requires continuity in monitoring and appraisal, and an ability to project the bigger picture. This may be difficult for key actors with short-term orientations seeking immediate results (Hughes 2013). In practice, navigating transitions requires connecting the past, the present and the future through a sense of trajectory. Because of their interest in transformational change, all three approaches call upon and link elements of past, present and future in their methodologies. Nonetheless, the primary focus of their analysis tends to be circumscribed within a given temporal frame. Analytically there is a major challenge in connecting approaches that have thick assessments of the past (socio-technical transitions analysis), detailed assessments of the present (initiative-based learning), with comprehensive projections of future trajectories (quantitative systems modelling).

Third, transitions involve connected processes of change at differing scales: global, national, regional and local, and across different types of phenomena: organisations, institutions, behaviours and practices. The differentiation and connectedness across socio-spatial scales has generated a 'geographical turn' in transitions studies (Coenen and Truffer, 2012; Carvalho et al., 2012; Hodson and Marvin, 2012; Hansen and Coenen, 2015).

2.2. Complexity and uncertainty

Technology and innovation dynamics are difficult to predict and control. In practice, attempts to foster their development have led to: slower development than foreseen (e.g. heat pumps and electric cars); hype/disappointment cycles (e.g. hydrogen, biofuels); unforeseen rapid diffusion (e.g. solar PV, meat-free Mondays); and competition from dominant incumbents and from alternatives (e.g. gas and CCS in power, hybrid cars) (Deetman et al., 2015). The more disruptive a socio-technical change, the more uncertain and uncommon it will be (hence reducing the potential for control). This is because of the greater scope and depth of the changes required, because of the more complex set of countervailing factors (losses, unforeseen costs of adjustment, trade-offs, resistance), and because of new problems that emerge in the complex process of systems change. A related consideration is the ability to capture fundamental system re-configurations that challenge the very performance criteria by which existing systems are analysed. While quantitative systems modelling is relatively constrained by fixed initial system definition and structure, socio-technical analysis has rested on 'process tracing' accommodating fundamental shifts in analytical units and determinants of change over time (Pettigrew Andrew, 1990).

Policy support for transitions needs to respond to unexpected accelerations and tipping points, as well as unforeseen risks and losses, and the distributional effects and power struggles associated with such 'wicked systems' (Andersson et al., 2014). Long-term commitments and signals are important, but so are the timing and modulation of interventions in accordance to innovation dynamics (e.g. experimentation, sunset clauses, degressive support.), and more generally a reflexive disposition.

2.3. Innovation and inertia

Path dependence and inertia of socio-technical systems has many features. Each analytical approach treats inertia differently, suggesting different approaches to the dual governance problem of sustaining momentum (and promoting radical innovations) (Smith and Raven, 2012) and overcoming inertia (and breaking up the resistance of mature and stable incumbents) (Turnheim and Geels, 2013). Quantitative systems models represent inertia via structural techno-economic constraints (e.g. sunk investments), but also carry an implicit understanding of inertia through the obduracy of system architectures and the assumption of past optimisation against economic criteria. For socio-technical analysis, inertia will be the outcome of an inherent, structural resilience of a dominant technology and regime (Geels, 2004), and all the advantages of efficiency, orderedness and normalcy that this confers. Regimes will be reproduced via prevailing regulatory, normative and behavioural practices, but also through active defence and resistance strategies of dominant market players. Market and political power (of incumbents) are major sources of resistance to change that will get in the way of transitions efforts (Geels, 2014). If transitions are about both the generation of novelty and the destabilisation of incumbent regimes, effective analytical approaches will also need to capture these two sides of the problem.

In practice, inertia and path dependence are manifest in, for instance, the persistence of fossil fuels subsidies (OECD, 2012), the centralised architecture of electricity supply and distribution, the preference for technological fixes by powerful actors under pressure (e.g. CCS and the coal industry). Behind each of these forms of inertia stand powerful social, political and economic interests, exerting an often-intangible influence. Including an analysis of inertia in the analysis of transformations and transitions is difficult, but vital, especially since it is not a 'dead weight' but an active exercise of power and custom.

2.4. Normative goals of transitions

Sustainability transitions require the emergence of new (normative) criteria to judge the appropriateness and effectiveness of innovation (cf. Kemp and van Lente 2011). Policy support for innovation to achieve public goods (health, education, environment) is subject to changes in values, ideology and public attention. Formulation and commitment to long-term goals may be especially vulnerable to this problem. Highly-mobile and contested public debates emerge around new technologies, and these are subject to the emergence of new narratives, and coalitions of advocacy and resistance. In this sense, sustainability transitions can also be regarded as processes of deep cultural change calling for new orientations for societal systems (Kemp and Martens, 2007). But normative prescriptions alone cannot drive sustainable transitions with the required sense of urgency. 'Sustainability' has yet to become an area of top strategic priority for policy, comparable, say, to the traditional core state imperatives of territorial, economic, and physical security (Dryzek et al., 2003). Frequently sustainability goals need to be linked to other more foundational goals, like human health, economic competitiveness, or security. Such normative flexibility and fragility is deepened by the multiplicity of objectives represented by the appeal to sustainability. Optimising on a single objective like inflation, growth or employment is a good deal more straightforward analytically and in governance than balancing across many objectives. The new UN Sustainable Development Goals embody this problem, while they can serve to guide transitions only if they can speak to a broad set of actors in global societies (Hajer et al., 2015). Neither is sustainability a core criterion reflected in mainstream consumers choices, or other economic considerations of (boundedly rational) actors. Again, the derived value of sustainability, such as cost-savings due to the reduction of waste or avoidance of environmental taxes, often serves as a rationale for action.

2.5. Perspectives on governing transitions

For all the reasons discussed, actively-shaping transition dynamics is difficult. But this problem is compounded by the diversity of opinion, scholarly and otherwise, that exists about governing and steering technology and structural changes in society. Different perspectives each have their respective assumptions concerning the main factors *supporting*,*shaping*, and *modulating* transitions and their dynamics. While there is an active academic debate about steering sustainability transitions (Hughes, 2013; Loorbach and Rotmans, 2010; Voss and Bornemann, 2011; Smith et al., 2005; Weber and Rohracher, 2012; Wise et al., 2014), there remains a great variety of perspectives on governing transitions. Accepting this variety, we believe that integrated appraisal approaches should seek to make contributions to each. Here, for simplicity, we summarise briefly the wide range of sometimes-related takes on governance that are implied in the three transitions approaches:

- '*Command and control' public policy*: using the classical distinction between public policy incentives, regulations and information steering towards politically-defined objectives. Main actor: Government. Problems: legitimacy and effectiveness (goal achievement in face of complexity and strategic behaviour by actors)
- *Public-private governance*: leveraging the dynamics in business and society through research, technology and innovation (RTI), and market-regulation policies, as well as partnerships, networks, discourse. Main actors: government and business. Problems: incentives, accountability and effectiveness (collective goods under-invested in, market capture).
- *Adaptive governance*: responding to emergent properties of complex transition processes, with an emphasis on visioning, experiments (pioneering, action, learning by doing), monitoring and evaluation, reflexivity, appropriate interventions during windows of opportunity. Main actors: business, civil society and government. Problems: coordination, assessment (need for real-time assessment) and intervention (risk of incumbents remaining dominant).

The diversity of perspectives on governance greatly complicates a more integrated analytical approach to sustainability transitions that seeks to contribute to policy and governance. With respect to informing decision-making, each approach emphasises specific aspects of transitions, while neglecting others. *Quantitative systems modelling* has accumulated sophisticated means of exploring future options to assist decision-making in relation to long-term policy targets, with only limited consideration of difficulties related to institutional or social inertia, and the interplay of interests and politics in a real-world context. *Socio-technical transition analyses* have accumulated insights from historical transformations that can inform and focus current transition efforts through knowledge of process and trajectory of development, but have a limited ability to formulate stylised future projections and to consider participation in local contexts. *Initiative-based learning* has accumulated considerable insights about local alternatives addressing long-term societal concerns and related sources of failure (e.g. resistance) or success (e.g. legitimation), with only limited attention to interactions with (established or emergent) regime trajectories and limited ability to formulate linkages with broader transformation dynamics. Not only does the observation of socio-technical and ecological transitions need to become more integrated, but perspectives on how to *support*, *shape* and *modulate* the dynamics of transitions also need to become both broadened and more integrated. We believe that more integrated methods may facilitate coordination and dialogue between often-disparate agents of change.

3. Three approaches to sustainability transitions

Quantitative systems modelling, socio-technical transition studies and initiative-based learning are inscribed in a tradition of problem-driven research addressing societally relevant issues. Within the main problem area of sustainability transitions, each approach provide their specific scientific outlook, sub-problems and explanatory style, how they handle each of the five analytical challenges discussed above, and adopt a different attitude towards governance. We here take a closer look at each approach, focussing on how they each contribute to the understanding and assessment of (sustainable) transition pathways, before examining how they fare against the five challenges.

3.1. Quantitative systems modelling

'If you want to go from A to B within 30 years, scenario x, y, z are all technically possible . . . We can not predict the future but point out the likely consequences of specific choices'.

Core messages (Moss et al., 2010; van Vuuren et al., 2011; van Vuuren, 2015): (1) future transitions pathways are scenarios that depart from 'reference futures' either by policies oriented towards politically-defined end-points or by a predefined set of policies; (2) scenarios are projections not predictions; (3) technological and behavioural options can contribute to achieve long-term (global, regional or national) political objectives; (4) subject to constraints imposed in models, lowest-cost options are usually assumed to be adopted in a clearing market; (5) transition pathways (distinct combinations of options) to achieve long-term goals radically depart from 'business as usual' pathways.

Quantitative systems modelling studies – a broad term we use to refer to a wide variety of quantitative modelling approaches including techno-economic, integrated assessment, system dynamic, network, agent-based, complex systems, etc. (Goodess et al., 2003; Kareiva et al., 2005; Kelly and Kolstad, 1999)—provide a forward-looking perspective of transitions. This can be done by analysing specific sets of policies or by backcasting (i.e. working backwards from a given policy target to identify measures to achieve it) from a social objective and forecasting (i.e. projecting the future based on current trends) against such an objective. In modelling studies, transitions are seen as fundamental change in (performance) parameters (e.g. emissions, land use, etc.), driven by changes in a modelled structure of drivers. What distinguishes models is their scale and the detail with which factors are represented. So, with low-carbon transition pathways, modelling researchers focus on the periodic *outcomes* and *performance* of the system under scrutiny (which may be a world region, a national economy or a sector within a country), and on the temporal profile of these outcomes that can deliver the desired performance improvements (e.g. 60–80% reduction in emissions to reach the 2 °C target).

The quantitative systems modelling literature typically characterises a variety of simulation runs for which input parameters often reflect policy objectives and instruments (e.g. 'business-as-usual' (BAU), 'high carbon', 'carbon tax') or technological avenues (e.g. 'more electric', 'hydrogen economy', 'no nuclear', etc.) (Foxon et al., 2013; Kriegler et al., 2014; Trutnevyte et al., 2014). From a modelling perspective, the terms scenarios and pathways are often used interchangeably. Scenarios are generally 'compositional' in that they frame a picture of a *total system* of technologies linked to efficiencies and performance metrics (emission factors, crop yields). To generate scenarios, an underlying 'storyline' is often posited which forms the basis for a narrative explaining the outcomes generated by the model. In a normative, back-casting mode of scenario development, pathways also relate to narrative and quantitative elaboration of trajectories to achieve specific outcomes (van Vuuren and Kok, 2012; Kok and Alkemade, 2014). Foxon et al. (2013) have explored a typology of transition pathways based on alternative governance patterns – where a specific governance 'logic' (market-, government, or civil society-led) takes precedence over the others and leads to fundamentally different kinds of parameterised models and outcomes. The distinction of clearly identifiable future scenarios is central to contrasting and assessing different options from an analytical or policy perspective, such as for instance the notion of 'policy paths' that brings greater attention to the dynamic contexts formed by governance and institutional aspects (Nilsson et al., 2011).

In practice, modelling researchers build models, collect data and run models under specific constraints (e.g. policy goals and objectives, emission targets, etc.). In general, models make standard assumptions about information, foresight and utility-maximising behaviour by rational actors. Several kinds of models can be distinguished including top-down versus bottom-up models (i.e. whole economy vs more technological detail), agent-based models vs "one-actor" models, simulation models vs optimization models and process-based vs cost-benefit models (van Beeck, 1999; Füssel, 2010; Goodess et al., 2003; Kelly and Kolstad, 1999; Kareiva et al., 2005; Weyant et al., 1996). Often, models are a combination of such elements.

One of the main strengths of quantitative systems modelling is that it focuses on system constraints from a relatively deterministic, quasi-physical perspective, looking mainly at observable quantitative variables (e.g. technological factors, crop yields, emissions, land use, etc.) and projecting change over the long-term. A considerable evidence-base of forward-looking projections and scenarios has been amassed over the years, and is influential in informing high-level policymaking (Strachan et al., 2009). For instance, the EU Roadmap for moving to a low-carbon economy in 2050 is strongly based on integrated assessment model runs:

"The transition towards a competitive low carbon economy means that the EU should prepare for reductions in its *domestic* emissions by 80% by 2050 compared to 1990. The Commission has carried out an extensive modelling analysis with several possible scenarios showing how this could be done" (European Commission, 2011a).

Modelling outcomes can also serve to assess policy promises in terms of the technological effort, the economic cost, the distribution of costs and benefits, and the trade-offs between different options. However, models also tend to overlook less tangible aspects of transitions, such as the institutional and cultural context of social and technological innovation, the role of power and legitimacy, the non-linearity (and non-rationality) of real-world processes. An obvious epistemic problem is that once projections are made, reflexive actors will tend to change their behaviour in response to them.

3.2. Socio-technical transition analysis

'Going from A to B in the past has never been easy, and has involved the co-evolution of x, y, z... We have identified some ideal patterns of change but are uncertain about how transition dynamics will unfold'.

Core messages (Geels, 2004; Smith et al., 2005; Geels and Schot, 2007; Markard et al., 2012; Turnheim and Geels, 2013): (1) sustainability transitions involve multiple processes of technical, institutional and social reconfiguration and alignment, taking time; (2) transitions pathways are an outcome of interactions in multiple levels of structuration in socio-technical systems described as niches, regimes and landscapes; (3) given the complexity of transitions processes, many future outcomes are possible; (4) projections towards long-term end-points of transitions are avoided, but counterfactual exploration can be used to envisage possible future developments (Hillman and Sandén, 2008).

Socio-technical transitions studies seek to analyse the multiple dimensions of change, including a broad range of technological, economic, political, socio-cultural aspects at different levels and temporalities. Starting from a conceptualisation of technology and associated practices as a (dynamically stable) 'configuration that works', transition studies focus on the interplay between novelty creation, external pressure and re-configuration of socio-technical systems over time.

The approach adopts a broad sociological frame, combined with a practical interest in historical methodologies, such as qualitative longitudinal case studies in which data from a broad range of sources is turned into rich socio-technical assessments. Policy insight is derived from the analysis of past governance and institutional patterns (Nilsson et al., 2012) and likely trajectories given recent dynamics. The representation of governance is rooted in co-evolutionary theories of change emphasising multiple actors and multi-dimensional arrangements.

The socio-technical transitions literature actively relies on pathway typologies, which are used as both theoretical constructs and analytical devices to make sense of transitions. Transition pathways characterise specific path-dependent regime trajectories defined by propositions of underlying relationships and processes of structural change, and the stabilisation of technologies and institutions within sectors of society (Geels 2004; Rip and Schot 2002; Jørgensen 2012). Berkhout et al. (2004) propose a typology of transitions pathways based on a differentiation of the resource mobilised (external or internal) and the degree of coordination in resource deployment (high or low). Geels and Schot (2007) suggest, instead, to base a pathway typology on the main kind of actors involved (incumbents and/or new external actors), the timing and nature of interactions. Socio-technical perspectives conceptualise transitions pathways in terms of gradual changes in socio-technical configurations, with attention to co-evolutionary dynamics, but does not explicitly address their influence on overall system performance (e.g. sustainability, emission profiles).

One of transition studies' main strengths is the high degree of context-specificity and nuance of its description of real-world (historical) processes, stemming from an attention to agency and institutional factors, and a nuanced take on process, causation, and time. This is also its main drawback as it struggles with identifying and communicating predictions and more tangible outcomes. Transitions studies favour general strategic guidance (attuned to context-dependencies) over traditional policy advice (e.g. centred on instruments). Transition studies, in their practical applications, also tend to be sector-specific, which can make the connection with broader (environmental) policy goals more difficult to establish.

3.3. Initiative-based learning

'Going from A to B will only be achieved if the relevant actors are involved in defining and legitimising new technologies and practices. Understanding the motives and strategies of actors on the ground is critical to making transitions socially-robust and sustainable.

Core messages (Argyris et al., 1985; Reason and Bradbury, 2001; Ozanne and Saatcioglu, 2008; Raven et al., 2008; Liedtke et al., 2014):

In general, the range of perspectives and methods we wish to group under initiative-based learning is less unified and more heterogeneous than modelling and transitions studies, but there are some common starting-points.

(1) understanding expectations and practices of actors in novel socio-technical configurations is critical; (2) learning by doing includes technical, organisational and cultural aspects; (3) while often driven by a longer-term vision, the rationality of actors in sustainability experiments are bounded by their immediate environment and resource constraints; (4) at the micro-scale, socio-technical innovation involves shaping and responding to emergent processes.

Initiative-based learning engages with concrete projects at the level of individual initiatives ('transitions in the making', sustainability experiments), involving diverse social actors such as citizens, businesses, civil society organisations and (local) government, with the aim of fostering innovation and upscaling innovative sustainability solutions (Raven et al., 2008). In choosing a more limited focus through the term 'initiative-based learning' we also draw on the broad tradition of work on action research (Lewin, 1946; Argyris et al., 1985; Huntjens et al., 2015). The focus is on agency and interactions at the level of individual initiatives and projects. Legitimation of novelty and public participation are seen as crucial for radically novel socio-technical configurations. These initiatives may be viewed as *microcosms* of future reconfigured systems. The true value of these 'real-world experiments' (Schot and Geels 2008) is that they reveal emergent properties in system change processes that are invisible or ignored by other approaches: the practical realities, emergent tensions and problems stemming from new ways of doing things. Transitions are seen as the up-scaling of successful (legitimate) solutions. Learning from initiatives on the ground is hence critical to the governance of transitions in the making, particularly effective forms of shaping and fostering transition efforts from the ground up.

Common research strategies consist in observing the mechanisms and dynamics of such localised activities e.g. through ethnographic observation and case study analysis (George and Bennett, 2005). Other, more engaged, strategies are based on participatory methodologies where researchers deliberately take an active role in shaping, or initiating the development of transition-oriented activities e.g. in real experiments or 'living labs' (Liedtke et al., 2014).

Table 1
Overview of strengths and weaknesses of the three approaches.

Approach	Strengths	Weaknesses
Quantitative systems modelling	Robust & highly formalised research methods	Oversimplification of social realities, little attention to actors and behaviours (politics, power struggles, beliefs, strategies)
	Consistent analysis of complex systems	
	Attention to system interactions (e.g. sectors)	
	Attention to problem interactions	Limited scope for changing economic, social and institutional rule-sets
	Synthetic analysis of multiple options	
	Links policy goals to required physical changes	Over-reliance on economic mechanisms
	Ability to calculate effects of policy options on transition pathways	Limited attention to implementation process
	Simple and coherent policy advice	
Socio-technical analysis	Fine-grained analysis and understanding	Mainly descriptive (qualitative case studies)
	Attention to different levels and temporalities	Qualified generalisation (context-specific, pattern-based, multiple and changing forms causal mechanisms)
	Attention to relevant socio-technical dimensions	
	Attention to multiple actors and behaviour types	
	Analysis of institutions and changing 'rules of the game' (including shared cognitions and norms)	Limited forward orientation to political targets
	Attention to inertia of existing systems	Policy advice focuses on general strategies (patterns) rather than instrumentality
	Policy advice sheds light on uncertainties	
Initiative-based learning	Analyses and/or engages in real-world initiatives as experiments	Limited methodological standardisation
	Attention to local level and implementation	Often context-specific and short-term oriented
	Attention to actor-relevant dimensions (behaviour, legitimacy, learning, inclusion, etc.)	Limited attention to wider structural contexts
	Relevance to stakeholders and practitioners	Difficulty to generalise lessons for entire transitions
	Policy advice is rooted in practice	

Initiative-based learning mobilises the notion of pathways in relation to strategic implementation processes – such as within the sub-strand of strategic niche management (SNM), which emphasises the protection of early innovation in niches (Kemp et al., 1998; Smith and Raven, 2012) and so provides a direct connection with the system transformation focus of *socio-technical transitions analysis*. Initiative-based learning focuses mainly on local socio-technical configurations, with greater attention to contextual factors and issues of spatial replication, but has little to say about overall system performance. It is concerned with more granular changes, theorised as shared visions and plans, the coordination of known and engaged actor networks (Seyfang et al., 2014), and the development of innovative practices and routines (Pelling et al., 2008). The process of learning is conceived as a participative process, with attention given to the practical arrangements for achieving legitimacy and localised social learning (van de Kerkhof and Wieczorek, 2005; Markusson et al., 2011). Increasingly, there is a conceptualisation of local initiatives as being connected and co-dependent across localities in significant national and global networks (Bulkeley et al., 2015). Learning approaches to transitions pathways emphasise the role of (protected) experimentation contexts as fruitful for trialling and adjustment of formulas that may be replicated and scaled-up elsewhere. Their focus on uncertainties and contingencies in local pathways allows capturing the possibility of failure and success.

A main strength of these approaches is their action and problem-solving orientation, dealing with the full complexity of capabilities, positions, perceptions and power of actors in specific

Table 2
Key differences between the three approaches.

		Quantitative systems modelling	Socio-technical analysis	Initiative-based learning
Scale and temporality	Analytical scale	Various – but often global, **national and sector-scale analysis**	Mainly national systems, with **comparisons across countries**	Local scale, sometimes with comparisons across contexts
	Multi-scale linkages	Linkages between sectoral models at different scales	**Landscape-regime-niche links processes at different scales and temporalities**	Not explicit
	Time horizon	Long-term perspective (decades)	Long-term perspective (decades)	Short timeframe (5–15 years)
	Time orientation	**Future** scenario projections	**Historical** and ongoing transitions	**Transitions in the making**
	Temporal articulation	Current decisions informed by future projections	Cases approached via pattern recognition over time	**Decision-making and implementation temporality**
Treatment of complexity	Methodological strategy	Modelling of systems through internally-consistent parameters and decision-rules	In-depth cases generate rich understanding of socio-technical dynamics and uncertainties	Detailed account of the contingencies, complexity and messiness of actor strategies and interactions
	Explanatory focus	Alternative scenarios representing differing starting conditions and parameter values	Emphasis on exploration and interpretation	Emphasis on subjectivities and deliberative processes, attention to behavioural aspects
	Predictive inclination	Projections based on a finite set of parameters and objectives	Limited capacity to make predictions	Limited focus on predictions
	Treatment of uncertainty	**Simulations allow exploring future uncertainties under specific constraints**	Future uncertainties explored via matching with familiar patterns (cf taxonomies of transitions)	**Realism about the actualisation of intended strategies**, and elicitation of uncertainties
Innovation and inertia	Sources of innovation	Innovation as option with evolving performance (cf learning as relative price changes). Novelty emerges when performance thresholds are crossed	Explains emergence of novelty in niches competing with established regime along developmental trajectories	Explains the local emergence of novelty as result of experimentation. Success is mediated by contextualized struggles
	System inertia	Formalisation of system inertia restricted to model structure and initial conditions, and modelled via long lifetime of technologies	**Detailed representation of system inertia (system configuration, regime rules, actor strategies), and relationship to niche (breakthrough)**	Inertia as justification for and obstacle to innovative experiments
Normative goals	Normative positioning & conceptualisation	**Unspecified normative position, concerned with technical and economic feasibility of achieving given policy targets**	**Problematises current normative positions**, concerned with the emergence of new norms and institutions in transitions	**Activist-orientation**, normative position intrinsic to the specific initiative are privileged
	Approach to sustainability	Sustainability targets and ambitions are exogenously defined with reference to geophysical tolerances	Sustainability ambitions are seen as outcome of socio-political negotiation processes that may result in institutional change but are not taken for granted	Sustainability effects are attributed to the action of individual agents and groups - derived from their motives, respective strengths and weaknesses, etc.
Governing transitions	Conceptualisation of policy	**Policy objectives as exogenous constraints in models**	**Policy and governance as one of many interacting dimensions of a complex transition process**	Policy as enabler of local initiatives
	Representation of decisionmakers	Policymakers 'outside' the system, pulling 'levers' to steer developments (cf 'illusion of control')	Policymakers as part of the system & dependent on other actors to 'modulate' ongoing dynamics, rather than steering	**Detailed and plural focus on actors & networks influencing decisions & 'situated' development of initiative**
	View on intervention	Clear model-based advice about intervention options. Policy intervention mainly through economic and regulatory instruments, with little attention to institutional or governance dynamics	Advice focuses on strategic 'lessons' and patterns (instead of specific tools and instruments). Choice and effectiveness of interventions depends on contexts	Emphasis on internal governance of processes and resources: learning and experimentation; network management; advocacy and dissemination

local settings. There is a concreteness about the struggles represented by these initiatives (and their reflexive analysis) that contrasts with the quite abstract frameworks inherent to modelling and transitions studies. The main weakness of initiative-based learning is its short-term orientation, and lesser concern with wider structural and institutional influences on innovation. It may also be difficult to generalise from a highly context-dependent cases (Ison et al., 2007).

We summarise this discussion of the three approaches in Table 1, which provides a synthetic and necessarily stylised overview of the main strengths and weaknesses of each approach, focussing on methodological, analytical, and policy considerations.

3.4. Treatment of key analytical challenges by the three approaches

In Section 2 above, we identified five challenges for analysing and governing sustainability transitions. Here we present in summary form (Table 2) key differences in the way the three approaches treat each of these challenges. What is striking is that each of the three approaches attends to related problems with its specific outlook, assumptions, conceptual frame, analytical lens and methods, hence shedding light on and emphasising different aspects, dimensions, temporalities and governance dilemmas of sustainability transitions. This suggests that the approaches might complement each other, if effective ways of integrating across and between them could be developed. In revealing the practical effect of the differences between the approaches, this assessment also points to the problems faced by integration of approaches carrying highly different assumptions, and suggests that selective linking may be a more desirable integration strategy than fusion. In Table 2, we highlight (in bold) outstanding elements that an integrated approach could encompass and actively mobilise to enrich a more comprehensive assessment of transitions pathways.

4. Towards integration of the three approaches

In this section, we lay out the features of an analysis of sustainability transitions pathways resting on the combination of different analytical approaches. While each approach may be strengthened by explicitly attending to the five transition challenges, the analysis presented in Table 2 has revealed that no single approach fares well across all five of them. Rather, it is only by connecting insights from different approaches and cross-examining transitions through their combined perspectives that we may reach a more robust understanding of sustainability transitions. We provide a set of guiding principles for the combination of different perspectives in the problem-context of sustainability transition and set out a strategy for integration based on two basic procedures – alignment and bridging – in continuous iterative cycle, always in support of analytical or governance objectives.

Having revealed and bearing in mind the main epistemic and methodological differences and complementarities that exist between approaches, we need to identify more specifically the joint elements around which an integrated 'meta-perspective' on sustainability transitions pathways can be articulated in terms of applied concepts, problem-frames and empirical domains. We term this step *alignment*.

Once such common understanding and coherence about the overall phenomenon has been established, there is then a need for a two-way interaction to occur, *in the context of a specific problem-solving process*. Integration is not an end in itself, but always occurs in the context of problem-solving, whether this is a specific analytical problem or in respect of a defined governance problem. The integration of differentiated perspectives can be fruitfully oriented towards improving the nature and quality of information for decision-making (for different actors) – that is, towards specific governance problems, explicitly mobilising the different *kinds* of information on offer to elicit the criteria around which situated transition strategies can be evaluated. We term this step *bridging*, and this will involve building active operational links between approaches around data and explanation in a common stream of analysis.

Finally, this *aligned interaction* between approaches will need to be done *iteratively*. Over the longer-run, we believe that a chain of interactions would be created, generating outputs attuned to the needs of stakeholders and decision-makers. These interactions may be continuous or periodic, the latter responding to specific windows of opportunity presented by cycles of attention, policy-making and practice.

4.1. Aligning problem frames

While no single approach is able to fully address the five challenges we have outlined, their combination enables an explicit positioning against the challenges associated with the governance of sustainability transitions. For example, combined attention to past, present and projected transitions, via the shared problem frame of transitions pathways, enables more nuanced and grounded evaluation of the options ahead and their strategic implications. We here formulate some general principles that an integrative approach should attend to with respect to each challenge – as ways to cut across related dilemmas –, and illustrate where relevant.

4.1.1. Scale and temporality

Transitions are understood as involving multiple scales and temporalities. Sustainability transitions involve co-constitutive dynamics between goal-setting and emergent transformative change, which calls for and understanding of the two-way relationships between different scales and sources of change. Multi-level governance perspectives usefully problematize different levels of decision-making in terms of opportunities for and actors influencing innovation processes (Nilsson et al., 2012). Sustainability transitions can only be steered in real time, over time, with knowledge of past developments. Steering transitions requires a particular kind of sense making: the ability to "zoom in and out" between levels of analysis and to "zip back and forth in time" (Garud and Gehman 2012). This can be done by linking the different perspectives and the multiplicities of scale and temporalities they offer (see Table 2).

For example, results from global integrated assessment modelling indicate that in order to reduce the environmental impacts of food production, sustainable intensification (higher crop yields with lower environmental impacts), reduction of food wastes and losses, as well as dietary changes are important options (Stehfest et al., 2013; van Vuuren and Kok, 2012; Westhoek et al., 2014). For both governments and consumers, only a limited set of these options is truly 'governable'. Changes in consumption patterns and reduction of food wastes are effective only when widely-practised, while agricultural production systems are typically shaped by markets and public policies. At the neighbourhood-scale, urban farming initiatives (Hardman and Larkham, 2014; Spaargaren et al., 2013) have emerged to tackle systemic options related to production, waste and consumption, but there is often a disconnect with the translation of this learning into assessments of transitions on the broader scale.

4.1.2. Treatment of complexity

Innovation and its related uncertainties are contextualised within long-term processes. Each approach offers a complementary type of realism in its evaluation of complexity: by exploring future constraints, identifying familiar patterns, and attention to the gap between intentions and actualisation. Greater steering potential comes with attention to process dimensions: trajectory, direction of change, momentum, inertia. Steering becomes about identifying, seizing, and generating positive (and lasting) conditions for change, partly through the control of specific variables (e.g. price-performance, R&D investment, etc.), but also through a balance of continuity and responsiveness to change. A processual understanding of change enables more adaptive forms of intervention, adjusted to innovation dynamics, support to experimentation, and the reflexive management of uncertainties.

For example, in the electricity domain, effective strategies for renewable energy deployment in Germany have relied on a combination of awareness of the determinants of innovation processes, artificial control over long-term conditions, and the ability to reflexively evaluate progress. In practice, this has taken the shape of early support with long-term horizon for investment (FIT), followed by a planned automatic degression, and further degressive interventions in the face of an overly successful programme.

4.1.3. Innovation and inertia

Transition efforts can be evaluated with respect to the challenges of overcoming inertia and path dependency. Specifically, this is often done in modelling approaches by comparing sustainability pathways against the no-action or business-as-usual scenarios, but remains limited to technological assumptions. Socio-technical analysis problematizes and explains inertia of established configurations in terms of broader sets of mechanisms, including structural factors in tangible elements, institutional factors (rule-sets), and agency (resistance of powerful actors). Making such a 'gap analysis' central to transition analysis across all approaches attracts attention to the considerable efforts required to achieve ambitious sustainability objectives as they are currently formulated, including the problem of overcoming the inertia of incumbent systems.

For example, in the heat domain, there is tremendous techno-economic inertia in the existing housing stock, which is relatively energy inefficient and poorly insulated, and has a notoriously slow replacement rate (Thomsen and van der Flier, 2009). On the other hand, efficiency improvement of individual housing units, e.g. through whole house retrofits, is a massive challenge in terms of technology, costs, capabilities, and regulatory hurdles (e.g. building protection and conservation). Current policy emphasis on raising efficiency standards for new buildings will not deliver transformations of the required scope and urgency. Attention to such sources of inertia points to the scale of the challenge of decarbonisation in the building sector, but also sheds light on dilemmas. Standards for new buildings should be combined with interventions that explicitly tackle inefficiencies of the existing stock on a large scale, as well as develop the industrial and services capacity for nation-wide retrofitting programmes.

4.1.4. Normative prescription

The multi-faceted understanding of transitions pathways attracts attention to the fact that sustainability transitions require a re-definition of performance criteria around emergent socio-technical systems and emergent aspirational values (in addition to economic logics). This is a fundamental change rooted in norms and values that is most challenging to purposefully steer and stabilise in the long run – an aspect that socio-technical analysis explicitly seeks to unpack, but are typically difficult to capture in quantitative modelling strategies. Attention to key metrics of performance, how these are adjusted and change and how they resonate in transitions discourses should be considered in more integrated approaches.

For example, in the mobility domain and for road-based transport in particular, norms and cultural values ascribed to cars have a profound influence on how performance and utility is evaluated, and such variables are key to understand mobility transitions (Nykvist and Nilsson, 2015; Nykvist and Whitmarsh, 2008). New values and synergies emerging from, e.g. the influence of information technology developments, enabling developments such as a product to service shift through advance car sharing and leasing options and future potential integration with the power system with benefits of vehicles to grid integration, will be instrumental in re-defining performance of car-based mobility. Their novelty generates further sources of uncertainty and path disruption.

4.1.5. Governance assumptions

There is general agreement that governance, in the sense of *supporting, shaping, and modulating* sustainability transitions, is more a question of adaptive coordination and problem-solving ('muddling through' chains of decisions) than of direct control (Wise et al., 2014). This leads to a focus on actors, key processes and the (re) formulation of transition objectives, about which each approach has something to offer. However, these actors, actions and objectives are clearly all future-facing, and in order to be useful, transitions analysis needs to be able to have a significant prospective disposition, as well as an ability to adapt to changing circumstances, problem framings, and societal objectives (Leach et al., 2010; Weaver and Rotmans, 2006).

For example, from a multi-functional land use perspective, different governance regimes determine biodiversity outcomes. Biodiversity protection is one of these regimes, which competes with other governance regimes such as agriculture, forestry, water management, urban planning (Kok and Alkemade, 2014). Depending on openings in other regimes, opportunities arise for improving biodiversity outcomes. Unless clear windows of opportunity occur, as in the case with combining nature development with new water management approaches (Rohdea et al., 2006), these remain incremental changes to the current regimes, with limited long-term benefits for biodiversity and climate.

4.2. Bridging between approaches

There is an emerging research stream that aims to integrate different approaches, recognising the benefits to be gained in more robustly shaping sustainability transitions (Holtz, 2011; Foxon, 2013; Papachristos, 2014; Trutnevyte et al., 2014). Integration strategies attending to the co-evolution of social and technological innovation processes in sustainability transitions pathways range from one-off enrichment to more recursive combinations based on iterative interactions and collaborative linkages.

At one end of this spectrum are one-off methodological enrichments. Such strategies have led to improvements in modelling, through for instance the integration of insights from the governance and institutional literature (Söderholm et al., 2011; Nilsson et al., 2011), the timely mobilisation of data from historic transitions to calibrate models, taking into account uncertainty (van Ruijven et al., 2010), or the identification of key parameter values through scenario storylines (McDowall, 2014:3). Transitions approaches have also benefited from data generated by models in terms of consistency and feasibility checks (McDowall, 2014). It has been suggested that socio-technical approaches should strive towards greater compatibility with future-oriented epistemologies reminiscent of modelling strategies: 'transition scenarios' (Elzen et al., 2004; Hillman and Sandén, 2008; van Bree et al., 2010; Marletto, 2014) have been developed as a form of future-oriented exercise in that direction. Transition studies have also benefited from the incorporation of learning and participatory perspectives (van de Kerkhof and Wieczorek, 2005; Seyfang et al., 2014).

An emerging strand of research has emerged with the development of modelling strategies informed by socio-technical analysis (Hughes et al., 2013; Foxon et al., 2013; Köhler et al., 2009; Köhler, 2014). These more ambitious integrative efforts go beyond one-off enrichment and seek to 'translate' insights from socio-technical theories into specific modelling features (e.g. actor configurations and dynamics, co-evolution of social and technical, the influence of shifts in motivations, etc.) (Hughes, 2013). 'Layering' strategies and the development of active linkages between different levels of analysis allow models to integrate insights from a variety of tools and methods. Hughes (2013) proposes the development of a reflexive scenario process (with an iteration of linkages) to more effectively link near-term decisions to long-term objectives through transitions pathways. Other integrative efforts have focussed on linking qualitative storylines (or narrative scenarios) with more quantitative modelling exercises (Nakicenovic et al., 2000; O'Neill et al., 2015; van Vuuren and Kok, 2012; Fortes et al., 2015; McDowall, 2014; Fontela, 2000; Alcamo, 2008; Trutnevyte et al., 2014).

A 'compare, contrast and revise' strategy may lead to mutual enrichment of insights from each approach. A research strategy based on 'two-way recursive collaboration' (Trutnevyte et al., 2014) and multiple iterations may lead to greater robustness of future scenarios and transitions pathways. In terms of concrete analytical integration, McDowall (2014:3) suggests a strategy based on 'dialogue', whereby methodologically distinct approaches are used in parallel to mutually inform each other: "modelling exercises are used to examine and inform elements of the scenarios, while the scenarios are used to challenge and confront the results suggested by the model". Mobilising such active links in an integrated chain of analysis can improve real-world assessments of concrete transition strategies and practice.

The challenge is to develop operational linkages around different types of explanation. We suggest bridging both via the research process (facilitating collaborative interaction around analytical tools, empirical data, etc.) and the outcomes and fresh outlook that a joint approach can deliver (integrated assessment) to a variety of decision-making publics. The extent to which such an integrated approach is feasible also hinges upon the balance that can be struck between achieving a sufficient degree of common understanding, and respecting approach-specific constraints, assumptions and analytical dimensions.

Clearly defining the focus and boundaries of integrated analysis is fundamental. Proceeding from the fertile ground identified thus far (i.e. overlaps and complementarity against five main challenges, shared problem frame of sustainability transitions pathways), and taking stock from the evaluative richness that each approach has to offer, we suggest bridging via those concepts that capture essential phenomenological attributes of transitions pathways: *goal-setting* (orientation towards collective normative objectives), *momentum* (relative to inertia and incremental change in existing regimes), *depth* (degree of radicality of systems change) and *scope* (number of dimensions that change in socio-technical systems). These shared concepts can be seen as vehicles for bridging as they are interpretively flexible enough to allow for the mobilisation of the different kinds of information offered by each approach, yet specific enough to enable systematic analysis and cumulative knowledge development. On a more practical level, they enable to capture the rich diversity of sustainability transitions in the making, and to selectively evaluate opportunities or define priorities to *support*, *shape* and *modulate* the dynamics of transitions.

4.3. An integrated approach to evaluating sustainability transitions pathways

By integration we mean a research strategy of aligning, bridging between largely separate analytical approaches, and iterations of such interactions. Integration is a procedure based on shared concepts, information and targets. The first aligning step is to adopt a broadly shared problem formulation and framing that can act as channels for dialogue between the three approaches for evaluating sustainability transitions pathways. Fig. 1 illustrates the basic set-up, with a shared framing around transitions pathways to achieve normative goals, the construction of pathways and agreement on basic analytical concepts that can be handled by each of the different approaches (different time horizons, analytical constructs and representations), and a broad view of how different representations of transitions can be made to converse.

Evaluating transition efforts requires agreement about the specific normative objectives to be met. For a given empirical domain, and measured against a specific societal target, the aim of the assessment will be to characterise goal-setting, momentum, depth and scope of systems changes leading to a transition, e.g. what is meant by the momentum of a sustainability transition? How can it be measured and evaluated?

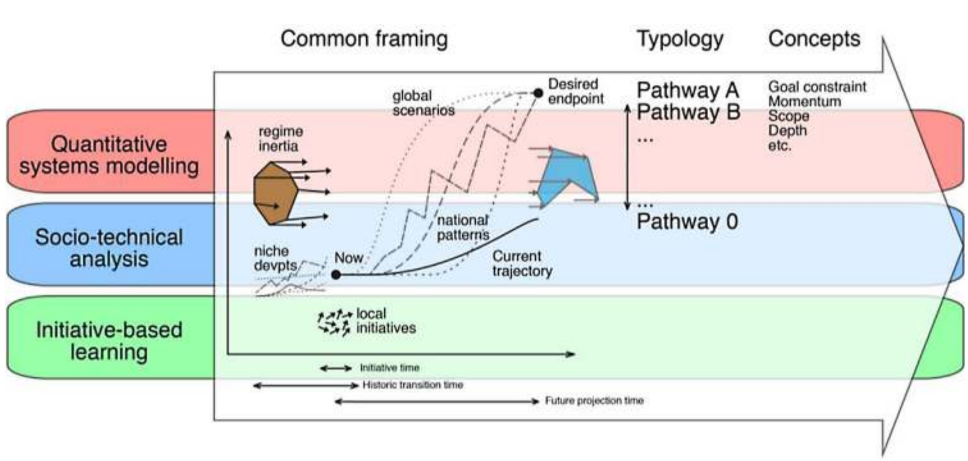

Fig. 1. Towards shared framings and concepts across the three analytical approaches.

A second bridging step is to orient analysis towards specific governance problems, explicitly mobilising different *kinds* of information in the assessment of transition strategies, to specify the empirical domains of the analysis to be carried out (setting clear boundaries, scales and temporalities), to establish the common metrics and data that will be transferred (and enable the consolidation of operational linkages) between analytical approaches, and to specify the type of assessment sought. A generalised schematic of transfers between approaches in an interlinked chain of analysis is given in Fig. 2, which represents how neighbouring perspective can be actively mobilised.

For a given empirical domain (electricity, heat, mobility, etc.) and context, approaches can be oriented towards a joint evaluation of current trajectories towards specified objectives (e.g. emissions reductions targets). Quantitative systems modelling can help translate objectives in terms of techno-economic requirements, i.e. preliminary future scenarios balancing a set of options over time. Socio-technical analysis, with its detailed appraisal of real-world niche momentum, current regime dynamics and interactions, can contribute to initial model parameterisation, but also critically-question the feasibility of transitions scenarios – for instance by suggesting that regulatory policies can only be introduced when well-developed alternatives are available, in a phased manner. Modelled pathways can also be strengthened through the development of rich narrative storylines taking into account policy paths that are more realistic as to the availability socio-technical alternatives. Initiative-based learning from local sustainability projects can benefit from being framed in the context of niche-regime relationships, and according to their contribution to policy targets. Real-world experiments can be seen as ‘pre-figurations’ of alternative socio-technical-ecological systems, drawing attention to the kinds of struggles encountered on the ground, and so deliver crucial lessons for the feasibility of different options for future-oriented scenarios.

Compounded, such steps result in a consolidated form of transition assessment, bridging between approaches via shared flows of information and bringing multiple dimensions into perspective. At each step, dialogue and information exchange proceeds via the shared concepts of *goal-setting*, *momentum*, *depth* and *scope* of transitions pathways. Concrete outcomes include realistic prospective scenarios to meet policy objectives, detailed supportive narrative storylines, and enriched evaluative capacity in relation to current transition efforts.

By bridging between approaches to transitions pathways it is possible to achieve a more multi-dimensional evaluation of transitions as they unfold, informing governance decisions and practices. Past and current transitions can be assessed by analysing recurring patterns and measurable variations. Future projections can be used to explore different alternative trajectories and their potential implications. Sustainability transitions pathways can be further operationalised so as to enable collaborative research, maximising the transferability of concepts and empirical evidence across approaches, and maintaining openness to new scientific developments.

Specifically, an integrated evaluation of sustainability transitions should compose with the respective strengths of quantitative systems modelling, socio-technical analysis and initiative-based learning:

- an ability for developing future projections/scenarios: explicit goals based on policy intentions and targets, and an assessment of how we can get from the present to these objectives,

  informed by,

- (focussed) in-depth analysis: an understanding of the recent past and present (the degree of inertia of regime trends, possible alternatives), an understanding of where are we currently heading (niche momentum, regime transformation, etc.),

  including

- (generalizable) lessons about the scaling of experimentation: an understanding of what is happening on the ground, emerging trends-in-the-making, the determinants of successful implementation and scaling up, etc.

The role of carbon capture and storage (CCS) in energy futures provides a useful illustration. Given current decarbonisation objectives in the energy domain, a number of quantitative systems modelling projections suggest an important role for CCS (Magné et al., 2010), particularly to comply with stricter decarbonisation targets (van Vuuren et al., 2010). A socio-technical analysis may point to current legitimacy and feasibility issues in practice, as “the slow pace and high cost of demonstration and deployment and an emerging opposition movement suggests that any projections for

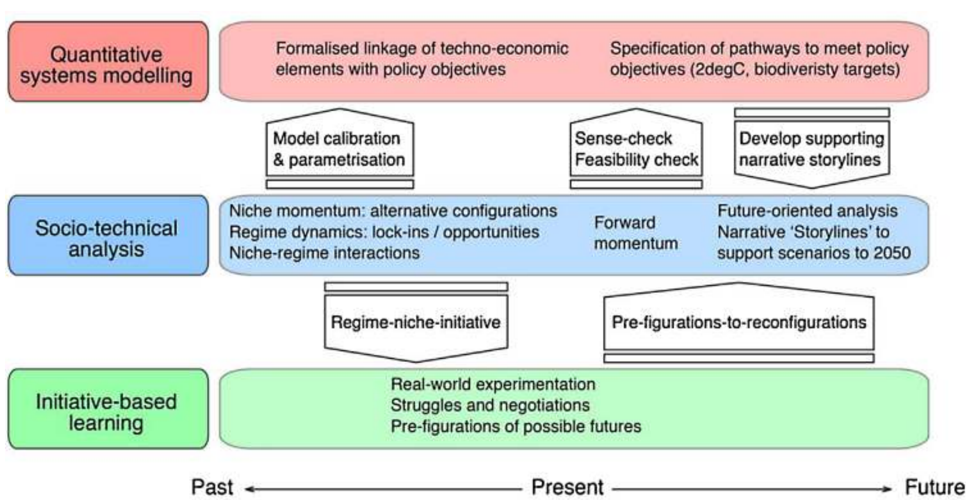

Fig. 2. Schematic representation of steps in an interlinked chain of analysis of future-oriented transitions pathways.

large-scale development remain highly uncertain" (Stephens and Jiusto, 2010:2023), but also emphasise its compatibility with incumbent strategies. Such insight can serve to critically modulate model parameters and ultimately how CCS fares in future scenarios, e.g. via an outline of key related uncertainties (Markusson et al., 2012). Focusing on local projects can point to the framing of resistance to CCS implementation, and the local circumstances leading to success or failure, such as concerns about safety and property devaluation, trust and fairness, and the lack of consultation (Terwel et al., 2012). Attention to differences across localities (e.g. very strong protests in Germany, and comparatively more acceptance in the UK) can sharpen understandings of CCS project implementation, and the conditions under which CCS may (not) be assumed to play a role in future energy pathways (Nykvist, 2013).

In terms of transitions pathways, CCS relates to ambitious low-carbon *goal-setting*, may be relatively low-*depth* (it is aligned with current power generation systems), but currently enjoys low *momentum*, partly due to the *scope* of change that its successful implementation would require (societal acceptance, technical feasibility, financial support, etc.).

In terms of governance, it is possible to mobilise such knowledge to inform strategies and offer an insightful and multi-dimensional analysis of the core issues around CCS pathways. For instance, CCS appears to be highly unlikely in the current German context given low societal acceptance and regional power to bar projects, but this may have to change to jointly deliver on commitments to decarbonisation and coal use (Praetorius and von Stechow, 2009). For high-CCS pathways to become more credible and feasible in the future, some critical uncertainties and requirements must be attended to, including local acceptance, coherent narratives and support build-up.

5. Conclusion

In this paper we have addressed the problem of integrating three analytical approaches – quantitative systems modelling, socio-technical transitions studies and initiative-based learning – which are widely applied in the analysis of sustainability transitions for problem-solving in governance. Each approach is a lens that generates only a partial understanding of sustainability transitions and their related challenges. Combining different approaches promises to take advantage of the strengths of multiple methodologies and approaches and thereby provide a more robust evaluation of sustainability transitions as they unfold in as complex systems transformations with emergent properties. Furthermore, the challenging nature of sustainability transitions needs to be recognised and accepted by decision-makers. Getting relevant actors to engage with the idea of transitions and transformations requires more integrated tools for understanding and guiding these complex societal processes, but also the emergence of governance styles that are more suited to deal with the challenges at hand (Geels et al., 2015). The approach that we have put forward in this paper suggests that a more nuanced approach is more complex, requires greater unpacking of uncertainties, debate, less precision and more learning-by-doing. It hence departs from the 'command-and control' or public management styles often favoured by policymakers because of the 'illusion of control' that they carry. The aim of integration is to develop more complete and flexible analysis of sustainability transitions, useful to decision-makers and practitioners. The benefits of integration for decision-makers include:

- plural perspective in the evaluation of transition dynamics and governance implications,
- new methods for monitoring, projecting and evaluating transitions pathways,
- new means of informing public governance and private strategies.

We have set out five major analytical challenges and considered how these challenges are addressed by each of the three approaches. This provided a synthesis of the characteristics of a flexible integrated approach. Despite the very wide epistemic and methodological differences, we believe there are good grounds for a common framing of analytical and governance problems that would be addressed by combining different lenses and styles of explanation. We then moved on to a proposal for integration in practice, arguing that this takes the form of bridging between approaches via an iterative dialogue around shared framing of transitions pathways with key concepts. We further illustrated how such an approach can work in practice, by sketching out some essential steps and mobilising a brief example. A practical next step would involve the specification of how such integrated evaluation can be mobilised in specific cases, from a multiplicity of viewpoints and decision-making capacities.

Given the current deadlock in terms of accelerating sustainability and low-carbon transitions, and given the difficulties of each approach in delivering effective support to decision-making in this direction, it is crucial to develop more multi-dimensional assessments. Research derived from the general approach outlined here promises to deliver richer analytical understandings of transitions pathways as it uncovers new ways of seeing, and the ability to observe transitions dynamics as they unfold, with attention to their emergent properties. It provides the basis for the development of a substantial body of empirical evidence about transitions pathways in a variety of domains and context.

A critical way forward is to unlock the potential for this kind of analysis to have an impact on policy and real-world decision-making. We have made initial steps in demonstrating why and how this kind of work can become useful to practitioners, as it can deliver richer forms of assessments, new and plural views on governance and accommodation of multiple challenges and dilemmas. In doing so, this article has contributed to a broader reflection on deliberatively *supporting*, *shaping* and *modulating* sustainability transitions pathways towards desirable outcomes in full awareness of the scale, scope and urgency of the effort required.

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References

Alcamo, J. (Ed.), 2008. Environmental Futures: The Practice of Environmental Scenario Analysis. Elsevier, Amsterdam.
Andersson, C., Törnberg, A., Törnberg, P., 2014. Societal systems – complex or worse? Futures 63, 145–157.
Argyris, C., Putnam, R., MacLain Smith, D. (Eds.), 1985. Action Science. Jossey-Bass Inc, Publishers, San Francisco, Jossey-Bass Limited, London.
Berkhout, F., Smith, A., Stirling, A., 2004. Socio-technological regimes and transition contexts. In: Elzen, B., Geels, F.W., Green, K. (Eds.), System Innovation and the Transition to Sustainability: Theory, Evidence and Policy. Edward Elgar, Cheltenham, pp. 48–75.
Bulkeley, H., Castán Broto, V., Edwards, G.A.S., 2015. An Urban Politics of Climate Change: Experimentation and the Governing of Socio-technical Transitions. Routledge, London.

Carvalho, L., Mingardo, G., van Haaren, J., 2012. Green urban transport policies and cleantech innovations: evidence from Curitiba, Göteborg and Hamburg. Eur. Plann. Stud. 20, 375–396.
Coenen, L., Truffer, B., 2012. Places and spaces of sustainability transitions: geographical contributions to an emerging research and policy field. Eur. Plann. Stud. 20 (3), 367–374.
Deetman, S., Hof, A.F., Girod, B., van Vuuren, D.P., 2015. Regional differences in mitigation strategies: an example for passenger transport. Reg. Environ. Change 15 (6), 987–995.
Dryzek, J., Downes, D., Hunold, C., Schlosberg, D., Hernes, H.-K., 2003. Green States and Social Movements: Environmentalism in the U.S., U.K., Germany and Norway. Oxford University Press, Oxford.
Elzen, B., Geels, F.W., Hofman, P.S., Green, K., 2004. Sociotechnical scenarios as a tool for transition policy: an example from the traffic and transport domain. In: Elzen, B., Geels, W.W., Green, K. (Eds.), System Innovation and the Transition to Sustainability: Theory, Evidence and Policy. Edward Elgar Publishers, Camberley, UK.
European Commission, 2011a. A Roadmap for Moving to a Competitive Low Carbon Economy in 2050. European Commission, Brussels.
European Commission, 2011b. Our Life Insurance, Our Natural Capital: An EU Biodiversity Strategy for 2020. European Union, Brussels.
European Commission, 2014. A policy framework for climate and energy in the period from 2020 to 2030. European Commission, Brussels.
Füssel, H.M., 2010. How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: a comprehensive indicator-based assessment. Global Environ. Change 20 (4), 597–611.
Fontela, E., 2000. Bridging the gap between scenarios and models. Foresight 2 (1), 10–14.
Fortes, P., Alvarenga, A., Seixas, J., Rodrigues, S., 2015. Long-term energy scenarios: bridging the gap between socio-economic storylines and energy modelling. Technol. Forecasting Social Change 91, 161–178.
Foxon, T.J., Hammond, G.P., Pearons, P.J.G., 2010. Developing transition pathways for a low carbon electricity system in the UK. Technol. Forecasting Social Change 77, 1203–1213.
Foxon, T.J., Pearson, P.J.G., Arapostathis, S., Carlsson-Hyslop, A., Thornton, J., 2013. Branching points for transition pathways: assessing responses of actors to challenges on pathways to a low carbon future. Energy Policy 52, 146–158.
Foxon, T.J., 2013. Transition pathways for a UK low carbon electricity future. Energy Policy 52, 10–24.
Garud, R., Gehman, J., 2012. Metatheoretical perspective son sustainability journeys: evolutionary, relational and durational. Res. Policy 14, 980–995.
Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Res. Policy 399–417.
Geels, F.W., McMeekin, A., Mylan, J., Southerton, D., 2015. A critical appraisal of sustainable consumption and production research: the reformist, revolutionary and reconfiguration positions. Global Environ. Change 34, 1–12.
Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Res. Policy 33 (6/7), 897–920.
Geels, F.W., 2014. Regime resistance against low-carbon energy transitions: introducing politics and power in the multi-level perspective. Theor. Cult. Soc. 31 (5), 21–40.
George, A.L., Bennett, A., 2005. Case Studies and Theory Development in the Social Sciences. Cambridge, MA and London, England, MIT Press.
Goodess, C.M., Hanson, C., Hulme, M., Osborn, T.J., 2003. Representing climate and extreme weather events in integrated assessment models: a review of existing methods and options for development. Integr. Assess. 4, 145–171.
Hajer, M., Nilsson, M., Raworth, K., Bakker, P., Berkhout, F., de Boer, Y., Rockström, J., Ludwig, K., Kok, M., 2015. Beyond cockpit-ism: four insights to enhance the transformative potential of the sustainable development goals. Sustainability 7 (2), 1651–1660.
Hansen, T., Coenen, L., 2015. The geography of sustainability transitions: review, synthesis and reflections on an emergent research field. Environ. Innovation Societal Transitions doi:http://dx.doi.org/10.1016/j.eist.2014.11.001 (in press).
Hara, K., Uwasu, M., Kobayashi, H., Kurimoto, S., Yamanaka, S., Shimoda, Y., Umeda, Y., 2012. Enhancing meso level research in sustainability science – challenges and research needs. Sustainability 4, 1833–1847.
Hardman, M., Larkham, P.J., 2014. The rise of the 'food charter': a mechanism to increase urban agriculture. Land Use Policy 39, 400–402.
Hillman, K.M., Sandén, B.A., 2008. Exploring technology paths: the development of alternative transport fuels in Sweden 2007–2020. Technol. Forecasting Social Change 75 (8), 1279–1302.
Hodson, M., Marvin, S., 2012. Mediating low-carbon urban transitions? Forms of organization, knowledge and action. Eur. Plann. Stud. 20, 421–439.
Holtz, G., 2011. Modelling transitions: an appraisal of experiences and suggestions for research. Environ. Innovation Societal Transitions 1 (2), 167–186.
Hughes, N., Strachan, N., Gross, R., 2013. The structure of uncertainty in future low carbon pathways. Energy Policy 52, 45–54.
Hughes, N., 2013. Towards improving the relevance of scenarios for public policy questions: a proposed methodological framework for policy relevant low carbon scenarios. Technol. Forecasting Social Change 80, 687–698.
Huntjens, P., Eshuis, J., Termeer, C., Van Buuren, A., 2015. Forms and foundations of action research. In: Buuren, A., van Eshuis, J., van Vliet, M. (Eds.), Action Research for Climate Change Adaptation: Developing and Applying Knowledge for Governance. Routledge, Abingdon, pp. 19–34.
Ison, R., Röling, N., Watson, D., 2007. Challenges to science and society in the sustainable management and use of water: investigating the role of social learning. Environ. Sci. Policy 20, 411–499.
Jørgensen, U., 2012. Mapping and navigating transitions – the multi-level perspective compared with arenas of development. Res. Policy 41 (6), 996–1010.
Köhler, J., Whitmarsh, L., Nykvist, B., Schilperoord, M., Bergman, N., Haxeltine, A., 2009. A transitions model for sustainable mobility. Ecol. Econ. 68, 2985–2995.
Köhler, J., 2014. Globalization and sustainable development: case study on international transport and sustainable development. J. Environ. Dev. 23 (1), 65–99.
Kareiva, P., Agard, J.B.R., Alder, J., Bennett, E., Butler, C., Carpenter, S., Cheung, W.W.L., Cumming, G.S., Defries, R., De Vries, B., Dickinson, R.E., Dobson, J., Foley, J.A., Geoghegan, J., Holland, B., Kabat, P., Keymer, J., Kleidon, A., Lodge, D., Manson, S., Mcglade, J., Mooney, H.A., Parma, A.M., Pascual, M.A., Pereira, H.M., Rosegrant, M., Ringler, C., Sala, O.E., Turner Ii, B.L., Van Vuuren, D., Wall, D.H., Wilkinson, P., Wolters, V., 2005. State of the art in simulating future changes in ecosystem services. In: Carpenter, S., Pingali, P.L., Bennett, E.M., Zurek, M.B. (Eds.), Ecosystems and Human Well-being: Scenarios: Findings of the Scenarios Working Group, Millennium Ecosystem Assessment. Island Press, Washington, pp. 71–115.
Kelly, D.L., Kolstad, C.D., 1999. Integrated assessment models for climate change control. In: Folmer, H., Tietenberg, T. (Eds.), The International Yearbook of Environmental and Resource Economics 1999–2000. Edward Elgar, Cheltenham.
Kemp, R., Martens, P., 2007. Sustainable development: how to manage something that is subjective and never can be achieved? Sustainability: Sci. Pract. Policy 3 (2), 5–14.
Kemp, R., van Lente, H., 2011. The dual challenge of sustainability transitions. Environ. Innovation Societal Transitions 1 (1), 121–124.
Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. Technol. Anal. Strat. Manage. 10, 175–195.
Kok, M.T.J., Alkemade, R., 2014. How sectors can contribute to sustainable use and conservation of biodiversity, Secretariat of the Convention on Biological Diversity, CBD Technical Series 79. PBL Netherlands Environmental Assessment Agency, The Hague.
Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V.J., Petermann, N., Bosetti, V., Marcucci, A., Otto, S., Paroussos, L., Rao, S., Arroyo Currás, T., Ashina, S., Bollen, J., Eom, J., Hamdi-Cherif, M., Longden, T., Kitous, A., Méjean, A., Sano, F., Schaeffer, M., Wada, K., Capros, P.P., van Vuuren, D., Edenhofer, O., 2015. Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy. Technol. Forecasting Social Change 90 (Part A), 24–44.
Kriegler, E., Weyant, J.P., Blanford, G.J., Krey, V., Clarke, L., Edmonds, J., Fawcett, A., Luderer, G., Riahi, K., Richels, R., Rose, S.K., Tavoni, M., van Vuuren, D.P., 2014. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. Climatic Change 123, 353–367.
Leach, M., Scoones, I., Stirling, A., 2010. Dynamic Sustainabilities. Technology, Environment, Social Justice. Earthscan, London.
Lewin, K., 1946. Action research and minority problems. J. Social Issues 2 (4), 34–46.
Liedtke, C., Baedeker, C., Hasselkuß, M., Rohn, H., Grinewitschus, V., 2014. User-integrated innovation in sustainable LivingLabs: an experimental infrastructure for researching and developing sustainable product service systems. J. Clean. Prod. (in press).
Loorbach, D., Rotmans, J., 2010. The practice of transition management: examples and lessons from four distinct cases. Futures 42 (3), 237–246.
Magné, B., Kypreos, S., Turton, H., 2010. Technology options for low stabilization pathways with MERGE. Energy J. 31.
Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: An emerging field of research and its prospects. Res. Policy 41 (6), 955–967.
Markusson, N., Ishii, A., Stephens, J.C., 2011. The social and political complexities of learning in CCS demonstration projects. Global Environ. Change 21, 293–302.
Markusson, N., Kern, F., Watson, J., Arapostathis, S., Chalmers, H., Ghaleigh, N., Heptonstall, P., Pearson, P., Rossati, D., Russell, S., 2012. A socio-technical framework for assessing the viability of carbon capture and storage technology. Technol. Forecasting Social Change 79 (5), 903–918.
Marletto, G., 2014. Car and the city: socio-technical transition pathways to 2030. Technol. Forecasting Social Change 87, 164–178.
McDowall, W., 2014. Exploring possible transition pathways for hydrogen energy: a hybrid approach using socio-technical scenarios and energy system modelling. Futures 63, 1–14.
Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463 (7282), 747–756.
Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., Emilio la Rovere, E., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooyen, S., Victor, N., Dadi, Z., 2000. IPCC Special Reports: Special Report on Emissions Scenarios. Cambridge University Press, Cambridge, UK.

Nilsson, M., Nilsson, L.J., Hildingsson, R., Stripple, J., Eikeland, P.O., 2011. The missing link: bringing institutions and politics into energy future studies. Futures 43 (10), 1117–1128.

Nilsson, M., Hillman, K., Magnusson, T., 2012. How do we govern sustainable innovation? Mapping patterns of governance for biofuels and hybrid-electric vehicle technologies. Environ. Innovation Societal Transitions 3, 50–66.

Nykvist, B., Nilsson, M., 2015. The EV paradox – a multilevel study of why Stockholm is not a leader in electric vehicles. Environ. Innovation Societal Transitions 14, 26–44.

Nykvist, B., Whitmarsh, L., 2008. A multi-level analysis of sustainable mobility transitions: niche development in the UK and Sweden. Technol. Forecasting Social Change 75, 1373–1387.

Nykvist, B., 2013. Ten times more difficult: quantifying the carbon capture and storage challenge. Energy Policy 55, 683–689.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2015. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environ. Change doi:http://dx.doi.org/10.1016/j.gloenvcha.2015.01.004 (in press).

OECD, 2012. Inventory of Estimated Budgetary Support and Tax Expenditures for Fossil Fuels 2013. OECD Publishing.

Orsato, R.J., Dijk, M., Kemp, R., Yarime, M., 2012. The electrification of automobility. the bumpy ride of electric vehicles towards regime transition. In: Geels, F.W., Kemp, R., Dudley, G., Lyons, G. (Eds.), Automobility in Transition? A Socio-Technical Analysis of Sustainable Transport. Routledge, New York.

Ozanne, J.L., Saatcioglu, B., 2008. Participatory action research. J. Consum. Res. 35, 423–439.

Papachristos, G., 2014. Towards multi-system sociotechnical transitions: why simulate. Technol. Anal. Strat. Manage. 26 (9), 1037–1055.

Pelling, M., High, C., Dearing, J., Smith, D., 2008. Shadow spaces for social learning: a relational understanding of adaptive capacity to climate change within organisations. Environ. Plann. A 40, 867–884.

Pettigrew Andrew, M., 1990. Longitudinal field research on change: theory and practice. Organ. Sci. 1 (3), 267–292.

Pielke, R.A., Wilby, R.S., Niyogi, D., Hossain, K., Dairuku, K., Adegoke, J., Kallos, G., Seastedt, T., Suding, K., 2012. Dealing with complexity and extreme events using a bottom-up, resource-based vulnerability perspective. In: Sharma, A.S. (Ed.), Extreme Events and Natural Hazards: The Complexity Perspective. Geophys. Monogr. Ser. AGU, Washington, D.C, pp. 345–359. doi:http://dx.doi.org/10.1029/2011GM001086.

Praetorius, B., von Stechow, C., 2009. Electricity gap versus climate change: electricity politics and the potential role of CCS in Germany. In: Meadowcroft, J., Langhelle, O. (Eds.), Caching the Carbon: the Politics and Policy of Carbon Capture and Storage. Edward Elgar, Cheltenham, pp. 125–157.

Raven, R.P., Heiskanen, E., Lovio, R., Hodson, M., Brohmann, B., 2008. The contribution of local experiments and negotiation processes to field-level learning in emerging (Niche) technologies. Meta-analysis of 27 new energy projects in Europe. Bull. Sci. Technol. Soc. 28 (6), 464–477.

Handbook of Action Research – Participative Inquiry and Practice. In: Reason, P., Bradbury, H. (Eds.), Sage Publications, London Thousand Oaks, New Delhi.

Rip, A., Schot, J., 2002. Identifying loci for influencing the dynamics of technological development. In: Sørensen, K.H., Williams, R. (Eds.), Shaping Technology, Guiding Policy: Concepts, Spaces and Tools. Edward Elgar, Cheltenham, pp. 156–176.

Roelfsema, M., den Elzen, M., Höhne, N., Hof, A.F., Braun, N., Fekete, H., Böttcher, H., Brandsma, R., Larkin, J., 2014. Are major economies on track to achieve their pledges for 2020? An assessment of domestic climate and energy policies. Energy Policy 67, 781–796.

Rohdea, S., Hostmann, M., Peter, A., Ewald, K.C., 2006. Room for rivers: an integrative search strategy for floodplain restoration. Landscape Urban Plann. 78 (1–2), 50–70.

Söderholm, P., Hildingsson, R., Johansson, B., Khan, J., Wilhelmsson, F., 2011. Governing the transition to low-carbon futures: a critical survey of energy scenarios for 2050. Futures 43 (10), 1105–1116.

Schot, J., Geels, F.W., 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. Technol. Anal. Strat. Manage. 20 (5), 537–554.

Seyfang, G., Hielscher, S., Hargreaves, T., Martiskainen, M., Smith, A., 2014. A grassroots sustainable energy niche? Reflections on community energy in the UK. Environ. Innovation Societal Transitions 13, 21–44.

Shove, E., Walker, G., 2010. Governing transitions in the sustainability of everyday life. Res. Policy 39 (4), 471–476.

Smith, A., Raven, R., 2012. What is protective space? Reconsidering niches in transitions to sustainability. Res. Policy 41, 1025–1036.

Smith, A., Stirling, A., Berkhout, F., 2005. The governance of sustainable sociotechnical transitions. Res. Policy 34, 1491–1510.

Späth, P., Rohracher, H., 2012. Local demonstrations for global transitions—Dynamics across governance levels fostering socio-technical regime change towards sustainability. Eur. Plan. Stud. 20 (3), 461–479.

Spaargaren, G., Oosterveer, P., Loeber, A., 2013. Food Practices in Transition: Changing Food Consumption, Retail and Production in the Age of Reflexive Modernity. Routledge, New York.

Stehfest, E., Berg, M.V.D., Woltjer, G., Msangi, S., Westhoek, H., 2013. Options to reduce the environmental effects of livestock production – comparison of two economic models. Agric. Syst. 114, 38–53.

Stephens, J.C., Jiusto, S., 2010. Assessing innovation in emerging energy technologies: socio-technical dynamics of carbon capture and storage (CCS) and enhanced geothermal systems (EGS) in the USA. Energy Policy 38, 2020–2031.

Strachan, N., Pye, S., Kannan, R., 2009. The iterative contribution and relevance of modelling to UK energy policy. Energy Policy 37, 850–860.

Tavoni, M., Kriegler, E., Riahi, K., van Vuuren, D.P., Aboumahboub, T., Bowen, A., Calvin, K., Campiglio, E., Kober, T., Jewell, J., Luderer, G., Marangoni, G., McCollum, D., van Sluisveld, M., Zimmer, A., van der Zwaan, B., 2015. Post-2020 climate agreements in the major economies assessed in the light of global models. Nat. Clim. Change 5, 119–126.

Terwel, B.W., ter Mors, E., Daamen, D.D.L., 2012. It's not only about safety: beliefs and attitudes of 811 local residents regarding a CCS project in Barendrecht. Int. J. Greenh. Gas Control 9, 41–51.

Thomsen, A., van der Flier, K., 2009. Replacement or renovation of dwellings: the relevance of a more sustainable approach. Build. Res. Inf. 37 (5–6), 649–659.

Tittensor, D.P., Walpole, M., Hill, S.L.L., Boyce, D.G., Brit-ten, G.L., Burgess, N.D., et al., 2014. A mid-term analysis of progress towards international biodiversity targets. Science 346, 241–244.

Trutnevyte, E., Barton, J., O'Grady, Á., Ogunkunle, D., Pudjianto, D., Robertson, E., 2014. Linking a storyline with multiple models: a cross-scale study of the UK power system transition. Technol. Forecasting Social Change 89, 26–42.

Turnheim, B., Geels, F.W., 2013. The destabilisation of existing regimes: confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967). Res. Policy 42, 1749–1767.

UN, 2012. The Future We Want. Outcome of the Conference. Rio + 20 United Nations Conference on Sustainable Development. Rio de Janeiro, Brazil.

UNEP, 2014. The Emissions Gap Report 2014. United Nations Environment Programme (UNEP), Nairobi.

UNFCC, 2011. Information provided by Parties relating to Appendix I of the Copenhagen Accord. Retrieved November 29, 2011, from http://unfccc.int/home/items/5264.php.

Voss, J.-P., Bornemann, B., 2011. The politics of reflexive governance: challenges for designing adaptive management and transition management. Ecol. Soc. 16 (2), 9.

Weaver P.M., Rotmans, J., 2006. Integrated Sustainability Assessment: what is it, why do it and how? MATISSE Working Paper 1.

Weber, M., Rohracher, H., 2012. Legitimizing research, technology and innovation policies for transformative change combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework. Res. Policy 41, 1037–1047.

Westhoek, H., Lesschen, J.P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M.A., Oenema, O., 2014. Food choices, health and environment: effects of cutting Europe's meat and dairy intake. Global Environ. Change 26, 196–205.

Weyant, J., Davidson, O., Dowlabathi, H., Edmonds, J., Grubb, M., Parson, E.A., Fankhauser, S., 1996. Integrated assessment of climate change: an overview and comparison of approaches and results. In: Bruce, J.P., Yi, H.-S., Haites, E.F. (Eds.), Climate Change 1995: Economic and Social Dimensions of Climate Change: Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change (pp. 367–396). Cambridge University Press, Cambridge, UK.

White House, 2014. U.S.–China Joint Announcement on Climate Change. White House, Beijing, China. http://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change.

Wise, R.M., Fazey, I., Stafford Smith, M., Park, S.E., Eakin, H.C., Archer van Garderen, E. R.M., Campbell, B., 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. Global Environ. Change 28, 325–336.

Wiseman, J., Edwards, T., Luckin, K., 2013. Post carbon pathways: a meta-analysis of 1 large-scale post carbon economy transition strategies. Environ. Innovation Societal Transitions 8, 76–93.

van Beeck, N.M.J.P., 1999. Classification of Energy Models. (FEW Research Memorandum; Vol. 777). Operations Research, Tilburg.

van Bree, B., Verbong, G.P.J., Kramer, G.J., 2010. A multi-level perspective on the introduction of hydrogen and battery-electric vehicles. Technol. Forecasting Social Change 77, 529–540.

van Ruijven, B., van der Sluijs, J.P., van Vuuren, D.P., Janssen, P., Heuberger, P.S.C., de Vries, B., 2010. Uncertainty from model calibration: applying a new method to transport energy demand modelling. Environ. Model. Assess. 15, 175–188.

van Vuuren, D.P., Kok, M., 2012. Roads from Rio + 20 Pathways to Achieve Global Sustainability Goals by 2050. PBL Netherlands Environmental Assessment Agency, Bilthoven.

van Vuuren, D.P., Isaac, M., den Elzen, M.G.J., Stehfest, E., van Vliet, J., 2010. Low stabilization scenarios and implications for major world regions from an integrated assessment perspective. Energy J. 31, 165–191.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Clim. Change 109 (1), 5–31.

van Vuuren, D.P., Kok, M., Lucas, P.L., Prins, A.G., Alkemade, R., van den Berg, M., Bouwman, L., et al., 2015. Pathways to achieve a set of ambitious global sustainability objectives by 2050: explorations using the IMAGE integrated assessment model. Technol. Forecasting Social Change .

van Vuuren, D.P., 2015. Integrated Assessment: Back to the Future. Utrecht University. http://www.uu.nl/sites/default/files/20150805-uu_oratie-van_vuuren.pdf.

van de Kerkhof, M., Wieczorek, A., 2005. Learning and stakeholder participation in transition processes towards sustainability: methodological considerations. Technol. Forecasting Social Change 72 (6), 733–747.