Opening up the feasibility of sustainability transitions pathways (STPs): Representations, potentials, and conditions

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Abstract

Addressing sustainability and low carbon objectives calls for radical departures from existing socio-technical trajectories. The substantial implementation gap between sustainability objectives and current unsustainable paths justifies a continued search for more ambitious system transformations and clarity as to how they can be realised. The aim of this article is to unpack the feasibility of such sustainability transitions pathways (STPs), by identifying the analytical dimensions that need to be considered to address challenges for transitions governance and specifying how they can inform comprehensive evaluation efforts. We aim to offer practical examples of how multiple forms of knowledge can be mobilised to support strategic decision-making, and so complement traditional modelling-based scenario tools. We base our evaluation of STPs on a broad understanding of feasibility and elaborate a frame to mobilise what we see as three 'facets' of STPs: *representations* for exploring sustainability transitions *potentials*, as well as the *conditions* under which STPs may have greater chances of becoming realised. The resulting evaluation frame allow us to generate specific prescriptions about STPs feasibility that can focus interdisciplinary research on the relevance of mobilising a plurality of forms of knowledge in evaluation efforts, a more detailed understanding of the potential of a given solution or pathway, and more detailed assessment of different key dimensions. We end by discussing how the notion of STPs feasibility can help open up decision-making processes and what tangible types of interventions are relevant.

Keywords

Sustainability transitions pathways; Feasibility; Transitions governance; Socio-technical analysis; Model-based pathways; Evaluation

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1 Introduction

Addressing sustainability and low-carbon objectives calls for radical departures from existing socio-technical trajectories. Sustainability transitions entail fundamental changes in the configuration of systems in domains such as electricity, mobility and agri-food. Despite rising interest and increasing literacy in the theory and practice of sustainability transitions (Markard et al., 2012), a number of biophysical trends are still alarming and expected to deteriorate without further action (see for instance EEA (2015) for a European account (notably pp.141-4) and Steffen et al. (2015) for a global review) and the window of opportunity to limit climate change to below 2ºC is closing fast (IPCC, 2018). There is a substantial implementation gap between environmental sustainability objectives and current paths, which point to significant inertia and lock-ins at the level of systems (Unruh, 2002) and justify continued search for more ambitious system transformations and clarity as to what they imply.

The notion of sustainability transitions pathways (STPs) (Rosenbloom, 2017; Turnheim et al., 2015) usefully captures the opportunities for system re-configurations, emphasising the processual linkages between starting- and envisioned end-points, suggesting that STPs may aptly be seen as open-ended journeys (Garud and Gehman, 2012). We examine prospective STPs as being mobilised by various epistemic communities to support the exploration of future-oriented trajectories specifically guided by long-term objective(s). Three main framings can be distinguished (Rosenbloom, 2017): biophysical pathways focus on the shifts in specific environmental quality indicators (e.g. emissions profiles, biodiversity, soil quality), techno-economic pathways focus on linking such environmental constraints to economic activity (e.g. decoupling environmental impact from growth in given sectors), and socio-technical pathways focus on the co-evolution of social, technological, and institutional dimensions of change in bringing about new system configurations. Each of these framings is related to a specific understanding of transitions as phenomenon, relevant analytical dimensions, supporting epistemic communities, and underlying ontological assumptions.

Modelling approaches and road-mapping exercises have gone a long way in identifying the scale of transition challenges, and offering a guiding frame for decision-making about the directionality of prospective transitions efforts. Quantitative systems modelling such as Integrated Assessment Models (IAMs) is particularly valuable in terms of linking specific sustainability objectives to change requirements on technical and economic dimensions, and linking long-term challenges to near-term action (Van Vuuren & Kok 2015; Turnheim et al.

2015; Geels et al. 2016). For instance, climate objectives are translated into decarbonisation pathways and biodiversity preservation objectives into roadmaps for reduction of land degradation and fragmentation. Models have been instrumental in establishing the need for and feasibility of commitments to a 2ºC climate target and beyond. Scenarios and roadmaps have become highly institutionalised and are often mobilised as support to policy formulation and strategic planning (Wiseman et al., 2013). Quantitative systems modelling allows for structured exploration of specific assumptions and constraints, drawing attention to possible alternative pathways.

At the same time, there is also increasing recognition that evaluations of pathways need to engage with overlooked dimensions of feasibility (IPCC, 2014; Loftus et al., 2015). So, there is a need to open up evaluation and decision-making beyond modelling logics, and there is some ambiguity as to how best to proceed. Quantitative system modelling approaches reduce decision-making to a 'bird's-eye' view on macro-economic interventions and hence risk overlooking other constraints at play. At the same time, the scope of sustainability transitions is challenging current governance arrangements, as they call for substantial departures from established socio-technical trajectories, and require overcoming major sources of lock-in (Turnheim and Geels, 2013; Unruh, 2002). Purposely supporting, accelerating and providing direction to this kind of deep transformation thus requires governance arrangements that go beyond traditional forms of assessments, policy interventions and measures. We note that opening up STPs to the evaluation of previously neglected dimensions of change is not new but remains crucial, and we suggest that new insights can be gained by more systematically attending to *feasibility*.

Following a number of recent calls for greater attention to the social, institutional, and policy dimensions of sustainability transitions challenges (Fuenfschilling and Truffer, 2014; Geels et al., 2016a; Kuzemko et al., 2016; Loftus et al., 2015; Nilsson et al., 2011; Patterson et al., 2015; Turnheim et al., 2015; Victor, 2015), we aim to contribute to this exploration of how prospective STPs may be realised in practice. That is, we are interested in a) evaluating pathway feasibility (analytical challenge), and b) supporting the elaboration of more feasible pathways (governance challenge). A key starting point for this analysis is that different approaches to sustainability transitions emphasise specific aspects of transitions but neglect others, and that associated types of knowledge may be effectively 'bridged' (Turnheim et al., 2015) to enable greater plurality in resulting evaluations. Building on this, Geels et al.

(2016:581) suggest that different approaches can be combined specifically for "addressing different governance dimensions and the knowledge needs of policymakers".

The aim of this article is to unpack the *feasibility* of STPs, by identifying overlooked analytical dimensions to address challenges for transitions governance. Building on an emerging body of work critically appraising the feasibility of STPs, we develop practical suggestions for complementing support to strategic decision-making largely dominated by modelling and scenario exercises.

In section 2, we summarise and specify the known core shortcomings of model-based knowledge for transitions governance, and suggest how to engage with other forms of knowledge. We elaborate a frame to mobilise what we see as three 'facets' of STPs. This leads us to consider *representations* for exploring sustainability transitions *potentials*, as well as the *conditions* under which transitions pathways may have greater chances of becoming realised. In section 3, we provide answers to the critique in section 2, expanding the knowledge horizon for transitions governance along these three main facets of pathways. In section 4, we discuss and illustrate how these notions can be operationalised around more systematic analysis and actionable knowledge.

2 Knowledge for prospective transitions governance – a call for realism

In this section, we critically examine the contribution of model-based knowledge to the governance of STPs around four main problems. This review identifies four core shortcomings that concern: 1) problems of understanding, 2) inference about the future, 3) real-world constraints, and 4) problems of governance. Following from this, we identify a need for opening up prospective STPs to different kinds of knowledge in order to better capture real-world constraints critical to their realisation.

2.1 Model-based transitions governance

Firstly, models have enabled a particular kind of integration of knowledge about complex systems. Global climate mitigation scenarios such as those used by the Intergovernmental Panel on Climate Change (IPCC, 2014), focussing on the interaction between biophysical and techno-economic pathways by modelling climate system dynamics and human activity via detailed emissions profiles, have supported global mitigation efforts across sectors and countries (Van Vuuren et al., 2011). Such scenarios are guided by the overarching objectives of limiting global warming, seeking least-cost technology portfolio, and strong assumptions have to be made about environmental objectives, abatement options, the dynamics of techno-economic systems, and the rationales and dynamics of decision-making. The simplification of complex systems by modelling strategies implies trade-offs with the accuracy and granularity of resulting evaluations (Turnheim et al., 2015):

> "In order to simplify the complexities of the real world and increase transparency, model applications often focus on rather idealized situations […], focusing on economic and technology factors in a stylized manner, while neglecting societal dynamics, politics, power and unpredictable human behavior" (Van Vuuren & Kok 2015:120)

Quantitative models thus tend to overlook some of the key constraints at play in transitions processes, including "technological readiness, economic costs, infrastructure and operational issues, and societal acceptability with respect to each of the relevant technology pathways" (Loftus et al. 2015:109), and how these constraints are linked to a variety of systemic sources of socio-technical, political, cultural inertia. They also run into difficulties accommodating the multiple and changing causal chains at play in historical transitions processes (Clemens, 2007; Haydu, 2010, 1998; Mahoney, 2000; Pettigrew, 1997). Thus, quantitative models generate little insight about strategies that can support the realisation of transitions. Important overlooked dimensions include socio-technical knowledge of innovation dynamics (Elzen et al., 2004; Geels, 2005; Geels and Schot, 2007; Grin et al., 2010), societal acceptability, political feasibility, system integration for different alternatives (Holtz, 2011; Loftus et al., 2015; Staub-Kaminski et al., 2014), governance assumptions and opportunities (Nilsson and Nykvist, 2016), the role of specific change agents (Hajer, 2011; Hajer et al., 2015; Schot et al., 2016), and unintended consequences of transitions (Eriksson and Weber, 2008; Genus and Stirling, 2018). A number of alternatives perspectives may be complementarily mobilised to explore these dimensions (Turnheim et al., 2015).

Secondly, models allow meaningful inferences about the future of techno-economic systems. A central rationale for scenario-based modelling is to enable forward-looking assessment of possible developments against current trends and objectives. For instance scenarios enable detailed discussions about the timing of peaking emissions and other branching points in time and space according to least-cost prioritisation (Tavoni et al., 2014), the decomposition of technological portfolios at regional and national scale (Deetman et al., 2014), or the financial implications of sets of options (Tavoni et al., 2014).

This paper focuses on pathway feasibility in the context of reaching explicit environmental sustainability goals. The techno-economic assessment undertaken with models is thus guided by normative goals and constitutes a form of backcasting, i.e. scenarios that attend to pathways through which a specific target can be reached (see Börjeson et al. (2006)). Such a backcasting approach is qualitatively different form forecasting and highly relevant in the context of sustainability transitions particularly when exploring paths of profound change of direction *away* from unsustainable tendencies, because they lead to the production of "target-fulfilling images of the future. Such images present a solution to a societal problem, together with a discussion of what changes would be needed in order to reach the images" (Börjeson et al. 2006:729).

Thirdly, models provide intelligible representations of pathways that serve to specify the urgency and ambition of overall transitions objectives, but lack detail about systemic and real-world constraints. Model-based scenarios point to the highly ambitious and challenging nature of transitions objectives at an aggregate level (Deetman et al., 2014) and provide effective representations of the fundamental direction of changes required. Environmental and climate indicators are stubbornly pointing in the wrong direction (EEA, 2015a; Patterson et al., 2015; Steffen et al., 2015). Increasingly critical forms of assessment are also pointing to the lack of appropriate responses (IPCC, 2018; Wiseman et al., 2013). Modelling efforts have had a crucial influence in putting transitions challenges and their urgency on the political agenda.

At the same time, model-based scenarios exploring *possible* STPs have been criticised for being unrealistic. Concerns are raised regarding historically unprecedented rates of technology deployment (Li and Strachan, 2016), often neglecting the role of social change and institutional inertia. It has for instance become relevant to engage with the temporality of transitions (Fouquet, 2016; Sovacool, 2016) and unpack the conditions under which accelerations may become possible (Grubler et al., 2016; Sovacool and Geels, 2016).

More fundamental critiques note that engineering-type knowledge can't simply be translated into applied solutions to societal problems (Castree et al., 2014) and sustainability challenges will not be met by purely technical solutions (Kramer and Haigh, 2009; Stirling, 2015). Indeed, no historical precedent of socio-technical transition can be found that has not involved fundamental re-configurations of not only technologies, but also markets, practices, norms and values concomitantly – and this is certainly true of the scarce historical precedents of normatively-motivated transitions (Berkhout, 2006; Fouquet and Pearson, 2012; Turnheim and Geels, 2013, 2012). This calls for fundamental analysis of a broad array of social-technical drivers and processes.

Fourthly, models carry with them specific assumptions about governance that do not represent the full extent of possible interventions. Quantitative systems modelling focuses mainly on techno-economic conditions and factors at an aggregate level. This narrow focus is reflected in its treatment of governance. For modelling, the main relevance of decision-making relates to the specification of long-term objectives and the design of policy instruments that in practice consist of 'blanket' interventions such as carbon tax or monetary incentives providing aggregate market signals to 'force' greater attractiveness of abatement options. Modellers acknowledge the inherent limitations of such simplifications, and recognise that decision-makers do not base their decisions on cost-effective logics alone:

> "To be reliable guides for policymaking, [scenarios] clearly need to be supplemented by more detailed analyses addressing the key constraints on […] system transformation" (Loftus et al. 2015:109)

Numerical representations of interventions can in turn effectively narrow down the space within which decision-makers craft intervention options, preventing greater attention to systemic interventions for transformative change. Model-based strategies have also been criticised for failing to attend to crucial governance aspects, including a) multiple levels and scales of transitions governance (Nilsson et al., 2012; Raven et al., 2012), b) multiple competences of decision-makers, c) alternatives to cockpitism and the 'illusion of control' this carries (Hajer et al., 2015), d) granularity as to interventions (e.g. policy mixes and the interaction of interventions) (Flanagan et al., 2011; Kivimaa and Kern, 2016; Rogge and Reichardt, 2016) and e) importance of temporal ordering of policy in order to realise a given scenario (Nilsson and Nykvist, 2016).

Modelling thus focuses implicitly on traditional policy actors, who are assumed to have an ability to 'steer' wide- and far-ranging transitions processes. Indeed, the widely-spread assumption of "'cockpit-ism': the illusion that top-down steering by governments and intergovernmental organizations alone can address global problems" (Hajer et al. 2015:1652) is particularly problematic in the context of inherently uncertain, complex, open-ended, and dependent on political choices. Such a focus neglects the role of agents of change (business, civil society, local authorities, etc.) (Hajer et al., 2015) and other qualitative and societal aspects (Loftus et al., 2015) crucial to the realisation of transitions potentials. In broader terms, such a frame on steering misses the need to move beyond state-centric perspectives focused on analysing government control in order to engage with more diffuse processes of governance (Pierre and Peters, 2005).

2.2 Opening up the knowledge base

It is precisely because of the substantial influence of modelling approaches, and notwithstanding transparency about inherent limitations of scope and methodology, that they need to be complemented by approaches considering a variety of overlooked constraints.

In order to overcome these limitations, a first strategy would consist in enhancing modelling methodologies to better take such constraints into account – 'endogenising' them, as it were – introducing more qualitative interpretations of governance issues and how they may play out in different contexts (Van Vuuren et al., 2015, 2014). These kinds of analyses, whether they mobilise 'second-best world' approaches, qualitative storylines, the integration of policy regime analysis in modelling (Van Vuuren and Kok, 2015), or integration of other types of knowledge within the modelling frame, are still rather patchy. This first strategy, considering matters for qualitative interpretation downstream from modelling exercises to nuance results, seeks full integration of qualitative aspects into modelling procedures when this may not lead to better understanding (Berkhout et al., 2002), not be feasible or even desirable (Castree, 2015; Castree et al., 2014; Geels et al., 2016a; Turnheim et al., 2015). It fails to consider fundamentally different perspectives on mechanisms and rationales underpinning transitions processes, and the potential for the emergence of alternative paths that do not 'fit' underlying assumptions or worldviews as well as critical insights as to their feasibility. Rather, a shift in perspective is needed. A fruitful way forward consists in linking and bridging different kinds of knowledge (Turnheim et al. 2015:250) to "develop more multi-dimensional assessments", more decidedly relying on input from the social sciences.

A second strategy consists in pluralising evaluation by building on different types of knowledge, recognising that models are more relevant as 'learning machines' than as 'truth machines' (Berkhout et al., 2002; Dorin and Joly, 2018), and hence that they only offer a partial picture of futures. This strategy, which we further explore here, calls on new ways to involve complementary approaches in the evaluation of STP feasibility, with attention to governance challenges and opportunities as they play out on the ground, and to the path-dependence of socio-technical trajectories – which in effect condition future challenges and opportunities. This implies finding ways in which such knowledge can be critiqued and complemented. Such an approach should build on the strengths of modelling in terms of exploring the general direction of travel and the scale of changes and their attention to the physical boundaries to possible futures, but seek to complement them with specific attention to those most salient points of friction between theoretical potentials and their realisation.

Furthermore, rather than suggesting that transitions can be actively managed in a top-down or planned fashion, critical challenges, uncertainties, and issues of choice should be brought to the foreground (Turnheim et al., 2015). But exactly how this can be done remains elusive. Significant exploratory steps have been made in recent years (Foxon et al., 2013, 2010; Hughes, 2013; Köhler et al., 2009; McDowall and Geels, 2016; Safarzyńska et al., 2012).

3 Multi-faceted STPs feasibility: expanding the knowledge horizon

In this section, we propose a way to pluralise STP feasibility in a way that starts to address some of the criticism and pitfalls identified in the previous sections. We do so by attending to three 'facets' of pathways: (i) pathways are *representations* of change processes that can support forward-looking evaluations; (ii) pathways are *potentials* in the sense of 'hopeful' new orientations providing focus to change efforts; and (iii) pathways are *(sets of) conditions* that can underpin the realisation of such potentials in practice.

3.1 Mobilising different representations and associated knowledge

In this section, we look into the contributions of and linkages between different *representations* of transitions as phenomenon, the different types of knowledge they mobilise to make sense of transitions pathways, and how they rely on different worldviews to propose different notional understandings of feasibility.

Different *representations* of STPs attend to realisation and feasibility. To expand representations of STPs means making sense of the kinds of mechanisms at play across spatial and temporal scales in transitions processes, and attending to associated challenges related to complexity and uncertainty, inertia and innovation, normativity, and politics (Turnheim et al., 2015). Doing so requires mobilising different framings of pathways which focus on different forms of knowledge, and so calling on different ontological assumptions (Geels et al., 2016a) and epistemological frames. A pluralist bridging approach involves the specification of how different types of knowledge can be articulated in an evaluation process, for instance around the particular strengths of each approach.[1]

Different pathways framings can be mobilised separately to identify specific constraints, and jointly to reveal tensions as they focus on different processes and emphasise different constraints (Rosenbloom, 2017). Biophysical pathways, focussing on environmental impact over the long run in order to identify the most pressing areas of human activity, are primarily constrained by their understanding of environmental system dynamics (nature, timing, and interactions), and assumptions about long-term socio-economic dynamics at an aggregate level (e.g. growth, demography, consumption patterns). Techno-economic pathways, focussing on the role that different technological options can play in reducing the environmental impacts in different domains of activity over the long run, are primarily constrained by self-imposed environmental objectives, and assumptions concerning technological readiness and systems configurations (e.g. supply architecture, demand decomposition). Socio-technical pathways, focussing on socio-technical innovation dynamics in different domains, are primarily constrained by near-term inferences about social, technical and institutional processes at different levels (momentum, inertia, and possible directions), and assumptions about co-evolutionary patterns resulting from the interplay of these change dimensions (e.g. generative mechanisms).

It has been suggested that socio-technical approaches can be mobilised to focus attention on how transitions challenges (Turnheim et al., 2015) and key governance issues (Nilsson and Nykvist, 2016) play out on the ground, how they can be anticipated and attended to, and the kinds of societal and political choices they call for. This can provide greater texture to techno-economic assumptions of technical feasibility. Certain options or pathways can be reconsidered on societal acceptability grounds or as unintended consequences become visible (Eriksson and Weber, 2008; Genus and Stirling, 2018), or the direction of search can be focused towards alternative options where hurdles may be less challenging. Jointly attending to these dimensions can reveal taken-for-granted assumptions, support multiple feasibility

[1] This approach to knowledge bridging, focusing on interdisciplinarity as a means of mobilising differentiated forms of *scientific* knowledge, is hence to be distinguished from bridging strategies in the context of overcoming the various science/non-science chasms engaged in controversies involving scientists and their authority in public debates (Garud et al., 2014; Gieryn, 1999). It does, however, present some similarities in the sense that it represents an effort in generating more porosity of existing boundaries (in our case, between analytical perspectives) that have largely been constructed as a means of demarcating epistemic communities.

checks, and critically expose tensions between approaches, resulting in greater realism and preparedness to real-world requirements when formulating STPs.

Unpacking how such knowledge can be articulated is tantamount to asking what makes a 'suitable' pathway, which in our view is not about making 'better' or 'more methodologically robust' pathways, but about making 'more useful' pathways[2] – in our case pathways that can support transformative change and enable evaluation as we go. In this, we agree with Van der Steen & Van Twist (2012), who suggest that future-oriented exercises need to develop 'connectivity' with the decision-making processes they intend to influence. This means that, in addition to extant analytical requirements, prospective pathways also need to take into account organisational and political cues in the decision-making context (e.g. policy cycles, public awareness, policy opportunities, legitimacy struggles), so that the knowledge created can become actionable.

This leads us to value the importance of representational devices that focus attention to relevant tensions, constraints, dimensions, in a way that supports strategic interventions (Auvinen et al., 2014), now and over time (Garud and Gehman, 2012). Indeed, the pathway construct aptly conveys the processual character of such ideal prospective change dynamics. Pathways offer stylised journeys towards long-term destinations (e.g. more or less desirable system configurations given how they satisfy existing or new evaluation criteria), along proposed trajectories. In practice, however, we can expect realised transitions paths to be inherently messy, much as innovation journeys are full of misalignments, tensions and discords (Ansari and Garud, 2009). In other words, the governance of real-world transitions is likely to arise from a combination of strategic orientation, including intended (goal-rational) and deliberate (contextual), as well as more emergent patterns of action (learning-oriented) (Geels et al., 2016a; Mintzberg et al., 1998).

Of particular interest are representations of STPs that explicitly link sustainability dimensions to socio-technical processes (Kemp and Van Lente, 2011), attend to the inherently open nature of socio-technical systems, their co-evolutionary dynamics, path dependence and inertia, discontinuity, qualitative change and multiple and changing causation (e.g.

[2] The suitability, desirability, and usefulness of pathways is clearly open for interpretation, dependent on many factors including the interests, motives, and standpoints of actors involved, as well as the context of application. Our specific concern with informing governance about the feasibility of STPs and learning from tensions arising from the confrontation of multiple analytical perspectives conditions our perspective on what a 'useful' pathway may be.

cumulative, cascading, interrupted) (Andersson et al., 2014). This may call on mobilising different styles of explanation such as (historical) narration, process theory and pattern analysis (Pettigrew, 1997), as well as dedicating attention to contextual shaping, conflict and power struggles in transitions (Meadowcroft, 2011), culturally-embedded lifestyles and social practices (Shove and Walker, 2010). Mobilising an essentially inductive logic to make sense of observations about past, current, and emergent trajectories (i.e., through pattern analysis) promises a useful counterpoint to the more predictive-deductive logic of modelling. In general, such socio-technical pathways framings usefully provide ways to represent a limited number of ideal-types to structure the exploration of transitions dynamics (historical or emergent) (see for instance Smith et al. 2005; Geels & Schot 2007; Foxon et al. 2010; Westley et al. 2014; Stirling 2011).

These socio-technical representations allow sharper focus on the specific hurdles, requirements and critical junctures in transitions processes that can guide the development of scenarios and strategies today. This includes for instance distinguishing pathways in terms of the lead actors involved (incumbents vs. new entrants), different competing agendas and interpretations of sustainability, or different sets of environmental objectives (e.g. 1.5ºC pathways). Pathways representations should also draw attention to trends that may enable, obstruct, or result from prospective transitions dynamics. This can be operationalised in terms of degrees of (mis)alignment with deeper societal trends and environmental dynamics (Bai et al., 2015; EEA, 2015a), nascent trends resulting from more experimental activities (Steward, 2012; Westley et al., 2014), and how these may be co-constitutive of transitions ahead. Lastly, and we have already evoked this, pathways should not be set in stone, but inherently reflexive tools that can enable the navigation of transitions, which are inherently uncertain processes. Envisioning a plurality of pathways, opening them up for wide scrutiny and participation, and regularly re-evaluating progress, targets and the emergence of new issues, as discussed below, is crucial in this regard.

To summarise, focusing on representations in analysing feasibility of STPs provides practical means to identify how different sets of knowledge can inform the feasibility of options considered in techno-economic modelling. Techno-economic modelling, on the other hand, enables evaluations of what a new set of constraints implies in terms of reaching specific goals. Finally, what is considered feasible is bound to change over time as technology and norms develop, and as new political alignments are formed. Iterative generation of knowledge using different representations is imperative to continuously evaluate pathways and question the conditions under which a given option may unfold. These two latter processes are now explained in turn.

3.2 Envisioning a variety of transitions potentials

In this section, we consider the envisioning of prospective transitions *potentials* as distinct possible futures that specify the overall shape of transitions pathways (speed, scope, directionality). Understood as potentials, pathways mobilise expectations about specific 'solution spaces', underpinning narratives, and the timing of their realisation.

We need to further develop means of exploring futures and prospective sustainability transitions *potentials* with a particular emphasis on 'opening up' plausible paths, scrutinising their desirability and laying out the terms of their realisation. Pathways enable the exploration and ordering of prospective futures, such as ruling out the 'infeasible' and exploring the scope of what is considered 'possible' or 'desirable' at any given time and according to given actors (pluralising feasibility). The exploration of STPs also provides a frame for linking long-term normative objectives to near-term strategies and priorities (temporal ordering).

Pluralising pathways and feasibility. Pluralising pathways is particularly relevant in the context of high levels of uncertainty and openness. Despite this, roadmaps too often consist of only one or few roads (Stirling, 2016), which can be seen as a narrowing down around dominant interests and values, instead of considering the "[m]ultiple – often radically different – orientations for change [that] are typically feasible and viable" (Stirling 2009:5) and may hence better align with the preferences of different actors or emerging forms of mobilisation. So, it is important to complement models by broadening the scope and direction of search to explore a multiplicity of possible pathways. Pluralising pathways provides an entry point for a) the ability to mobilise widely by representing a number of voices "even [in situations] when consensus is unlikely to be attained" (Ferraro et al., 2015:378), b) openness to counterfactual narratives and the consideration of more imaginative paths (i.e. recognising that change comes from surprising places) which may be particularly relevant in light of the radical and urgent transformations required, c) strategic nurturing of diverse paths (i.e. keeping options open, namely in light of expectable unexpected outcomes), and d) a strategic focus on seeking out truly disruptive change and disruptive paths (i.e. 'out of the box'). Our position resonates with recent calls for greater engagement with discontinuous paths:

> "current mainstream thinking tends to revolve around "business as usual" futures that emphasize continuity and predictability based on known patterns of change, rather than focusing on potential discontinuities, emergent patterns of change and plausible and desirable futures (…) We argue that sustainability debates

> should focus less on the continuity of present pathways and be more inclusive of new visions and opportunities offered by desirable and plausible futures, opening up a wider range of 'outside-the-box' possibilities as well as new ways to achieve them" (Bai et al. 2015:352)

This requires a particular mindset to challenge the conventional frame from which futures are envisioned, related rationales and motivations.

Temporal ordering: branching points, interim steps and dynamics feasibility. First, unpacking the temporal dimension of pathways reveals a multiplicity of temporal horizons of change (Turnheim et al., 2015) and can support the specification of intermediate goals in a transition. It also focuses attention on the relevance of different modelling strategies as future-oriented epistemology (i.e. can models resolve interim points to begin with?), and opens up for granularity of socio-technical understandings of event sequences (Nilsson and Nykvist, 2016). It hence becomes possible to identify critical junctures or tensions where difficulties can be expected, and branching points along pathways (Foxon et al. 2013; van Bree et al. 2010) where critical choices have to be enacted (Rosenbloom et al., 2018).

Such future 'events' can serve as focussing devices to convene alternative perspectives in a coherent analytical stream, for instance "in order to illuminate the dynamics and choices along those pathways" (Foxon et al. 2013:157). Socio-technical change is rarely linear, and instead can be seen as the opening up and closing down of multiple and sometimes competing paths, obstacles along the way, detours, surprises, etc., which means that recognising the availability of multiple options at any given time positively influences the ability to navigate towards any particular direction. Recent research efforts have started to operationalise these aspects, focussing attention to critical junctures and branching points in prospective STPs (Arapostathis et al., 2013; Foxon et al., 2013; Rosenbloom et al., 2018; van Bree et al., 2010), and how they can be mobilised as analytical and strategic focussing devices – whether these relate to the degree of (mis-)alignment of socio-technical processes or related opportunities for catalytic intervention:

> "the study of branching points provides useful granularity that enriches the study of transition pathways; key moments in transitions are identified for in-depth study, enabling the intervening periods to be better understood within their historical context, which may include a degree of lock in and path dependency relating to these branching points" (Arapostathis et al 2013)

This resonates with our call for attending to sequences of change within pathways, which includes focussing on interim steps as hurdles, e.g. what are the significant critical 'events' (in

2020, 2025, 2030, etc.) that need to happen on the way to delivering at a 2050 or 2100 horizon.

Lastly, feasibility (of options, of pathways) is inherently dynamic and prone to change over time. This is currently reflected in modelling strategies, through prospective learning curves and regularly updated parameters, but also needs to account for changing conditions and circumstances reflecting temporal differences in the desirability, social acceptability, and political feasibility of technological options and pathways (see section 3.3 below).

To summarise, attending to the envisioning dimension ensures that a plurality of pathways is considered. Even if a given solution is most cost-optimal form techno-economic modelling results, ruling out further analysis of second-best options as a distraction, a single underestimated barrier or unforeseen issue might change the equation. Similarly, rapid change in costs due to unappreciated learning effects and other unpredictably changes in circumstance can suddenly make other options feasible. Feasibility assessment in STPs through the lens of envisioning practically means to dynamically re-evaluate knowledge about different options and to envision a variety of solutions, as well as the temporal ordering under which these could develop.

3.3 Attending to the conditions for pathways realisation

In this section, we look into the *conditions* under which the realisation of transitions pathways may become more feasible, in terms of the critical real-world constraints at play and the specific hurdles and requirements that may be anticipated.

It is important to engage with the real-world *conditions* for the realisation of pathways, and to scrutinise their feasibility and implications on such grounds. Prospective pathways offer a way into plausible and potentially desirable futures that can frame strategic decision-making (Bai et al., 2015), but only if we open them up to questions of political and social feasibility (Schubert et al., 2015). This implies particular attention to those salient aspects of transitions pathways where theoretical *potentials* collide with real-world settings and systems, leading to significant observed deviations, exposing contradictions or significant tensions. In section 4, we provide numerous illustrations of how attention to a range different types of conditions leads to richer feasibility assessments. To briefly exemplify, the low-carbon modelling community has started to acknowledge the substantial disappointment with expected CCS deployment, but also to internalise the contrasting and an encouraging ‘explosive’ growth of solar and wind deployment also proposition (Peters et al., 2017). This calls for an appreciation of the reasons as to why promising visions so obstinately fail to materialise and implies a shift from *if* to *how* (a pathway may be feasible). Pathways are hence more than scenarios or visions. This implies a shift from "How long does it take?" to "What does it take?" to realise rapid transitions (Grubler et al., 2016; Sovacool, 2016).

Thinking about the conditions for pathways realisation can hence be translated into the formulation of relevant feasibility dimensions and related criteria. Largely indebted to Loftus et al. (2015), we here suggest specific knowledge entry points regarding crucial feasibility dimensions: 1) the maturity of options, 2) system integration and infrastructure requirements, 3) societal acceptability, and 4) political feasibility.

Maturity of options. The maturity of a specific option (i.e. technical, social, organisational, or institutional innovation) at any given time is crucial to the feasibility of pathways, as evidenced by the controversy over the inclusion BECCS (carbon capture and storage using biomass) as a critical yet until recently largely unchallenged means to achieve 2degC targets in low-carbon pathways. Disappointment with the maturity of carbon capture and storage in general and BECCS in particular is linked to issues of readiness and commercial availability (Loftus et al. 2015), the lack of high enough global carbon price and successful trials at large scale (Nykvist, 2013) as well as issues with organisational forms and business models (Bolton and Hannon, 2016). It is well known that carbon capture and storage under certain conditions offers a cost-optimal pathway to deep emission reductions, but given the actual feasibility of CCS projects and long lead times to actual climate mitigation (Myhrvold and Caldeira, 2012) its actual maturity is very low compared to the reliance on the technology in many mitigation scenarios. Challenges are amplified for BECCS as biomass resources are constrained and raise important issues of land use competition across sectors.

Another example is organic food, that has taken more than 50 years to develop from vision to a 'mainstream niche' (Smith, 2006), is still far from having succeeded in transforming dominant agri-food regimes, but thrives in particular local settings. For more prospective options, it is relevant to understand emerging and current trends (Hughes, 2013), specify the hurdles ahead, formulate realistic deployment and scaling paths and related portfolio of measures, e.g. to support experimentation, learning opportunities, actor networks, infrastructure development, or lifestyles changes. Historic exemplars of deployment trajectories are also useful feasibility comparators regarding the plausibility of expectations in this area (Sovacool, 2016), although important concerns remain about the consistency of comparisons (Grubler et al., 2016). Concerning mature technologies routinely considered as ‘available from the shelf’, comparative studies also show us that options are not always readily transferrable, and may require active work in terms of embedding into new contexts, whether this concerns developing supply-chains, markets, business models, stable investment environments, greater user exposure, preferences, behaviours and practices, or overcoming political hurdles. Attending more consistently to the maturity of options considered is likely to provide some insurance against reliance on evoking “a *deus ex machina* (such as speculative negative emissions or changing the past) to ensure our analyses conform with today’s political and economic hegemony” (Anderson 2015:900).

System integration and infrastructure. Integration into systems and infrastructure requirements (Loftus et al., 2015) are critical determinants of getting alternatives to ‘work’ (Rip and Kemp, 1998), as evidenced by the history of large technical systems, but also more dramatic infrastructure failures and blackouts. Whether related to the edification of entirely new systems (e.g. dealing with energy intermittency and storage, batteries for electric mobility) or the transformation of existing infrastructure (e.g. land use conversions, housing retrofits, the re-orientation of food supply chains), system integration typically involves substantial investments, long lead times, the expansion of supporting knowledge, and clear strategic orientation. These significant hurdles cannot be taken for granted and need to be accounted for.

Societal acceptability. Concerning societal acceptability (Loftus et al., 2015; Schubert et al., 2015), it is necessary to take into account issues, controversies, or anxieties with the expected deployment and use of any particular option, how these may be anticipated or addressed, and how this may affect the likelihood of deployment. Illustrative examples of acceptability issues include opposition to nuclear power (which has taken very different expressions in different times and places), low societal legitimacy for CCS, visual impact concerns with windmills, consumer concerns with GMOs, and so on. Apart from the above acceptability-sensing requirements, we note with interest the development of participatory approaches to emergent futures (Ferraro et al., 2015), and an increasing focus on change agents in transitions as attending to a need for “a better understanding of changes that may lead to transitions and of how such changes can be induced by actors capable of structuring a social agenda for transition” (Jørgensen 2012:1009). The societal acceptability of given STPs hinges upon issues of desirability (of the underlying societal transformation project), the perceived legitimacy (Deephouse et al., 2017) of the actors and arrangements mobilising or advocating for such visions (Suchman, 1995), but also the particulars of implementation on the ground.

Political feasibility. Political feasibility is rarely considered explicitly in prospective pathways (Schubert et al., 2015). It can be understood as the likelihood of decisions supporting a particular path to become implemented, or conversely of obstacles that may result from the resistance of particular actors. Political feasibility is hence highly dependent on actors with substantial influence, power, and vested interests – whether in politics, industry, civil society, or knowledge production. For example, BECCS is dependent on successful development and testing of large scale CCS technology, which in turn requires political commitment on CO2 pricing at a level not seen. No matter the technological maturity of CCS, and historically strong political support, currently the actual political feasibility of CCS remains very low (Nykvist, 2013). Political feasibility may become salient in relation to required changes in policy frame conditions (e.g. environmental or innovation policies), support for major investments (infrastructure, R&D, deployment), coordination in actor coalitions (resistive or change-oriented), or societal mobilisation for alternatives (e.g. social movements, consumer associations) – all of which are crucial to set transformation dynamics in motion. On a more instrumental level, the political feasibility of a particular pathway can be linked to the likelihood of an advocacy coalition to form, establish support and a mandate for change, and seize opportunities to implement required changes. In the context of transitions, this requires considerable persistence, entrepreneurial and political skills, ability to navigate policy cycles and opportunities, and may also call for new forms of knowledge.

To summarise, there is considerable available knowledge to be combined with model-based forward-looking STP evaluations concerning crucial determinants of implementation and realisation. In most cases, this requires more focussed analysis of particular options (technological or otherwise) enrolled in particular pathways. A closer inspection of the maturity and system integration of individual options are perhaps the first point of call for inter-disciplinary bridging. Societal acceptability and political feasibility are more difficult to address but nonetheless crucial determinants of the overall feasibility of STPs, which cannot be relegated to a downstream implementation issue: STP evaluations need to become much more explicit about critical tensions and uncertainties concerning these dimensions and present them as a priority concern for evaluation and political choice.

4 Discussion: Operationalising STP feasibility

Table 1 provides an overview of three pathway facets discussed in section 3. In a more operational step, we now discuss analytical and governance implications of our three-tiered argument, in sections 4.1 and 4.2 respectively, actively mobilising case illustrations to substantiate each point of the argument.

Table 1: STP feasibility evaluation - an overview of three facets

Pathways as representations: multiple approaches	
Model-based knowledge	Quantitative evaluations of scenarios (i.e., emission profiles and costs). Emphasis on cost-optimisation and goal-oriented constraints.
	Which pathways are *possible* given techno-economic and environmental constraints?
Socio-technical transitions studies	Reconfigurations of socio-technical systems and regimes. Emphasis on different pathways and core generative mechanisms (e.g., niche development, regime inertia).
	Which pathways are *possible* given prevailing socio-technical dynamics and constraints?
Pathways as potentials: multiple orientations	
Plurality	Opening up futures to keep options open, to enrol wider publics and address persistent blindspots.
	How can a wider variety of possible pathways be represented in STP evaluation? How can established knowledge and imaginative potential be better balanced in such exercises?
Temporal ordering & dynamic feasibility	Current and prospective feasibility of options and pathways
	How does STP feasibility change over time? Can critical branching points conditioning future feasibility (positively or negatively) be identified?
Pathways as conditions: multiple dimensions & criteria	
Maturity & momentum of options	Maturity, momentum and preparedness concerning specific options (technical, social, organisational, institutional) at any given time.
	What is the current (and expected) state of development of particular options?
System integration and infrastructure	Integration into systems and infrastructure requirements as determinants of 'working' alternatives.
	What requirements and interdependencies can be identified likely to constrain the effective integration of new options in existing systems and infrastructures?
Societal acceptability	Issues and controversies related to particular options that may affect the likelihood of deployment.
	How societally acceptable are different options and pathways?
Political feasibility and delivery	Key decisions supporting the implementation of a particular path and obstacles that may result from the resistance of particular actors.
	What is the degree of political traction (current and prospective) in favour of a given pathway?

4.1 Analytical implications

How, then, can we start combining different forms of knowledge to contribute to more nuanced and plural evaluations of STPs? What kind of outcomes can we expect from such feasibility evaluations?

4.1.1 Combining pathway representations

At the level of STP representations, socio-technical approaches provide a focus on the (re-) configuration of actors, systems, and institutions. In terms of STP feasibility, this can support finer-grained understandings of current systems and re-configuration prospects and anticipation of possible delays linked to lack of niche momentum and regime inertia. Furthermore, such analysis can lead to the exclusion or delayed introduction of options in modelling scenarios by better identifying unrealistic technological expectations, or explicitly formulating non-technological conditions for their realisation (e.g. political, social, institutional requirements). The following examples illustrate how confronting such knowledge empirically with standard outcomes of model-based approaches points to critical unresolved tensions.

In the electricity domain, negative emission technologies heavily relied on in scenarios (e.g. BECCS and CCS) are currently not showing the degree of maturity that can support their rapid deployment. Research also shows that CCS is among the slowest of mitigation technologies to gain deep emission cuts (Myhrvold and Caldeira, 2012; Peters et al., 2017) calling its feasibility into question. For options becoming more mature, such as solar PV and windmills, there are significant national variations due to differences in the development of markets, supply-chains, and incentive structures, but the pace of change has instead been fundamentally underappreciated (Creutzig et al., 2017). In the mobility domain, difficulties can be expected with rapid technology phase-out (as implied concerning conventional cars in most scenarios), notably because phase-out is not a purely technical matter and is likely to raise important resistance by automakers and motorists. Also, policymakers are highly receptive to the jobs question arising with the transformation of a major industry. Other sources of tension and uncertainty include a) hype-disappointment cycles with alternative fuels (Bakker, 2010; Bakker et al., 2014; Budde et al., 2012) and b) the need to include alternatives that radically differentiate themselves from automobility and present important challenges in terms of enabling infrastructure (e.g. multi-modality) and behavioural change (e.g. slow modes). In the agro-food domain, the inherent heterogeneity of systems, characterised by a large number of product classes (e.g. dairy, meat, grains, fruits, vegetables, processed foods) and qualitative distinctions therein, diets and practices, as well as a plurality of production systems (e.g. extensive, intensive, agro-ecological) needs to be considered. This suggests that a useful way forward concerns finer-grained understandings of multiple system configurations (Elzen et al., 2017; McMichael, 2011; Thompson and Scoones, 2009) and dedicated STP explorations efforts in relation to these configurations.

Confronting such tensions emanating from very different feasibility criteria improves the understanding of proposed pathways and prospective options in all domains by introducing more detail to statements about STP feasibility. Some of these tensions can be reconciled with model-based efforts and methodologies, producing refined assumptions about the speed and scale of diffusion that can be assumed for technological options in any given context (Myhrvold and Caldeira, 2012; van Sluisveld et al., 2018). This concerns, for instance:

- in-depth qualitative evaluations of the current momentum of specific options;
- evaluations of the stability of current configurations and various sources of inertia;
- finer system descriptions requiring adjustments in the unit of analysis.

Enrolling social scientists to work with modelling teams has proved useful in recent collaborative research projects (Foxon et al., 2010; Hughes, 2013; Safarzyńska et al., 2012; van Sluisveld et al., 2018). Such work, mobilising new kinds of evidence to formulate more realistic STPs, requires important translation efforts (from qualitative to quantitative, from current to prospective), multiple iterations and regular updating.

Other tensions require more than fine-tuning model assumptions and parameters, as they point to inherent blindspots produced by model structures and strategies. Such cases call for broader strategies to inform STP evaluations on the basis of multiple assessments side by side that can yield contradictory outlooks. The issue of system inertia and how fast a phase-out of existing technology can take place provides an illustration. Currently, model structures use rather simplistic assumptions about the drivers of phase-out (e.g., stock turnover). These can be adjusted to modulate delays in introduction of new technologies, but are unlikely to capture complexities related to the enactment of new technology in response to more fundamental destabilisation of established regimes. An illustrative point is the emerging evidence of rapidly declining residual values of diesel cars in Europe[3], suggesting that consumer values are shifting in ways that may underpin more rapid stock turnover than otherwise modelled.

The representation used to explain (or not) the inherent role of power, politics, and strategic games involved in a transition, puts limits on role that each approach can play. It is crucial that a) prospective scenarios engage with and highlight related uncertainties, and b) that

[3] https://www.autovistagroup.com/news-and-insights/insight-eroding-residual-value-advantage-diesel-cars-eu5

different forms of knowledge are brought to bear on STP evaluation (e.g. case studies, typologies, decision-trees). So, in such cases, a more relevant strategy consists in generating greater clarity concerning the limits to prediction, emphasising strong uncertainties and the need to maintain a high level of plurality in terms of underlying representation used. This approach will assist in identifying critical matters calling for societal, political and strategic choices.

4.1.2 Combining knowledge about pathways as potentials

Viewing pathways as potentials, we have identified two priorities: pluralising pathways to generate greater variety and introducing more reflexivity as to the temporal ordering within pathways.

Concerning pathway plurality, it is important to generate more imaginative STPs to compensate for an inherent bias for less disruptive paths in model-based scenarios. Important ways forward include considering the role of deep structural change (e.g. fundamental changes in value systems) and developing the means to sense weak signals about different sources of innovation (technological, societal, governance-oriented, etc.). How can such emerging dynamics underpin prospective pathways, and what scope for methodological combination is there in this area?

In the electricity domain, it is important to explore the relevance of alternative forms of electricity production and distribution (e.g. decentralised grids, the role of new entrants such as cooperatives, growing momentum for battery storage and solar PVs) that are emerging on the ground and likely to lead to significant knock-on effects. Similarly in, the mobility domain, alternatives beyond the 'greening of cars' (e.g. car-sharing, teleworking, shortening of trip length, reduced need to travel) or emerging trends (e.g. shifts away from vehicle ownership) are rarely captured in scenarios and in policy roadmaps – yet may prove to have significant societal or business traction. In the agro-food domain, numerous alternative ways of configuring production and consumption systems are emerging on the ground (Barbier et al., 2017; Spaargaren et al., 2012b), with no establishment of a single dominant model. There are also suggestions that multiple regimes may co-exist, which presents a challenge to the inherent bias for substitution logics in scenarios.

There is scope for refining models by inclusion of socio-technical knowledge, namely by:

- including a wider portfolio of prospective options;

- mobilising a wider variety of logics underpinning different pathways (see for instance market-, government- or civic-led pathways presented in Foxon et al. (2013, 2010));
- exploring how non-technological options can be included in modelling strategies.

However, there are also structural limitations for such combinations, including:

- the tendency for more complex models encompassing several sectors or systems, such as IAMs, to represent monolithic users and monolithic options (i.e., one type of personal vehicle). This tends to iron out the very diversity (e.g. co-existence of multiple users, behavioural patterns, practices, market niches) that drives innovation dynamics;
- difficulties with incorporating the role of normative preferences and political choices (i.e. non-rational decision-making) as determinants of model outcomes.

Concerning temporal ordering, socio-technical scenario methodologies (Hofman et al., 2004; Hofman and Elzen, 2010) offer structured ways to explore a variety of mechanisms underpinning path creation by mobilising historically-observed innovation patterns. These generative mechanisms, crucially affecting the speed and direction of innovation paths, include the role of hybridisation (Raven, 2007), stepping stones, cumulative and recombinant paths (Safarzyńska et al., 2012), scaling-up mechanisms (Wilson, 2012), innovation cascades, sailing ship effects (Geels, 2002), technological hypes and dead ends (Bakker et al., 2014; Geels, 2012), and so on.

In many cases, exploring such mechanisms of path creation can support the formulation of branching points around significant innovation 'events', turning points and associate critical choices (Rosenbloom et al., 2018). Two types of branching points appear particularly relevant: a) the mainstreaming of alternatives (breaking out of their niche) can significantly alter diffusion dynamics, namely as actor strategies change, and b) interdependences between innovations and their infrastructural requirements.

In the electricity domain, as RETs acquire increasing momentum, a host of new challenges emerge that have to do with grid architectures and markets, and the role that incumbent utility actors may play in capturing or resisting accelerated diffusion (Markard, 2018; Turnheim et al., 2018). In the mobility domain, understanding societal acceptance (e.g. desire for long range) is key to understanding the rapid technological development of BEVs in terms of range and the charging power needed for larger battery packs. The rapidly changing conditions for infrastructure development appear as critical branching point for BEVs diffusion (Nilsson and Nykvist, 2016; Nykvist and Nilsson, 2015). Experimental programmes in countries like

Norway supporting the rapid diffusion of BEV show promising signs that these challenges can be overcome with ambitious policies (Figenbaum, 2016). Interventions can also be usefully implemented according to temporal considerations, i.e. the gradual layering of intervention steps that can produce favourable contexts for innovation. In the agro-food domain, the mainstreaming of radical alternative food visions (e.g. 'organic', 'local', 'fair') has to date largely been captured by increasingly powerful transnational food retailers (Spaargaren et al., 2012a). This has tended to water down ambitions by focussing on narrow standards, raising questions about the societal acceptability of the proposed scaling pathway as initial visions lose their significance. The resulting tension has spurred the emergence of "second generation" local food initiatives (Goodman et al., 2011) and various generations of organic food (von Oelreich and Milestad, 2017), suggesting possible branching points around new configurations.

Combining traditional model-based approaches with more process-oriented accounts, such as socio-technical scenarios (Hofman et al., 2004; Hofman and Elzen, 2010), and awareness of the sequencing of intervention strategies is a key new frontier for forward-looking STP elaboration (Rosenbloom et al., 2018).

4.1.3 Combining knowledge about pathway conditions

First, on a general level, there is scope for learning qualitatively about the overlooked dimensions affecting the feasibility of certain options and pathways, namely via more systematic comparative efforts. The European context provides a case in point where, in spite of shared long-term environmental objectives and institutional settings, stark differences exist in existing socio-technical configurations, transitions paths pursued, the particular means deployed for their realisation, and the extent to which they have supported transformations. There is tremendous scope for systematic learning from national and local variations within the shared European context[4]. As innovations tend to emerge in specific geographical localities, momentum in one jurisdiction can help jumpstart global progress such as is now the case in Solar PV or BEV technologies. Comparative differences underscore how existing configurations enable and constrain future paths, and show the relevance of finer-grained evaluations.

[4] Comparisons beyond this European context are more challenging but nonetheless critical.

In the electricity domain, for instance, RET deployment to date has occurred at different speeds, and according to different priorities. This includes different national preferences for certain technologies with different lead actors (e.g., more reliance on working with incumbents in a British context as opposed to greater space for new entrants in Germany (Geels et al., 2016b)), but also varying institutional structures and policy priorities generating divergent paths (Lockwood, 2015) that cannot be explained by techno-economic considerations alone. In the mobility domain, the rapid breakthrough of BEVs in Norway, attributed to the coherent build-up of a supportive stakeholder coalition and an effective policy mix that raised electric mobility's convenience and desirability (Figenbaum, 2016) is in stark contrast with continuing difficulties supporting this technology in other national settings. In the agro-food domain, the development of organic food production and consumption presents considerable national variability (EEA, 2015b), pointing to fundamental differences in the configuration of agricultural systems and the shaping of consumer preferences.

Second, concerning the maturity and system integration of specific innovations (the first two overlooked dimensions considered in section 3.3), there is a need for critically reviewing expectations about technology diffusion based on learning curves and capital stock replacement (Li and Strachan, 2016). We suggest complementing cost- and learning-oriented model parameterisation by mobilising in-depth qualitative assessments of the momentum of innovations and the relative inertia of established systems, focussing on technological, market, actors, and institutional dynamics in particular. Socio-technical analyses can support the evaluation of recent niche developments and expected hurdles for their breakthrough, as well as informed inferences about progress towards addressing the tensions, obstacles and contradictions hindering change. Significant hurdles exist concerning the introduction of promising (or even mature) technical options to new contexts, their standardisation and scaling up. Such dynamics should be taken into account when evaluating expectations about the viability of specific future options. Furthermore, current levels of momentum with specific technologies cannot be extrapolated unconditionally of a continuation of existing support structures, given that long-term coherent signals (e.g. from regulatory frameworks or policy commitments) are paramount to generate trust and support niche expansion, but are also vulnerable to changing political winds.

In the electricity domain, despite the relative maturity of a number of RETs, their national deployment rates differ significantly in practice. This denotes the importance of better understanding – and modelling – of the contextual determinants of diffusion, including the availability of a local supply and maintenance ecosystem, political determination, and the relative absence of resistance from established regime actors. In the mobility domain, an important issue relates to the rollout of appropriate infrastructure, in what is often seen as 'chicken-and-egg' problems for different alternatives (e.g. electric vehicles, biofuels, bicycles). In the agro-food domain, detailed analysis of prevailing sources of inertia and possible resistance to change points to the importance of local cultural factors (e.g. influencing diets and food practices), as well as significant industry concentration (e.g. the significant power of the retail industry) (Grin, 2012).

Third, greater consideration of issues of political and societal feasibility is crucial to developing more informative STPs. This is not only a downstream concern, requiring choosing between alternative pathways: political and societal dynamics are also determinants of which pathways can be envisioned and become possible. Furthermore it is important to introduce more reflexivity about the inherent value judgements that are embedded in the ways prospective pathways are developed (e.g. prioritising techno-economic drivers, bias for technological solutions) and in implicit collective commitments to particular trajectories (Rosenbloom et al., 2018).

In the electricity domain, many of the current barriers and opportunities for transitions have to do with the structure of the industry. Governance styles and national visions for system development vary, in particularly grid architecture and fuel choice. This is closely tied to strategic priorities, while 'rational' technological and economic feasibility issues are less important – as e.g. evidenced by historic support for nuclear power despite high costs and continued commitments to coal (Pahle, 2010). In the mobility domain, pathways relying mainly on the electrification of cars or multi-modality are inherently different in terms of the underlying societal visions and political choices that they invoke. While the former suggests technological disruption with significant socio-political continuity, the latter requires additional efforts in terms of reorienting mobility practices, new mobility cultures away from individual ownership, and large infrastructure investments (public transport, accessibility, multi-modality). In the agro-food domain, agro-ecological pathways suggest important departures from the current ways of organising food production and consumption, with significant reliance on emerging normative frames and a strong role for new actors and practices (Gordon et al., 2017). The resulting change process is likely to generate conflicts requiring political arbitration, rather than the 'hands-off' reform approach that has been characteristic in this domain (Giménez and Shattuck, 2011).

4.2 Opening up decision-making about pathways

In this section, we consider implications for governance and the kinds of interventions strategies stemming from the proposed STP feasibility evaluation.

The strong uncertainties involved in prospective transitions efforts need to be recognised as a challenge for evaluation and governance. The complexity of transitions processes "reveals the limits of applicability of a particular theoretical toolbox" (Andersson et al. 2014:147). We suggest that this challenges conventional understandings of planning and the practice of (*ex ante* and more rarely *ex post*) evaluation. So, we argue for a more humble, open and iterative form of governance and evaluation that avoids claims of certainty or control, focussing instead on linking objectives to a reflection on a multiplicity of paths ahead, signs of their realisation on the ground, and identifying challenges to be overcome as a means to prioritise action. Such a shift in perspective has been formulated as a move away from results- or output-based evaluation, towards process-based (or '*ex durante*') evaluation (Bussels, 2013). This means recognising a much more central role for learning, visioning, measuring progress along trajectories, and curbing trends *over time*. STPs should be understood as moving targets calling for an on-going to-and-fro movement between intervention and evaluation. This presupposes the crafting of governance strategies that are reflexive about the pace and direction of change (Avelino & Grin 2016) and governance actors that can acquire the means to evaluate the (non-)realisation of transitions paths on the ground (how would we know that we are engaging on a transitions path and steering in the intended direction?), adjusting priorities as these dynamics unfold over time.

4.2.1 Knowing and influencing transitions contexts through plural representations

Policy actors need to recognise the limits of control over socio-technical systems and transitions, and adopt governance styles and approaches favouring flexibility and the long-term coherence of overall direction over certainty or predictive accuracy. Transitions governance requires a corresponding degree of humility to enable flexible navigation (Olsson et al., 2006) of changing contexts and opportunities to shape them (Smith et al. 2005:1498). Yet, we also need to recognise that as sustainability problems become more acute and urgent, the temporal window for effective action is rapidly narrowing – putting additional constraints on deliberation. In this context, combining representations of STP feasibility should focus on understanding, identifying, and anticipating challenges associated with proposed pathways.

So, while the governance of transitions can largely be seen as an open and distributed process of facilitation of certain dynamics and favourable conditions, the benefit to policymaking of combining representations should be to provide more grounded reality checks of the merit of prospective solutions, aiming to narrow down the portfolio of options considered, or introduce greater sensitivity about the conditions for their realisation. It is against this background that the pathways construct – if opened up to new forms of knowledge in STPs – may support greater coherence of intervention over the long term.

4.2.2 Engaging with transitions potentials

Building consensus and commitment around specific sustainability objectives – though crucial – may not be enough to support constructive steps towards system change, as it does not inform us about *how* sustainability objectives can be met. Pursuing a particular prospective pathway implies specifying system transformation objectives and navigating significant societal and political choices and trade-offs. For policymaking, experimentation may be useful to support the exploration of multiple alternative pathways (Meadowcroft, 2009). Policy strategies cannot only focus on technology neutral cost optimal solutions, but need to engage with and support several competing solutions, and seek to inscribe these more clearly in long-term visions that are coherent about the overall direction of travel. Formulating aspirational transitions narratives involves societal and political choices that are ultimately tied to deeper societal and normative goals (which kind of society is being proposed?) and more immediate political feasibility considerations (what room for manoeuvre is there?).

Transitions interventions should be underpinned by concerted efforts to concretely examine the feasibly of different prospective pathways. Decision-makers have to engage with a variety of futures, but also seek to generate clarity and consensus around those socio-technical visions that may be more realistic and gain substantial traction. For knowledge about STPs to become actionable, it is necessary to translate long-term transition objectives into sequences of smaller, more near-term actions. Working backwards from long-term objectives, intervention strategies should be informed by the most critical obstacles along prospective STPs, order these along a temporal continuum (e.g. emergence, diffusion, reconfiguration and phase-out of socio-technical propositions), and devise a layering of supporting interventions accordingly (Schot and Steinmueller, 2018).

4.2.3 Intervening on system conditions

We have proposed an elaboration on overlooked STP feasibility dimensions in terms of the maturity of options, system integration and infrastructure requirements, societal acceptability, and political viability. More balanced feasibility evaluations of prospective pathways and options can lead to the re-evaluation of expectations about future options and pathways (positively or negatively), more emphasis on critical realism, and the anticipation of major tensions within or across these dimensions. When arguing for attention to overlooked feasibility dimensions, we should keep in mind that "not all that is technically achievable, economically feasible or socially viable is actually historically realizable" (Stirling, 2011), and that politics and various forms of path dependence play an important role in determining what ultimately is realisable. This is something that decision-makers know too well in the context of politics ('the art of the possible'), but that continues to require attention in the context of STP evaluation, namely due to an over-reliance on techno-scientific visions. Past choices constrain what is currently possible through various forms of lock-in (Arthur, 1989; Unruh, 2000), but is may also be possible to design interventions today that lock us into more ambitious pathways due to positive feedback mechanisms (Ürge-Vorsatz et al., 2018), namely by investing in critical infrastructures.

Concerning policy interventions, we suggested a need for linking STPs to finer grained interventions than the usual 'blanket' instruments underpinning model-based scenarios. New intervention tools may also be needed to complement existing policy portfolios (Schot and Steinmueller, 2018). We note, for instance, the importance of developing policy instruments that can link long-term pathway orientation (e.g. strategic visions and plans) to lasting support mechanisms on the ground. Such interventions can broadly be organised around ideal-typical transition phases (emergence, diffusion, reconfiguration and phase-out). Accordingly, it is useful to distinguish between interventions for:

- the emergence of innovations, which include strengthening commitments to distributed experimentation with alternatives (e.g. support for piloting, R&D and demonstration, developing knowledge infrastructures, mobilising 'coalitions of the willing');
- the diffusion and mainstreaming of innovations, by investing in material infrastructures and acting on selection environments (through new standards, financial support for innovation commercialization, support to long-term investments, arbitration between established and emerging interests, as well as more generic pricing mechanisms such as carbon pricing); and

- the reconfiguration and phase-out of undesirable systems, which may include regulatory bans, the gradual withdrawal of subsidies for related activities, blanket financial instruments signaling a preference for sustainable options, and interventions targeted at breaking up dependencies and sources of resistance, e.g. through forms of compensation and re-skilling.

Lastly, attending to the societal and political feasibility transitions governance will involve different kinds of decision-makers, including "agents of change from business, civil society, and cities around the world" (Hajer et al. 2015:1658), and may require crafting more participatory ways of envisioning futures that can generate greater societal buy-in (Ferraro et al., 2015) and improve societal acceptability by focussing on legitimation strategies (Deephouse et al., 2017). While this is beyond the scope of this paper, we agree with calls for greater attention to the variety of actors and roles involved in transitions (Schot et al., 2016), namely the important role that cities may play in leading transitions (Hodson and Marvin, 2009; Pancost, 2016; Rosenzweig et al., 2010), as well as the trade-offs, messiness and other practical challenges of the politics of sustainability transitions (Cherp et al., 2018; Meadowcroft, 2011). These challenges add to the typical difficulties of crafting governance interventions that are also legitimate, accountable and effective. To make things worse, decision-makers often have to operate within functional silos, with incomplete knowledge, within existing sense-making frames (e.g. cost-benefit analysis, short-termism), and influenced by vested interests. This means that there is a need for simplicity and prioritisation when informing governance. Re-orienting more traditional policy arsenals (e.g. regulations, fiscal instruments) towards such long-term transformation priorities will also be necessary, and require political determination so that they can be more than a governance blip, but pave the way for positive lock-ins to more sustainable trajectories.

5 Conclusion

So, model-based evaluations of STPs are valuable but present limited insights about their realisation, potentially missing crucial dimensions and tensions when supporting decision-making. Failing to look beyond familiar analytical and governance frames risks a path where too little is done too late. The main priority is to shift discussions towards understanding of the requirements for pathway *realisation*. This calls for different kinds of knowledge to explore real-world constraints and requirements of transitions. It is important to orient the evaluation of transitions potentials towards the identification of *feasible* options, pathways and strategies, and the recognition of transformation opportunities at and across multiple levels (beyond top-down steering logics).

In line with others before us, we have here argued for involving a broader base of social science and historically-informed views in thinking about sustainable futures. To do so, we have focussed specifically on complementing model-based knowledge with evaluation derived from socio-technical knowledge – a significant but by no means definitive step towards expanding the knowledge base. We have suggested that there is considerable scope for structured exploration of pathways feasibility. This has supported an engagement with STPs as multi-faceted objects that can be interpreted as: *representations* of transitions, transitions *potentials*, *conditions* for the realisation of transitions, with implications for analysis and governance in support of related processes.

The resulting evaluation frame, rather than seeking methodological synthesis and robustness in spite of fundamental ontological divides, supports the selective identification of prospective tensions and salient challenges. This has allowed us to generate specific prescriptions about STPs, what they entail, how they can be approached, and the relevance of mobilising a plurality of forms of knowledge in governance and evaluation efforts. Focusing on feasibility evaluation enables to more explicitly identify the main transitions *challenges* and associated *choices*, and so move from problem-based to solutions-oriented evaluation agendas that engage with the requirements of systemic change and their practical implications (Kowarsch et al., 2017). Recognising this may lead to new forms of participation towards a more dialogic relationship between science and society (Bai et al., 2015). The proposed approach offers specific entry points for engaging with the real-world constraints at play in transitions, and so clarifies the horizon of deliberate and emergent governance strategies that can be expanded so as to move closer towards realising transitions potentials.

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