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Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: Bridging computer models and the multi-level perspective in UK electricity generation (2010–2050)

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ABSTRACT

Social acceptance and political feasibility are important issues in low-carbon transitions. Since computer models struggle to address these issues, the paper advances socio-technical scenarios as a novel methodological tool. Contributing to recent dialogue approaches, we develop an eight-step methodological procedure that produces socio-technical scenarios through various interactions between the multi-level perspective and computer models. As a specific contribution, we propose 'transition bottlenecks' as a methodological aid to mediate dialogue between qualitative MLP-based analysis of *contemporary* dynamics and quantitative, model-generated *future* pathways. The transition bottlenecks also guide the articulation of socio-technical storylines that suggest how the social acceptance and political feasibility of particular low-carbon innovations can be improved through social interactions and endogenous changes in discourses, preferences, support coalitions and policies. Drawing on results from the 3-year PATHWAYS project, we demonstrate these contributions for the UK electricity system, developing two low-carbon transition pathways to 2050 commensurate with the 2 °C target, one based on technological substitution (enacted by incumbent actors), and one based on broader system transformation (enacted by new entrants).

1. Introduction

Computer models are powerful tools to explore low-carbon transition pathways that have various strengths, e.g. an ability to combine scientific, engineering and economic information, capacity to make aggregate projections, and an ability to simulate different mitigation pathways and policy scenarios. Computer models are therefore widely used, e.g. by the Intergovernmental Panel on Climate Change. Like any tool, however, computer models also have limitations (Ackerman et al., 2009; McDowall and Geels, 2017; Stern, 2016). Some of these limitations are due to the simplifying assumptions in bottom-up models (with detailed technical information) and integrated assessment models, which abstract away from real-world complexities of low-carbon transitions, focusing instead on quantifiable techno-economic variables.

Methodological reviews of dozens of low-carbon model-based scenarios have stimulated discussion of these limitations (Hughes and Strachan, 2010; Loftus et al., 2015; Winskel et al., 2014; Wiseman et al., 2013). Table 1 summarises the main limitations under three categories, supporting them with quotes from recent articles. The first limitation is that model-based scenarios pay limited attention to the actors, organizations and activities that ultimately bring about transitions. The second limitation is that model-based scenarios pay little attention to social acceptance, political feasibility, and institutional change. The third limitation is that model-based scenarios represent transition pathways as smooth diffusion curves, which policy-makers can steer from an outside position. This technocratic, expert-based view on policymaking ignores the fact that policymakers are embedded within systems and are influenced by other actors.

The three limitations also have increasing real-world relevance for low-carbon transitions. The UK electricity transition, for instance, which is the empirical focus of this paper, is experiencing implementation problems with regard to onshore wind, biomass, CCS and nuclear power (further discussed in Section 4). A better understanding of agency, social acceptance, and political feasibility of low-carbon transitions is therefore rapidly gaining importance, as the Paris agreement shifted the climate change debate towards real-world implementation.

In response to the limitations, scholars have suggested that quantitative models should be combined with qualitative storylines (Fortes et al., 2015; Foxon, 2013; Foxon et al., 2010; Geels et al., 2016a;

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Table 1
Three limitations of model-based low-carbon scenarios, based on a summary of recent literature.

Limitation	Illustrative quotes
1) Lack of actors and agency	"Actor-based approaches are rare in low carbon scenarios. Thus the low carbon scenario literature is rich in qualitative and quantitative descriptions of possible future low carbon systems, but much less rich in scenarios which connect such possible outcomes to the near and mid-term decisions by specific system actors, which would be necessary to bring these outcomes about" (Hughes, 2013:692). "Most UK scenario work has focused on the rates of adoption of low-carbon technologies needed and the additional energy system costs involved, with relatively little discussion of the motivations of the different actors involved, the interactions between them and the choices and actions needed to get from here to there" (Foxon, 2013:10). "More abstracted, quantified and output-oriented approaches tend to capture a high degree of complexity in terms of input factors, interdependencies and outputs, enabling systematic exploration of techno-economic interactions and trade-offs, but may neglect the processes, organizations, institutions and behaviours involved" (Winskel et al., 2014:101).
2) Limited attention for social acceptance and political feasibility	"The plethora of low-carbon scenarios, roadmaps and pathways developed in recent years by academia, businesses, governmental agencies and NGOs do not have a remote chance of becoming reality without conducive political and institutional conditions" (Nilsson et al., 2011:1127). "On the mitigation side, the range of carbon prices simulated in the literature is largely disjointed from the analysis of the institutional and social changes that would need to accompany any transition to a low-carbon world" (Scrieciu et al., 2013:160). "Peer-reviewed, transparently documented models (…) still have difficulty in capturing softer and subtler aspects (…) such as organizational and institutional changes needed to deliver a wanted transition, even if these elements are important for decision makers to envision and manage this transition" (Trutnevyte et al., 2014: 27). "The MARKAL model can envisage new technical configurations for the energy system but questions about the political feasibility of achieving such changes, and the institutional arrangements and political strategies necessary for this, are unaddressed" (Taylor et al., 2014:38). "As the question of how – rather than if – to implement a new energy system currently emerges, scenarios will have to find answers to how societal acceptance and political feasibility can be integrated within their methodology" (Schubert et al., 2015:53).
3) Representation of transition process and role of policymakers	"There is a strong tendency within scenario studies to treat policy as external to the analysis. (…) However, on reflection it is clear that policy (…) takes place within a societal context, and within the context of technologies and technological practices" (Hughes and Strachan, 2010:6064). "(…) the need to secure and sustain broad social and political support is the greatest obstacle to taking the actions needed to drive a rapid and effective transition to a post-carbon economy. While many strategies acknowledge this, the analysis revealed a lack of detailed steps for achieving broad social and political support and for driving transformational social change. This frequently reflects an implicit assumption of a rational policy-making process in which the objective merits of the strategy provide a sufficient basis for driving change" (Wiseman et al., 2013:88). "In giving the image of a clear, technology-based pathway, the model also provides some sense of control over the structure and evolution of the energy system. As such, it facilitates the (perhaps tacit) belief that it is possible to 'plan' an explicitly 'optimal' (in cost terms) transition to a low-carbon energy system" (Taylor et al., 2014:38).

Trutnevyte et al., 2014; Turnheim et al., 2015). McDowall (2014) distinguished three ways for such combinations. The first way is that qualitative scenarios describe broad and exogenous future trends in politics (e.g. international cooperation or fragmentation), culture (e.g. do consumerist or environmentalist values dominate), or economics (e.g. high/low economic growth), which are then translated into quantitative models inputs. This approach, which often creates scenarios based on a 2 × 2 matrix, was advocated, for instance, in the IPCC Special Report on Emission Scenarios (Nakicenovic et al., 2000). Qualitative context scenarios thus remain relatively *exogenous* to the models in this approach. These trend-based scenarios may appear circular and tautological (Hughes and Strachan, 2010), because it is hardly surprising that climate change targets are likely to be met in future scenarios with environmentalist values, international cooperation and high growth.

The second approach is the detailed quantification of narrative transition scenarios, to ensure that they are technically feasible and consistent (Auvinen et al., 2015; Fortes et al., 2015). This approach may be useful in participatory settings, where stakeholders first articulate visions of low-carbon societies and qualitative storylines about how to get there, which are then subsequently translated into model parameters. Quantitative results of transition pathways are then communicated back to stakeholders, leading to adjustments in the storylines (Trutnevyte et al., 2014). This approach may facilitate learning by participants, but assumes that the models are unproblematic tools for feasibility checks.

The third approach is a dialogue between models and qualitative storylines to compare and contrast insights from both methods (Foxon, 2013; Geels et al., 2016a; McDowall, 2014; Turnheim et al., 2015). So, the methods are not integrated, but used recursively. This approach accepts that both methods have strengths and weaknesses and may usefully highlight different dimensions of low-carbon transition pathways. Instead of aiming for single prescriptive answers, this approach acknowledges non-linearities and branching points in transitions, and offers policy advice in terms of possibilities and risks.

We aim to contribute to this third approach by developing and illustrating a methodological procedure for dialogue between computer models and the Multi-Level Perspective (MLP), which result in Socio-Technical Scenarios (STSc) that develop plausible storylines for model-generated transition pathways. This procedure consists of eight iterative steps and uses *transition bottlenecks* as a novel methodological aid to focus the dialogue between models and the MLP, which is a widely used social science approach that understands transition pathways as enacted by social groups at niche, regime and landscape levels (Geels, 2002a; Geels and Schot, 2007). Focusing on concrete innovations, these transition bottlenecks clarify tensions between MLP analyses (which focus on path dependencies and *recent* developments) and goal-oriented model-generated scenarios (which focus on desired *future* diffusion trajectories needed to reach the target of 2 °C climate change). Dialogue between models and MLP helps identify these bottlenecks, which then become the focus for STSc that aim to articulate ways for overcoming them.

These STSc will focus on changes in policies and actor strategies that may improve social acceptance and political feasibility of low-carbon innovations, while also touching on techno-economic and infrastructural challenges (Loftus et al., 2015). These STSc aim to increase the reflexivity of modelers (and policymakers) about the non-economic considerations that need to be addressed in low-carbon transitions.

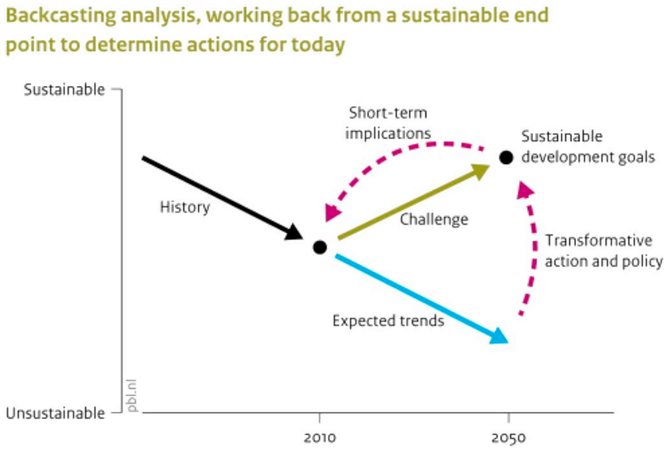

Fig. 1. Transitions from historical trajectories towards future goals (Van Vuuren et al., 2015: 305).

Modelers already commonly make off-model interpretations of modelling outputs, noting for instance that 'X-level of installed capacity would require stronger policies to boost deployment', or 'Y-level of demand reduction would imply considerable lifestyle change'.[1] But they usually do not explain the processes that create favorable contexts for radically new policies, lifestyle change or social acceptance of low-carbon innovations. STSc aim to 'open this black box' by articulating the associated socio-political processes and mechanisms.

The paper is structured as follows. Section 2 elaborates the socio-technical scenario methodology and our eight-step methodological procedure. Section 3 presents quantitative model-based scenarios for the future of UK electricity generation (2010–2050). Section 4 makes an MLP-analysis of recent developments (2000–2015). Section 5 identifies tensions and transition bottlenecks between modelling outcomes and MLP-analyses. Section 6 develops two socio-technical scenarios (A and B) indicating how transition bottlenecks can be overcome. Section 7 discusses policy implications and reflects on the scenarios and bridging methodology. Section 8 concludes.

2. Socio-technical scenarios (STSc)

2.1. Origin and development of STSc methodology

The idea of socio-technical scenarios (STSc) was developed in the early 2000s (Elzen et al., 2004; Geels, 2002b; Hofman et al., 2004) in response to limitations of model-based scenarios, which were seen to focus too much on technologies and too little on wider socio-technical systems, and to "lack attention for actors, their decisions, interactions and learning processes, and the way these shape twisting transition paths" (Hofman et al., 2004: 349). Based on the emergent understanding of socio-technical transitions (particularly the MLP), these early STSc advanced two points: 1) they addressed the co-evolution of multiple dimensions (both techno-economic and socio-political), 2) instead of deterministically relying on external forces or macro-trends, they focused on the *endogenous enactment logic*, describing how "attitudes and behaviour of actors change in the course of new developments. (…) Thus, a transition path does not come out of the blue but it becomes clear *why* it develops" (Hofman and Elzen, 2010:656).

A challenge for such actor-based scenarios is that there *many degrees of freedom*: there are so many variables that anything can happen. STSc therefore need to somehow introduce *constraints* that guide the development of qualitative storylines. Early STSc (Elzen et al., 2004; Hofman et al., 2004) used the MLP to provide a conceptual logic for the scenarios, organized in terms of niche-innovations (with particular attention for learning processes, social networks and shared expectations) struggling against existing regimes (incumbent actors, institutionalized structures). Subsequent STSc used both the MLP and typology of transition pathways (Geels and Schot, 2007) to structure storylines (Hofman and Elzen, 2010; Van Bree et al., 2010; Verbong and Geels, 2010). Marletto (2014) further added a new graphical tool (the socio-technical map), which he used to plot different combinations of social coalitions and socio-technical solutions.

These early STSc were qualitative and used the MLP to speculate about possible future pathways in electricity and transport systems. More recently, scholars have developed STSc in which actor-based storylines are (partially) constrained by quantitative models (Auvinen et al., 2015; Foxon, 2013; McDowall, 2014).

2.2. Contribution to STSc methodology

This paper aims to contribute to this research stream that bridges computer models and the MLP. In particular, we aim to develop and illustrate a methodological procedure to facilitate iterative dialogue between both approaches that results in socio-technical scenarios that are normative and model-oriented, i.e. they aim to design plausible actor-based transition pathways for the quantitative model-based scenarios that are assumed to reach the target of 2 °C climate change. So, we aim for a *socio-technical qualification of model-based scenarios*. This differs from a strategy that first develops storylines and then enters dialogue with model-based scenarios (Foxon, 2013; McDowall, 2014). Our design-oriented approach is timely because real-world transitions are encountering problems with political feasibility and social acceptance. These problems create *transition bottlenecks*, which we use as methodological aid to focus socio-technical scenarios.

Fig. 1 further clarifies the rationale behind our methodological approach, which was developed and applied in the EU-funded PATHWAYS project (http://www.pathways-project.eu/).[2] It schematically portrays the relation between long-term *future* sustainability goals (like 2 °C) and *present* trajectories, characterized by historical path dependencies. Normative model-based scenarios start from future goals and quantitatively design backwards what possible pathways could lead from the present to these goals (the green line in Fig. 1). MLP-based studies tend to analyze niche and regime trajectories in the recent past (last 10–15 years) and present (the black line in Fig. 1), but often do not address long-term futures. There is analytical tension between the two approaches: the model-based scenarios identify transition pathways that *should* happen to reach the targets; MLP-based analyses of empirical domains often shows that the transition is not yet happening (at sufficient speed), because regimes are locked-in and niche-innovations have insufficient momentum. For concrete innovations (like onshore wind or nuclear power), we represent these analytical tensions as 'transition bottlenecks'. Our socio-technical scenarios aim to create bridges between the MLP-based analyses of *present* trajectories and model-based transition pathways towards *future* goals. So, instead of criticizing computer models for unrealistic assumptions, we aim to use our socio-technical insights constructively and try to develop plausible storylines in which innovation trajectories overcome the transition bottlenecks. Our storylines thus aim to develop actor-based pathways for 'bending the curve' towards the model-based scenarios (represented with upward dotted purple line in Fig. 1).

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[1] We want to thank one of the reviewers for this suggestion.

[2] The PATHWAYS project (2013–2016) investigated low-carbon transitions from three analytical angles: computer models, socio-technical transition theory (MLP), and action research of on-the-ground projects. This article focuses on dialogue between the first two approaches.

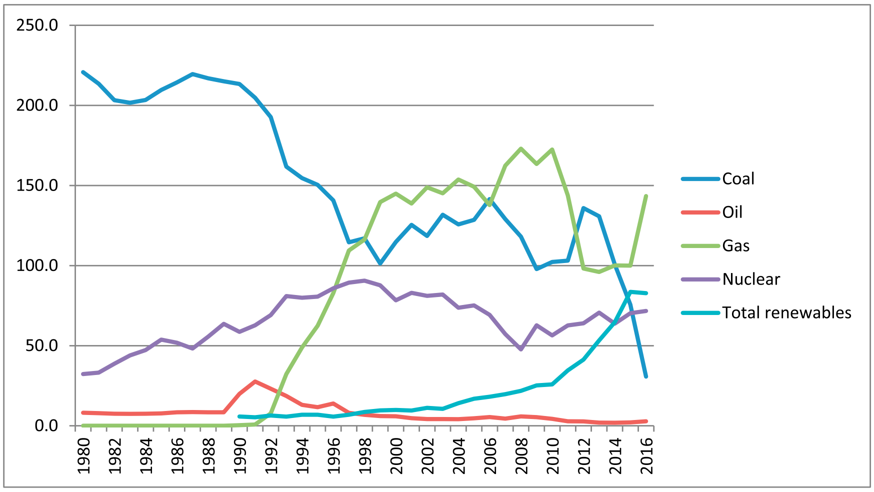

Fig. 2. UK electricity generation by fuel type, 1990–2016, in TWh (data from Digest of UK Energy Statistics, https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes).

2.3. Methodological procedure and operational steps

Building on earlier work that emphasizes the importance of iterative steps and dialogue (Foxon, 2013; Hughes, 2013; McDowall, 2014), our methodological procedure consists of eight steps with several interactions between models and socio-technical transitions theory. Model results play a central role in the dialogue procedure: early steps lead to adjustment in model inputs and parameters, based on socio-technical inputs and feedbacks; later steps take model results as given and use socio-technical insights to develop qualitative storylines about the societal embedding of technologies. The text below articulates the steps and briefly illustrates the empirical choices for the first steps. The later steps are further discussed in separate sections.

Step 1 consists of the choice of systems and countries. For climate change, the PATHWAYS project focuses on electricity systems (UK, Germany), mobility systems (Netherlands, UK), heat/buildings (Sweden, Germany, UK), and agro-food systems (Netherlands, Hungary). This paper focuses on low-carbon transitions in UK electricity generation, which is a suitable case because a low-carbon transition has begun to unfold. Renewable electricity has increased to 24.4% of power generation in 2016 (Fig. 2). Coal use has declined to 9.3% in 2016. CO_2 emissions from electricity production decreased by 55% between 2008 and 2016 (CCC, 2017). Fig. 2 demonstrates the twists-and-turns in the last thirty-six years. Similar non-linear dynamics should therefore be expected for future decades.

Step 2 develop a baseline scenario for the UK system, named ‘Neutral pathway’, which is assumed to reach 80% reduction in greenhouse gas emissions in 2050 compared to 1990 levels (which we take as commensurate with 2 °C climate change). To develop this scenario, we used three existing models: the Integrated Assessment Models IMAGE and WITCH, which have a global perspective on energy, and the detailed sectoral model Enertile.[3] The IAMs provided boundary conditions for demand and global developments. First, electricity demand was provided by IMAGE, taking into account GDP, population-based demand growth, efficiency measures, and the diffusion of electric vehicles and heat pumps. These data were then broken down from the spatial resolution of IMAGE (in which ‘Western Europe’ is the region containing UK) to national demand in Enertile. Second, IMAGE and WITCH provided emission caps: the global models indicated the amount of European emissions that are in line with the 2 °C target, which was then also applied in Enertile. So, the emissions from the sectoral European model cannot exceed the emissions provided by the IAMs. Third, fuel prices and biomass availability for Europe are taken from the IAMs, because both result from global trade. The European biomass amount is distributed to the countries, taking into account the availability of hydro resources: the more flexible hydro resources a country has, the less biomass it is attributed, in an effort to distribute flexibility as evenly as possible.

Within these boundary conditions, we used Enertile, a detailed power-system model with country-specific resolution and data, to develop a UK baseline scenario, which has strong climate policies, modelled as a high CO_2-price or carbon cap. The technical assumptions were chosen to be ‘middle-of-the-road’: costs of all technologies develop at an average speed, and no further settings are defined for promoting some technologies over others. This model configuration thus represents a purely techno-economic solution: the model picks the technologies that it considers most cost-efficient. The results of the ‘Neutral pathway’ are shown in Fig. 3 and include the following.

- No new investments occur in nuclear power, due to its high costs.
- The capacity of gas power plants reduces quickly, as its task moves towards peak capacity provision.
- Biomass and offshore wind remain at the 2020 level planned in the UK renewable energy action plan.
- The most dramatic change is the large deployment of onshore wind, which increases to 326 TWh in 2050, corresponding to 70% of the UK's electricity demand. This huge increase relates to the excellent wind conditions on the British Isles, which, in the context of increasing carbon prices, makes onshore wind highly competitive. Without further intervention, the model therefore prioritizes onshore sites over offshore locations, as the higher wind speeds at sea do not outweigh the larger investments.

These results are rather extreme, as the model fully uses techno-economic potentials without consideration of moderating factors, such as social or political acceptance. The model does, however, include costs for various integration measures, such as electricity grid expansions and back-up capacities.

To enhance the understanding of actors, social acceptance and political feasibility, step 3 is a conceptual move towards a socio-technical understanding of transition pathways, based on ‘endogenous enactment’ (Hofman and Elzen, 2010; Geels et al., 2016b). Transition pathways thus involve not just technologies diffusing in markets, but also social groups (with shared beliefs, interests, capabilities) acting in the context of institutions. Combining aspects from existing socio-technical transition pathway typologies (Geels and Schot, 2007; Smith et al.,

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[3] For documentation, please see: www.enertile.eu.

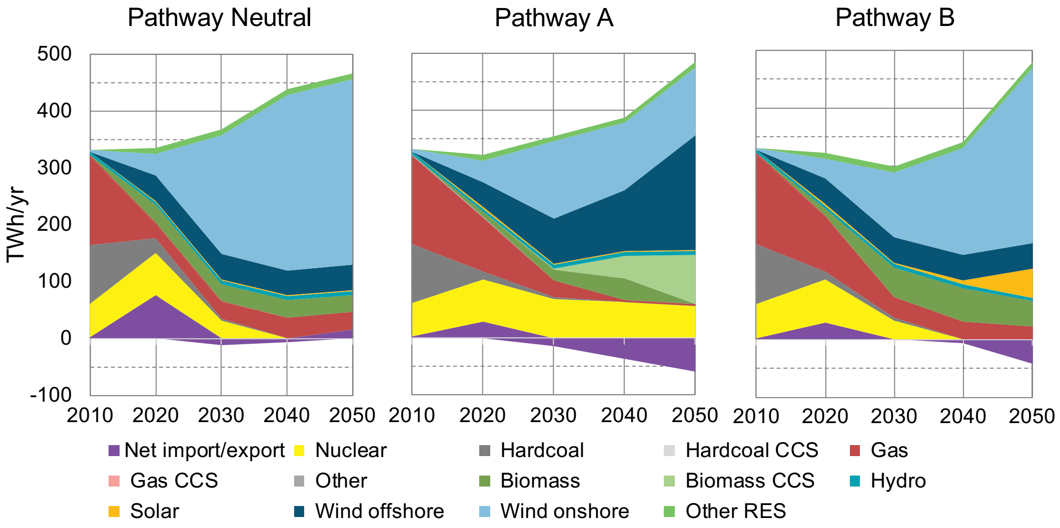

Fig. 3. Model-based scenarios of annual UK power generation, 2010–2050, in TWh.

Table 2
Ideal-type transition pathways.

	Pathway A: Technical component substitution	Pathway B: Broader system transformation
Change in system performance	Substantial	Substantial
Lead actors	Incumbent actors (often industry and policy actors)	New entrants, including new firms, social movements, civil society actors.
Depth of change	Radical technical change (substitution), but leaving other system elements mostly intact	Transformative change in entire systems (system architectures, technologies, practices)
Scope of change	Technical components and markets	Multi-dimensional change (markets, technology, organizational, policy, social, cultural, consumer practices)

2005), we distinguish two transition pathways (A and B), which differ in terms of lead actors, depth of change and scope of change (Table 2).

Step 4 aims to implement Pathways A and B into the models, by adjusting parameters and linking parameters in all involved models to fit with the underlying assumptions. The process and the resulting model-generated A and B scenarios are described further in Section 3.

Step 5 was a qualitative MLP-based analysis of the main innovations in the model-based scenarios. For niche-innovations, we analyzed the endogenous momentum of onshore wind, offshore wind, bio-energy, solar-PV and smart meters. Expanding on the niche-innovation literature (Schot and Geels, 2008), we assessed three dimensions of endogenous momentum in the last 5–10 years: a) techno-economic (market shares, investments, price/performance improvements), b) socio-cognitive (social network size, beliefs, strategies, expectations), c) governance (degree and continuity of policy support). For regime technologies, we analyzed trajectories of nuclear power, gas, coal and CCS in the last 5–10 years, focusing on the same three dimensions (techno-economic, socio-cognitive, governance), assessing degrees of regime stability and tensions. This MLP-based analysis of specific innovations provided a deeper understanding of the drivers and barriers behind the quantitative trends in Fig. 2. The analyses also showed that the political momentum for low-carbon transitions was weakening and that several innovations faced social acceptance problems (see below).

Step 6 confronted the quantitative *future* scenarios from step 4 with the qualitative assessments of *contemporary* developments in step 5, leading to another dialogue between modelers and transition researchers about the feasibility of some of the model-generated pathways and the identification of 'transition bottlenecks' with concrete innovations (based on tensions between MLP-analyses and model-based scenarios).

Step 7 developed qualitative socio-technical scenarios aimed at articulating plausible actor-based storylines for the quantitative pathways produced in step 4. These storylines were guided by the following considerations:

- Start with ongoing trajectories in the present, based on the MLP-analysis from step 5 (momentum of niche-innovations, and lock-in of existing regimes). 'Bending the curve' can therefore not start immediately, but requires preparatory processes.
- Explain how transition bottlenecks (identified in step 6) can be overcome.
- Orient storylines towards the normative goals and quantitative pathways from step 4. Offer MLP-based explanations for how the goals can be reached.
- Use Pathway A and B logic to differentiate storylines in terms of actors, depth and scope of system change.

Step 8 discussed policy implications from the STSc and the model-based scenarios.

The remainder of this paper aims to illustrate parts of this STSc methodology for bridging computer models and transition theory for UK electricity generation. Space constraints prevent systematic discussion of each step. We therefore decided to focus on the more novel, later steps, particularly step 4, 5, 6, 7, and 8, which are addressed in subsequent sections.

3. Quantitative model-based scenarios for UK electricity generation

Step 4 implements the assumptions of two socio-technical transition pathways (A and B) in the models (both Enertile and IAMs) to produce adjusted scenarios that differ from the 'neutral pathway'. For Pathway A, this implementation led to the following adjustments in parameter settings for the UK electricity system: a) we assume that incumbent actors have a preference for large-scale, centralized options like nuclear power. The expansion of nuclear power had to be defined exogenously,

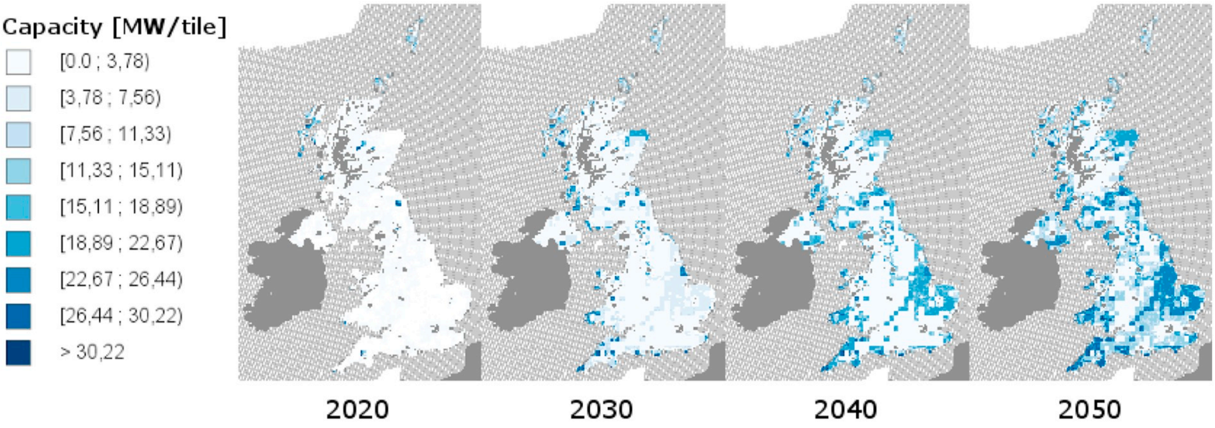

Fig. 4. Spatial distribution of onshore wind turbines in Pathway B.

because the model, relying on economic optimization, does not built nuclear power plants due to their high specific investments, as can be observed in Pathway Neutral. We assume that three large new nuclear plants are built, replacing plants that reach their end-of-life and slightly expand capacity. b) CCS is favored in Pathway A through optimistic cost assumptions. In the UK, this mostly takes the form of biomass-CCS.[4] c) We also assume that incumbent actors in Pathway A prefer offshore wind, because of large-scale operational characteristics and capital structures. This is realized in the model via subsidies, which reduce offshore wind costs to the levels of its onshore counterpart. d) Compared to the Pathway Neutral setting, we also lowered the spatial potential for wind onshore sites, which represents lower social acceptance.

For Pathway B, we made the following adjustments. a) Electricity demand decreases until 2030 because consumers participate more in energy efficiency measures (from IMAGE model). After 2030, electricity demand increases, as more electric vehicles were deployed and more houses use electric heat pumps, compared to Pathway A. b) We assume that nuclear power plants are phased-out at the end of their lifetime, and are not replaced because of social acceptance problems. c) It is also assumed that CCS is not implemented in Pathway B, due to lack of acceptance. d) Solar-PV is subsidized in two ways. Firstly, a lowered interest rate of 1% reflects a greater tendency of consumers to buy rooftop PV systems. Secondly, the spatial potential for free-field sites was increased compared to Pathway Neutral, representing for example a higher willingness of public bodies to provide building permits.

Based on these assumptions and parameter changes, the models were run again to produce two scenarios for low-carbon electricity transition Pathways A and B. The resulting scenarios were quite different to the initial Pathway Neutral in terms of specific innovation trajectories. The quantitative model results are shown in Fig. 3, which represents all three transition pathways in terms of actual power generation (design details can be found at http://www.pathways-project.eu/).

Compared to the ‘neutral’ scenario, Pathway A and B both (partially) substitute the enormous onshore wind generation by other options. There is more offshore wind, nuclear power and ‘big biomass’-with-CCS combustion in Pathway A, compared to the neutral scenario; and there is more solar-PV and dedicated biomass in Pathway B, compared to the neutral scenario.

More specifically, in **Pathway A**, coal and gas-fired power plants are replaced mostly by large-scale renewable energy technologies (RETs). Coal-without-CCS is phased out by 2030. Coal-with-CCS does not diffuse in the UK, because after 2025 it cannot compete with cheaper RETs.[5] Gas-fired generation gradually declines and after 2030 only provides back-up capacity for wind. Onshore wind expands due to its high competitiveness in the context of an increasing carbon price, and offshore wind is subsidized to be at a comparable price level. After 2030, offshore wind expands faster because it is favored by big incumbents and because offshore wind becomes cheaper due to larger turbines and technological learning. By 2050, onshore and offshore wind generate 65% of UK's electricity demand. Wind expansion requires grid transformation, particularly long-distance transmission grids, offshore grids, and interconnectors to European countries. In the 2020s and 2030s, nuclear power manages a slightly higher utilization of existing plants, but in the long run capacity and generation declines, contributing about 12% of power generation in 2050. Bio-energy expands slowly until 2030 and then accelerates in the form of BECCS (Bio-Energy with Carbon Capture and Storage). CCS becomes competitive as BECCS because climate policy enables this option to gain two carbon credits per unit of power generation: one because biomass is a renewable energy source and one because CO_2 emissions are captured and stored. After 2030, expanded biomass adds flexibility to power-generation, thus alleviating intermittency problems. After 2030, the UK exports electricity in windy periods and often imports in times of calms.

In **Pathway B**, the role of wind onshore is smaller than in Pathway Neutral, but still very large. Onshore wind increases faster than in Pathway A throughout the whole scenario. It becomes the central pillar of UK electricity supply, generating 54% of electricity by 2040 and 63% by 2050. It is the most competitive RET, which in Pathway B also benefits from high social acceptance as new entrants (communities, farmers, cities) become increasingly involved. Initially, it is deployed in windy coastal areas, but increasingly also on inland sites (Fig. 4).

Offshore wind also increases, but less than in Pathway A (because incumbent actors are less dominant in Pathway B). Solar-PV increases only gradually to 2040 (because of high costs), but then diffuses rapidly to generate about 11% of power in 2050. Solar-PV becomes competitive, because the price of *additional* onshore wind increases as the best wind sites are taken by 2040. Until 2030, biomass utilization increases in the form of small-scale dedicated biomass plants. After 2030, biomass is additionally used to provide flexible back-up capacity for intermittent renewables. A similar task is carried out by gas turbines, which still account for 4.5% of power generation in 2050. As in Pathway A, unabated coal is phased out by 2030. Nuclear energy is phased out by not replacing decommissioned plants. After 2030, the UK starts exporting electricity to Europe.

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[4] On continental Europe, this setting leads to a substantial number of CCS coal and lignite power plants.

[5] However, in the rest of the continent, a substantial CCS capacity is constructed.

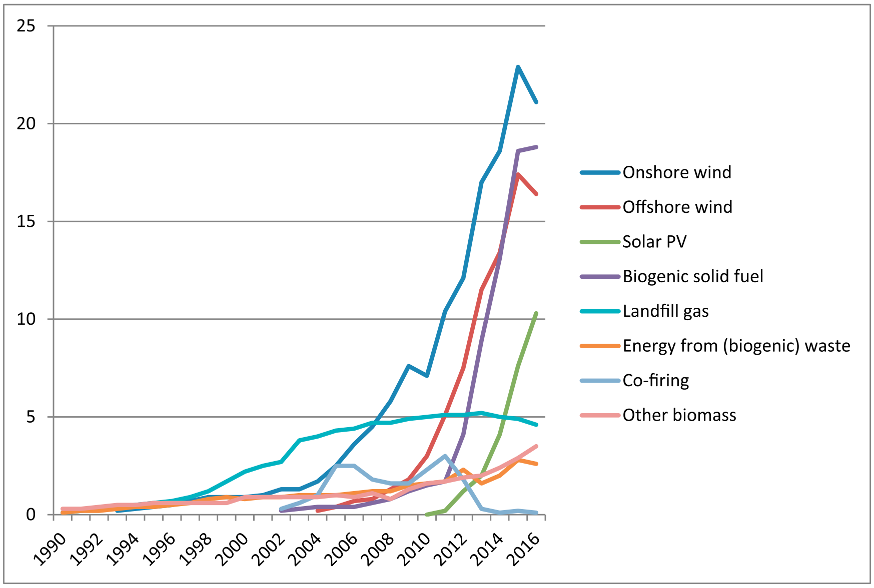

Fig. 5. UK power production from RETs, excluding hydro, in TWh, 1990–2016 (data from data from DUKES).

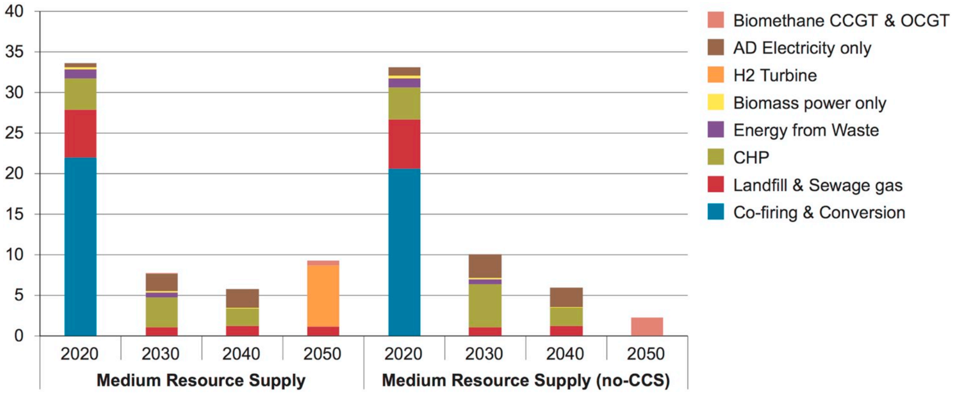

Fig. 6. Energy delivered from biomass use in power generation under medium feedstock availability scenario (DECC, 2012a: 44).

4. Socio-technical analysis of recent developments (2000–2015)

In step 5, we used the MLP to analyze socio-technical dynamics in niche-innovations and regime trajectories in the last 5–10 years (in-depth descriptions can be found in Geels et al., 2016b, and in the PATHWAYS reports on http://www.pathways-project.eu/).

Three large-scale niche-innovations (onshore wind, offshore wind, biomass) have diffused fastest in recent years (Fig. 5), because of government support and incumbent actor strategies (utilities, project developers).

For **onshore wind**, we diagnose that the momentum is decreasing, because of problems with social acceptance and political will. Because developers paid limited attention to stakeholder concerns (Ellis et al., 2009), wind farm projects encountered increasing local opposition, leading to decreasing approval rates in planning procedures from 73% in 2007 to 50% in 2012 (CCC, 2013). The public wind discourse became increasingly negative, because of concerns about subsidies, visual and landscape impacts, and the perceived invasion of the countryside by corporate interests (Kern et al., 2014). Although onshore wind is the cheapest RET, the newly elected (2015) Conservative government promised not to build new wind turbines after 2020 and has halted new subsidies. Techno-economic momentum is still substantial (because of projects in the pipeline), but decreasing because of socio-political problems and post-2020 uncertainties.

Offshore wind has high momentum. The UK is world leader and more projects are in the pipeline. Significant learning occurred during the 2000s, but some technical obstacles remain, especially with expansion into deeper, more hostile marine environments. Offshore wind is supported by a powerful network of actors from industry, government and NGOs, which advance enthusiastic visions for future expansion (Kern et al., 2014). In the two years since 2015, Contract for Difference (CfD) auctions led to price decreases of more than 50%, with recent auctions (September 2017) resulting in a lower than expected strike price (£57.50/MWh).

Bio-power consists in many forms: landfill gas, energy-from-waste, co-firing of biomass and coal, small-scale dedicated biomass plants, biomass conversion of coal plants. Policy support has been uneven and fluctuating, but the 2012 *UK Bioenergy Strategy* favored coal plant conversion by offering substantial subsidies to incumbent actors such as those operating Drax power station. The 2012 Biomass Strategy envisaged rapid bio-power expansion until 2020 (especially for conversion), followed by downscaling (Fig. 6), and re-direction of biomass use towards heat and transport (see Figs. 11 and 12 in DECC, 2012a), which are seen to have fewer decarbonization options.

This envisaged 'boom-and-bust' pattern created some uncertainty. Uncertainty also arose from a public controversy about the sustainability of imported biomass pellets. A 2012 report by the Royal Society for the Protection of Birds, Friends of the Earth, and Greenpeace (titled '*Dirtier than coal? Why government plans to burn trees are bad news for the planet*') criticized DECC's assumptions for sustainability assessments, which ignored 'carbon debt' and indirect substitution emissions. The NGOs therefore campaigned against industrial-scale 'Big Biomass', including via direct protests at the 2013 opening of a converted unit of the Drax coal-fired plant. In 2014, the government admitted mistakes in calculating carbon savings from large-scale biomass (DECC, 2014), and said that biomass sustainability policies would be adjusted. In 2015, the newly elected Conservative government slashed financial support schemes for RETs, including biomass, which created uncertainty. Subsequently, Drax won a CfD auction for a third biomass unit, but this was met with EU-level contestation regarding state aid. In December 2016 the European Commission ruled in favor of Drax, allowing its third unit to convert to wood pellets. This was met by NGO protests, indicating that sustainability concerns are still a potential risk for the socio-political legitimacy of bio-power.

The diffusion of **solar-PV** was low until 2010, but then accelerated to produce 10.3 TWh in 2016 (Fig. 5). Solar-PV diffusion was faster than was anticipated, and the government tried to catch up with a *Solar PV Strategy Part 1* (in 2013) and a *Solar PV Strategy Part 2* (in 2014). Solar-PV diffused rapidly, because of a feed-in-tariff (introduced in 2010), decreasing PV-module costs, and public enthusiasm (Smith et al., 2013). Compared to other RETs, solar-PV is still relatively expensive, however. Although module costs are expected to decrease further, balance-of-system costs and wider system (grid-related) costs may decline less rapidly (Candelise et al., 2013). Solar-PV is supported by social networks (technology suppliers, installers, famers, consumers, NGOs) and a positive public discourse. Advocates advance the vision of decentralized energy generation with active 'prosumers'. In 2015, the newly elected Conservative government slashed feed-in tariffs, which has slowed implementation and caused problems for UK installation firms.

The UK **electricity *generation* regime** is under-pinned by a stable alliance of policymakers and utilities, producing a policy style that can be characterized as 'working with incumbents' (Geels et al., 2016b). In the mid-2000s, climate change became an important consideration, besides energy security and affordability. The 2008 Climate Change Act was a radical policy, aimed at 80% GHG-reduction by 2050. The subsequent translation into more specific targets (30% renewable electricity by 2020) and policy plans (2011 Carbon Plan, 2012 Energy Bill, 2013 Electricity Market Reform) created *policy* delivery momentum. *Political* commitment weakened, however, since the financial-economic crisis (Geels et al., 2016b). Public attention to climate change diminished, leading politicians to realize that they were ahead of their voters. Concerns about energy prices, competitiveness and jobs increased. In 2013, rising energy bills escalated into a full-scale political row, which led the government to scrap, delay or water down various green policies. The government also refused to commit to long-term renewable electricity targets beyond 2020. In July 2015, these political counter-trends led the newly elected Conservative to 're-set' energy policy and slash support for onshore wind, solar-PV (especially 1–5 MW installations), and biomass plants.

With regard to regime technologies, developments can be summarized as follows:

- In 2008, a government White Paper announced intentions to stimulate a 'nuclear renaissance' (BERR, 2008), with Chancellor Gordon Brown using a speech (July 2008) to call for 8 new nuclear plants by 2025. A 2011 National Policy Statement elaborated this with a proposal for 16GW new capacity (DECC, 2011). Subsequently, the opening of the first new 3.2 GW plant (Hinkley C) has been delayed repeatedly from 2018 to 2025, because of problems in securing finance for the £18 billion investment. A deal was finally agreed in September 2016, but immediately criticized for high costs: a guaranteed electricity price of £92.50/MWh (twice the current retail price) for 35 years. Subsequent price decreases in RETs (especially offshore wind) have reignited these cost criticisms. Negotiations for two more nuclear plants are under way, but not yet concluded.
- In 2012, the government's *Gas Generation Strategy* (DECC, 2012b: 14) announced that it saw the "need for investment in up to 26 GW of new gas capacity by 2030", which would amount to about 30 new gas-fired power stations. In subsequent years, the government also offered attractive incentives for the exploration and development of shale gas, while enabling greater flexibility in the planning system.
- Coal use increased substantially between 2009 and 2012 (Fig. 2), because of cheap American coal. Subsequently, coal use decreased as several old coal-fired power plants closed because of the European LCPD-Directive and others (partially) converted to biomass (Drax, Ironbridge). More plants are scheduled to close by 2023 under the Industrial Emissions Directive. In 2009 the Department for Energy and Climate Change announced that new coal-fired power plants could not be built without CCS-facilities (DECC, 2009). Since then, however, CCS has progressed very slowly, and in 2015, the Conservative government scrapped a £1 billion subsidy scheme for CCS-demonstration projects. The new government also committed to phasing out unabated coal by 2025 *if* feasible alternatives are then available.

The **electricity *network* regime** has seen incremental changes in *transmission* networks, such as grid extensions to connect wind-farms, new grid connections between Scotland (which generates most wind power) and England (which uses most power), *offshore* grid construction, and the building of *inter-connectors* linking the UK to other countries (to facilitate imports). These changes do not substantially change transmission architectures. Deeper changes to address the intermittency of RETs (via storage, back-up capacity) and bi-directional flows from distributed generation (via smart grids, monitoring and controls) have been limited. Distribution networks, in particular, are characterized by high inertia (Bolton and Foxon, 2015). Despite various policies aimed at stimulating R&D and innovation, Distribution Network Operators (DNOs) appear reluctant to engage with radical innovations, because they have lost technical capabilities, have limited future planning skills, and are constrained by business models focused on efficiency and cost reduction (Lockwood, 2016).

The network regime has been described as 'locked-in' (Bolton and Foxon, 2015; Lockwood, 2016), because it is characterized by a limited set of actors (the system operator (National Grid), Transmission Network Operators (TNOs), the regulator Ofgem, and DNOs), who meet regularly to discuss future plans and share mind-sets based on engineering and economic outlooks (Lockwood, 2016). There have been complaints from policymakers[6] (who worry that electricity networks need to be adjusted quicker) and local communities (who protest against new overhead cables), but these are not (yet) causing major regime tensions. Ofgem is relatively sheltered from such criticisms, because it was set up as an independent regulator (Lockwood, 2016).

5. Transition bottlenecks

For several innovations, step 6 identified tensions between the model-based scenarios from step 4 and socio-technical analyses from step 5. Given the paper's focus, Table 3 summarizes the main socio-political bottlenecks for six innovations for Pathway A and B.

6. Scenario storylines about transition bottlenecks

In step 7 we wrote two scenarios to make socio-technical sense of the two model outcomes for Pathway A and B. Rather than presenting the scenarios in full (see http://www.pathways-project.eu/), we here

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[6] In October 2012, the Labour Party announced that Ofgem was no longer 'fit for purpose' and that it would scrap the organization if it came to power. In July 2013, Members of the Parliamentary Energy and Climate Change Committee criticized Ofgem for having a "relatively light touch approach" of energy companies.

Table 3
'Socio-political bottlenecks' between model-based future scenarios and socio-technical analyses of current developments.

Innovation	Pathway A	Pathway B
1. Onshore wind	*Model scenario*: Rapid expansion after 2020. *Bottlenecks*: This conflicts with social acceptance problems, downscaled political support and post-2020 subsidy ban.c	*Model scenario*: Massive expansion after 2020. *Bottlenecks*: Same as Pathway A, but more problematic because: 1) extent of deployment is higher; 2) current incumbent-led wind deployment is inconsistent with Pathway B specification.
2. Solar-PV	*Model scenario*: Little solar uptake in Pathway A *Bottleneck*: This conflicts with recent rapid solar-PV diffusion and price decreases.	*Model scenario*: Massive (though very late) solar uptake after 2040. *Bottleneck*: Late diffusion conflicts with recent rapid solar-PV diffusion and price decreases. Large diffusion conflicts with recent cuts in policy support, which decimated supply capacity.
3. Biomass	*Model scenario*: high amounts of bio-energy after 2030. *Bottlenecks*: High bio-energy assumptions are vulnerable to public acceptance problems with regard to the sustainability of imported wood pellets and broader concerns (e.g. land-use competition).	*Model scenario:* high amounts of bio-energy after 2020. *Bottlenecks*: Same as Pathway A, but even more problematic because of earlier deployment. Social acceptance may be higher if bio-energy is locally sourced and used in small-scale plants.
4. BECCS (bio- energy with CCS)	*Model scenario*: BECCS after 2030. *Bottlenecks*: At present, BECCS is only a concept and there is not much happening 'on-the-ground'. Since the CCS trajectory has halted, there are few innovation actors pushing for BECCS. Assumed future upscaling of bio-energy may face social acceptance problems.	No CCS in Pathway B (and no BECCS).
5. Nuclear	*Model scenario*: Nuclear power is somewhat increased in Pathway A, which requires building several new plants to replace those that are scheduled to retire by the mid-2020s. *Bottleneck*: The financing problems of Hinkley C create major investment uncertainties for further new plants.	No new nuclear in Pathway B.
6. Grid expansion	*Model scenario:* Transformation of transmission and distribution grids. *Bottlenecks*: This conflicts with current trajectories (particularly for distribution), which show high inertia and some local resistance to grid-projects.	*Model scenario*: Same as Pathway A, but more change because of growing importance of distributed generation. *Bottlenecks*: Same as Pathway A, but more problematic because more (smart) grid innovation needed.

present the storylines we developed to envisage how transition bottlenecks, described in Table 3, could be overcome in the coming decades in Pathway A and B.[7] The storylines are not predictions of what is *likely* to happen. Instead, they aim to show how social interactions, learning processes, debates, and controversies could change the beliefs, strategies and coalitions of relevant actors so that the socio-political feasibility of Pathway A and B, as generated by computer models, is improved.

In Pathway A, incumbent actors like utilities and government remain the dominant actors. The introduction of new policies (which incentivize incumbent firms to reorient) thus needs to be underpinned by business coalitions and pro-market discourses (like 'green growth' or ecological modernization) to create societal legitimacy. In Pathway B, new entrants (community groups, farmers, active consumers) engage in bottom-up mobilization, which is accompanied by cultural discourses about prosumers and low-carbon lifestyles that, in turn, create pressure on policymakers for more radical policies and a broader, more inclusive governance style (beyond large firms and technologies), leading to a more distributed generation logic. Stronger policies in both pathways require political U-turns to reverse the recent downscaling in technology-specific climate change strategies.

We now turn to the more specific storylines for different transition bottlenecks. Some aspects of the model outcomes were relatively easy to envisage through socio-technical sensitivities (e.g. offshore wind in Pathway A, which fits well with incumbent interests and ongoing developments) and are consequently less interesting to consider in light of the argument we wish to develop. Therefore, we focus here on the storylines that we developed to overcome the bottlenecks in onshore wind (for both pathways), biomass (for both pathways), solar-PV (towards the end of pathway B), nuclear (mainly for pathway A) and grid expansion (for both pathways). So, the discussion below does not provide comprehensive scenarios, but focuses on socio-political storylines for most of the bottlenecks.

6.1. Onshore wind

Model outcomes show rapid deployment of onshore wind for both Pathway A and B, with massive growth for Pathway B after 2030. Given the currently low levels of social and political support for onshore wind, both pathways required storylines involving an early political U-turn. These storylines envisage that the recent cost-reductions in *offshore* wind (especially under the Contract for Difference auctions) led policymakers to rethink the potential of onshore wind: because onshore wind was the cheapest RET, it could help to keep bills down (especially if costs could be further reduced). During 2018 and 2019, politicians used speeches and briefings to 'rebrand' onshore wind from 'green crap' to 'cheap and British'. In 2019, this culminated in an early policy change, labelled the 'renewables-reset' (a direct dig at the previous government 'energy-reset'), which allowed onshore wind to participate in new auction schemes.

For Pathway A, storylines were developed to further envisage how social acceptance problems (relating to concerns over the countryside and the poor quality of earlier consultation processes) were alleviated with the introduction of various new requirements and initiatives: 1) The government required utilities and project developers to improve their consultation procedures for new projects, leading to real involvement of local residents in planning. 2) Firms were required to pay 2.5% of revenues to local residents as compensation for burdens. 3) A 'Broad Societal Discussion' was organized to discuss the new government strategy. Environmental NGOs contributed positively to this discussion and helped articulate a discourse that prioritized climate change over countryside concerns and portrayed wind turbines as 'modern'. Not everyone agreed with this prioritization, which led to heated debates. 4) But a broad business coalition, including electric utilities, car companies (who increasingly reoriented towards electric vehicles) and ICT-firms (who increasingly deployed RETs and engaged in smart grids), supported the new strategy, which decisively enhanced its credibility. The strengthening and alignment of these developments increased public support for more onshore wind, facilitating a significant expansion of onshore wind to 2030, with levels plateauing thereafter because policy frameworks favored other RETs.

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[7] Implications of Brexit are not addressed in the scenarios, because these were written before the referendum and because the form of Brexit is still very unclear.

Pathway B required similar storylines to alleviate social acceptance problems, but additionally needed to account for much more significant expansion after 2030 and for wider changes in social arrangements, including deeper cultural changes and the emergence of new actors in the onshore generation system. This was envisaged through the following storylines: 1) Onshore wind expansion plans by incumbent actors encountered resistance, because they reignited frustrations about large firms trampling over planning processes and disregarding local concerns. Environmental NGOs complained that the 'renewable-reset' lacked ambition by failing to recognize opportunities for alternative, more decentralized models for energy provision. This initial resistance triggered several further developments: 2) incumbent utilities started to experiment with new business models for smaller scale wind-farms which actively included local stakeholders (community groups, farmers) into ownership structures. Late 2019, several high-profile 'Private-Community Partnerships' (PCPs) generated significant interest as an alternative model for distributed generation; 3) in 2020, government introduced a new PCP wind-power scheme, with generous incentives that were bolstered by high levels of social and political legitimacy, based on fall-out from the Hinkley debacle (see below). The new PCP initiatives gradually gained popularity with local residents, and started to erode longer-standing NIMBYism; 4) in 2021 the annual Turner Prize art prize was awarded to a community wind-farm in Norfolk, accompanied by photographic art that blended turbines with the natural landscape. Although initially derided, this introduced an alternative aesthetic presenting wind-power and nature in a symbiotic relationship. By 2025, onshore wind provided 23% of electricity generation with increasing enthusiasm for the PCP business model.

These developments provided a platform for further massive expansion after 2030 in Pathway B, which were envisaged through the following storylines: 1) The climate change debate, triggered by the 2025 international pledge-and-review process, gained public traction because of growing confidence that renewable generation could and would be central to the UK's electricity system. Pressure from academic, civil society and reorienting business actors resulted in the 2028 Low Carbon Electricity Act (LCEA), which introduced a carbon tax and further policies to expand renewable generation into a viable supply mix that could deal with intermittency problems. 2) The 2028 carbon tax especially stimulated onshore wind (the most cost-efficient low-carbon technology), increasing investment plans through PCP arrangements (in areas close to rural towns and villages) and incumbent-only plants (in remote rural areas); 3) Conservationists did not object, because of a deepening appreciation of the new wind-nature aesthetic, combined with government commitments to accompany new wind farms and pylon projects with tree planting and the promotion of biodiversity; 4) In the early 2030s, technical momentum also increased because new and well-funded university-industry consortia boosted wind turbine R&D efforts, focusing both on technical optimization and small-scale designs; 5) Community wind farm initiatives reduced local acceptance issues. Indirectly, they also increased the appeal of distributed generation and broader low-carbon lifestyles, which were further propagated through alignments with smart grids and other low-carbon technologies (see below); 6) By 2035, onshore wind enjoyed very high levels of social acceptance and cultural enthusiasm, with strong endogenous momentum. This facilitated a further doubling of generation taking advantage of new technologies from earlier R&D efforts: new materials (graphene and carbon nano-tubes) for lighter and stronger blades, larger turbine designs for remote locations, and smaller rooftop turbines for cities and villages.

6.2. Solar-PV

The model outcomes showed very little UK deployment of solar-PV in Pathway A (because of assumed persistent high costs relative to wind). This thus required no storyline. In Pathway B, solar-PV deployment was limited to 2040 for the same reason, but then accelerated significantly (generating 11% of total generation by 2050). The storyline envisaged that government policy adopted a 'wait-and-see' strategy through the 2020s, waiting for technical change to further reduce solar-PV costs and conversion efficiency. Policies did not stimulate solar-PV deployment, because many social groups remained unconvinced of solar-PV viability based on balance-of-system cost concerns (compared to other RETs) and the relatively poor volume of sunlight in the UK.

Policymakers were therefore surprised when some high-profile solar-PV schemes started to emerge in the early 2030s, sponsored by organizations that wanted to raise corporate reputations. Football clubs and supermarkets, for instance, adopted solar-PV to become carbon-neutral and tap into the bottom-up societal enthusiasm for renewables. These projects created a small solar installation sector, leading to skill formation and new supply chains. Seeing the potential of positive PR, some utilities invested in large-scale project. Domestic rooftop solar also grew among lead-users with low-carbon lifestyles. These bottom-up initiatives and growing enthusiasm increased pressure on the government to integrate solar-PV in the national energy strategy.

These storylines, which envisage various social and cultural developments in advance of political support, were deemed necessary to explain the sudden and significant acceleration of solar-PV in the 2040s, which the scenario envisaged as being based on policy change on the basis of social pressure. The following storylines account for the rapid expansion from a fairly low starting point. Building on the earlier high-profile initiatives and cultural enthusiasm, government energy policy introduced solar-PV as a major component of the national energy strategy in the mid-2030s. This was supported by a ten-year trade deal with the Chinese government to secure the supply of solar panels. In 2040, the government committed to installing solar-PV on all viable state-owned buildings. Many other organizations followed. On the basis of strong socio-political legitimacy, the government also re-instituted a very generous feed-in-tariff to encourage adoption of domestic solar and in-home-battery packages. Diffusion sky-rocketed leading to a six-fold increase in installed capacity in one decade.

6.3. Biomass and BECCS

Model outcomes show biomass generation accelerating after 2030 in Pathway A (when it starts to be used with CCS technology) and after 2020 in Pathway B. This large-scale deployment would currently meet with social acceptance problems, especially in the case of imported wood pellets. Post-2030 BECCS-deployment in pathway A also faces tensions with current government policy, which slashed CCS-support in 2015 (although the 2017 Clean Growth Strategy signaled new explorations). Pathway B is assumed to have no CCS and BECCS. The storylines for pathways A and B consequently differ significantly.

For Pathway A, biomass expanded slowly in the early period (2015–2025), following the CfD auction to Drax. Little further policy support was introduced because of sustainability concerns about imported wood pellets. After 2030, however, biomass generation accelerated rapidly, with an increasing proportion installed as BECCS. The storyline envisages this change in fortunes as being stimulated by the introduction of a carbon tax in 2028, which was possible because of rising political concerns (as extreme weather events and melting polar ice seemed to validate climate science predictions) and several powerful industries, including the car industry (which desired clarity to enable strategic reorientation towards electric vehicles), the financial sector (which wanted clarity about long-term investments) and utilities (who saw opportunities in converting the remaining coal plants to biomass and CCS). The 2028 carbon tax allowed utilities to gain double carbon credits by implementing BECCS (one for biomass and one for storing CO2 emissions). This policy change was possible because prior developments improved social acceptance and political feasibility of BECCS: 1) Efforts to bolster the proper management and harvesting procedures alleviated sustainability concerns about biomass, 2) International experiences demonstrated the viability of negative emissions via BECCS, 3) Increasing concerns about climate change stimulated socio-political interest in negative emissions and BECCS, 4) BECCS was also viewed positively because it offered low-carbon back-up capacity for the increasing amount of intermittent renewables (biomass increasingly took over this function from gas-fired power plants, which were maintained for emergency periods), 5) Utilities with remaining coal-fired power plants were keen to convert to biomass (and BECCS), because this offered a way to extend their assets beyond the (delayed) coal phase-out. Utilities therefore worked hard to establish robust standards and inspections for sustainable biomass supply chains.

Because the UK had no domestic CCS experience, utilities imported the technology from abroad, installing it on their plants. Initial BECCS-installations faced technical teething problems, particularly with regard to dimensioning and operation. Once these problems were overcome, BECCS continued to expand substantially after 2030, because negative emissions were needed to compensate for decarbonization problems elsewhere (e.g. manufacturing, agriculture).

Pathway B required different storylines because biomass expanded earlier (from 2020) and the assumptions ruled out CCS, which thus required smaller-scale and decentralized deployment with a role for new entrants. This was envisaged through the following developments: 1) Coal-to-biomass conversion continued gradually, because of the Drax conversion. But enhanced NGO action against ‘Big Biomass’ and imported wood pellets increased social acceptance problems; 2) Smaller, dedicated biomass plants started to emerge as an unanticipated consequence of the government-supported PCP model, initially introduced to support wind. Incumbents joined forces with regional farmer's co-operatives to install medium-sized anaerobic digesters and CHP-plants and to develop local supply chain logistics for agricultural waste. Supermarkets also joined, feeding in post-retail waste streams; 3) This renewed interest in dedicated biomass re-ignited innovation trajectories for efficient biomass-to-energy conversion, especially for small- to medium-scale equipment; R&D into next generation feedstocks, including dedicated energy crops, also gained momentum, thus increasing biomass use in the 2020s.

After 2030, bioenergy use further expanded because: 1) Policymakers supported it via the 2028 carbon tax because of climate and energy security considerations (bio-energy provided back-up capacity for intermittent RETs such as onshore wind); 2) Dedicated and decentralized biomass generation (including neighborhood CHP-systems) became increasingly popular, because of technical progress (in high-throughput anaerobic digestion and micro-CHP technologies) and because of a groundswell of societal engagement with climate change.

By 2035, converted coal plants using imported pellets were being decommissioned in favor of decentralized generation and local biomass waste, including new feedstocks from sustainable energy crops (e.g. *Miscanthus*). In the final period to 2050, biomass-to-energy generation decreased somewhat, because biomass became a key input for the high-value bio-economy (in agricultural, health and materials industries). This had knock-on effects for gas-fired power, which gained importance for providing back-up capacity supported by attractive market incentives.

6.4. Nuclear

Model outcomes showed some growth of nuclear power in Pathway A, implying that several new nuclear plants were built to replace those that were decommissioned. In Pathway B, nuclear was ruled out, which we explained with a Hinkley C debacle’ storyline: persistent delays and cost inflation with Hinkley C created crises in socio-political legitimacy and the cancellation of further new nuclear plans, which resulted in gradual decommissioning of existing plants and a full phase out by 2040. We used the ‘Hinkley debacle’ above to explain stronger support for RETs in Pathway B (especially onshore wind) to address public concerns about energy security.

The storyline for Pathway A entailed the following developments: 1) Although an agreement for Hinkley C was finally reached in September 2016, the ongoing discussions and delays eroded the social and political acceptance of a broader nuclear renaissance; 2) Nevertheless, the government pushed ahead with two other nuclear plants (Wylfa and Moorside), starting negotiations in 2018, which by 2020 resulted in concrete plans; 3) Meanwhile, Hinkley C faced construction problems: final construction costs were higher than planned (£22 billion instead of £18 billion), which, combined with the high guaranteed price for nuclear power, led to a negative discourse of nuclear power being too expensive; 4) The government spent political capital to push through the other two nuclear plants, but had little appetite to build more nuclear plants. Since several older nuclear plants were decommissioned, the installed capacity did not increase much. But the new plants (which came online in 2027 and 2030) ran at higher load factors and thus generated more power.

6.5. Grid expansion and flexibility

Grid innovation does not appear explicitly in model outcomes as a quantitative indicator. But the increased use of intermittent renewables requires significant grid expansion and greater flexibility in both pathways, although in different ways. Both storylines also envisaged government-led radical changes (albeit to different extents and in different ways) to actors (Ofgem, National Grid and DNOs) in the network regime to overcome inertia and lock-in.

For Pathway A, the following storylines were envisaged. Increasing onshore and offshore wind required major infrastructure changes: 1) long-distance transmission grids were expanded to connect remote wind farms, 2) an entirely new offshore grid was constructed, based on seabed cables, 3) expanding interconnectors increasingly linked the UK into an emerging European super-grid. To support these developments, several tactics were pursued to reduce social acceptance problems in the countryside: 1) new pylon designs with less visual intrusion were deployed, and, in some instances, cables were constructed underground, 2) local residents were better consulted in infrastructure design and planning processes, 3) the National Grid was forced to offer compensation, either financially or by planting new trees that would mask the pylons.

With the increasing use of ICTs across networks, intermittency problems could be addressed more effectively as smart grids offered improved controls of electricity flows in response to accurate weather forecasts and measurement stations. Additional flexibility came from international spot markets, which allowed electricity purchase and import in emergencies. The result was a low-carbon flexible electricity system by 2050.

Pathway B needed to envisage deeper changes across a wider range of socio-technical dimensions, which were envisaged through the following developments: 1) the increasing promise and popularity of distributed generation meant that Ofgem was tasked with a remit to deliver smart grids that improved the management and monitoring of electricity flows and enabled local micro-grids and flexible load-matching. 2) Distributed generation, micro-grids and flexible load-matching then had knock-on effects, leading to higher ‘energy awareness’ and engagement with low-carbon lifestyles. Community groups and households not only installed small-scale power generation, but also engaged in power distribution, sales and accounting, which created new mind-sets and routines that spilled over to further actions, including electric vehicle acquisition, insulation and smart meter use. 3) These innovations combined in a new ‘package’ that underpinned the idea of low carbon lifestyles. While this lead-user group was initially small, they provided evidence for the viability and attractiveness of low-carbon lifestyles, leading to sustained media interest.

By the end of the scenario, smart grid management was envisaged to have become routine and efficient. A multi-layered grid was established, in which the European super-grid facilitated international flows; smart micro-grids enabled local flows (between distributed generation and consumption); and the national high-voltage grid mediated between regions. With high levels of battery storage and full ICT integration at all levels, this smart network system had significant flexibility for managing generation and consumption.

7. Discussion

7.1. Policy implications

In step 8, we reflected on policy implications, noting that scenarios A and B show that low-carbon electricity transitions commensurate with 2 °C are possible in the UK but require major policy changes to overcome 'transition bottlenecks' and accelerate developments for various innovations.

Although scenarios A and B exemplify different pathways, rapid expansion of *onshore wind* is crucial in both (and in the 'neutral scenario'). Since this conflicts with current policy (which has halted post-2020 subsidies), both our scenarios involve a political U-turn and improved social acceptance. The former is obviously difficult, but we suggested that increased low-cost awareness (and stronger alignment with the 'keeping bills low' narrative) may provide an opportunity. For the latter, we suggested various strategic options such as greater public participation in wind-siting approval processes, financial compensation for local communities, and a government-led societal debate. Massive onshore wind expansion (especially after 2030 in Pathway B) would also require deeper changes such as an alternative aesthetic (perceiving wind-power and nature in a symbiotic relationship), new business models like 'Private-Community Partnerships', financial support (for PCP wind-power schemes, carbon tax), stronger public concerns about climate change, supportive coalitions (from civil society, academia, business), and new low-carbon lifestyles.

Increased *bio-power* is also crucial in both scenarios, mostly as large-scale combustion in Pathway A (with CCS after 2030) and as smaller, dedicated biomass in Pathway B. The 2012 Biomass Strategy favors the former (particularly biomass conversion of coal-fired plants) over the latter, but also envisages redirection of biomass from electricity towards transport and heating after 2020, which would conflict both our scenarios. Additionally, social acceptance problems form a risk for large-scale biomass combustion, particularly concerns over the sustainability of imported pellets. The government and industry are trying to address this risk with stronger standards and auditing. An alternative strategic direction (as suggested by Pathway B) is to focus on smaller, dedicated biomass plants and local supply chains (e.g. enhanced domestic energy crops or agricultural, domestic, building and supermarket waste streams), which would involve substantial policy changes.

The BECCS-option in Pathway A is highly uncertain, because the government scrapped CCS-support in 2015. Our socio-technical scenario therefore assumed that the UK would import CCS technology (in the late 2020s), which would create dependencies on other countries. If the UK government wants to mitigate against associated vulnerabilities (and stimulate the BECCS-option), it should reverse its 2015 decision and invest more strongly in CCS-development. As an additional benefit, this would also strengthen the current unabated coal phase-out strategy: if sufficient feasible alternatives are insufficiently developed by 2025, coal-with-CCS would then be an option. With favorable cost developments, gas-with-CCS could also become attractive.

The government still assumes that *nuclear power* generation will be substantially expanded, to 113 TWh in 2035 according to recently updated energy projections (BEIS, 2018). This contrasts substantially with our scenarios, which show nuclear decline in two scenarios (Pathway B and neutral). Only in Pathway A is nuclear power slightly expanded (generating 65 TWh in 2035), but mostly by exogenous definition. Our socio-technical analysis suggests that substantial nuclear expansion is politically difficult because of increasing concerns about construction delays and high costs (especially as renewables costs decrease). Our scenarios thus suggest that the government's nuclear power assumptions are vulnerable to broader feasibility risks. Hedging against this risk could be done by increasing support for alternative options (like CCS, onshore wind and solar-PV), including more attention for social acceptance.

Grid improvements are crucial in both scenarios to connect renewables and enhance flexibility (through smart grids, storage, and back-up capacities). Our socio-technical analysis suggests that inertia (especially in the distribution network regime) may create delays, which could limit the system's ability to integrate fluctuating generation. The scenarios therefore assume that policymakers overhaul the remits of Ofgem, National Grid and DNOs by the mid-2020s, although we did not discuss specific policies because of our focus on social acceptance. To address potential local acceptance problems with grid expansion, our scenarios suggest that policymakers should stimulate grid actors to consult more with local residents, offer compensation, or use new pylon designs and underground cables. While the latter may improve local acceptance, there is a trade-off because underground cables would increase costs, which may hinder broader social acceptance.

Solar-PV plays a small role in Pathway A and diffuses very late (2040s) in Pathway B, where it becomes part of low-carbon lifestyles, especially when rooftop-PV, micro-grids, flexible load-matching, and smart meters stimulate energy awareness and behavior change. In light of recent rapid expansion (Fig. 5) and (further) anticipated cost decreases, our scenarios (and government policy, which slashed support) may underestimate the potential role of solar-PV. Despite load-matching challenges (in daily and seasonal demand cycles), we therefore suggest that policymakers should enhance solar-PV support, which would thus reverse the 2015 energy-reset (which may be politically sensitive).

Beyond specific innovations, our scenarios point to different governance styles. For Pathway A, policy is developed centrally by national government working closely with incumbent actors, with limited participation from civil society actors or new entrants. Some scholars (Geels et al., 2016b) suggest that the UK policy style has similarities to this 'working with incumbents' pattern, which led to an emphasis on large-scale options (offshore wind, nuclear, biomass conversion) and may have contributed to social acceptance problems by side-lining public concerns (shale gas, nuclear, 'Big Biomass'). Pathway B assumes a more distributed governance style with greater attention for unleashing new entrants and involving a wide range of societal actors. As suggested by our scenarios, social acceptance can be addressed with both governance styles, although approaches vary. In Pathway A, these approaches would require utilities and project developers to improve consultation procedures, financially compensate local residents for burdens, or make technical adjustments. In pathway B, these approaches would additionally involve organization of a Broad Societal Discussion to discuss various low-carbon pathways, incentives for new business models (like 'Private-Community Partnerships'), and more support for decentralized options, new entrants and communities, which may enhance social awareness and engagement. Since many low-carbon innovations currently face socio-political feasibility problems (Table 3), the coming years are likely to provide further information about the different approaches.

7.2. Reflections on scenarios

Although the storylines in Section 6 aim to *illustrate* the methodological procedure rather than *predict* the future, we want to end with some reflections on the socio-technical scenarios. First, the assumptions underlying Pathway A are closer to the existing UK electricity regime, which means that the pathways and policies may appear more credible than in Pathway B, where the system experiences deeper change (in technologies, actors, institutions). This would be less the case for Germany, where the unfolding transition has more Pathway B characteristics (Geels et al., 2016b).

Second, we sometimes struggled to fully implement the Pathway B logic. Especially for onshore wind (but also for bio-energy), it did not seem feasible to assume a wholesale switch from currently dominant incumbents to new entrants (like communities and farmers). Our storylines therefore envisaged a hybrid business model (private-community partnerships) with A and B characteristics.

Third, some quantitative model outcomes seem rather extreme, e.g. no or very late solar-PV deployment in respectively pathway A and B, massive onshore wind expansion in pathway B. Both Pathways were intentionally stylized to generate distinct Pathways, deviating from middle-of-the-road developments. Therefore, the strategy pursued in Pathway B differs substantially from the current trajectory in the UK. For various model outcomes, we felt that we had to stretch the socio-technical storylines (e.g. assuming very high levels of social acceptance, community activity and cultural enthusiasm for onshore wind). These high model outcomes relate to underlying assumptions: by excluding nuclear and CCS, the model forces very high renewables diffusion, based mostly on the cheapest option (onshore wind).

Fourth, because the socio-technical storylines focus on endogenous change (related to actors, interactions and cumulative processes), they arguably exclude the MLP's ‘landscape’ level. Although some storylines referred to extreme weather events, the scenarios did not include (geo) political changes (e.g. Brexit, America First, populism), shocks or crises. Arguably, this exclusion made the socio-technical scenarios more conservative and gradualist, and also made it more difficult to develop plausible Pathway B storylines.

Fifth, the storylines focus on the supply side (with some attention for grids), because the applied models provide more detailed information about this. In the results discussed here, electricity demand is only addressed as aggregate context variable (mostly provided by the IMAGE and WITCH models). Our socio-technical storylines consequently also hardly addressed electricity consumption and the underlying daily life practices (lighting, cooking, heating, home computing, consumer electronics entertainment). Expanding the approach to detailed demand-side developments is therefore an important future opportunity.

7.3. Reflections on dialogue and bridging

Our 8-step methodological procedure aimed to contribute to recent dialogue and bridging approaches between models and qualitative storylines (Foxon, 2013; McDowall, 2014; Turnheim et al., 2015). Our procedure moved from theoretical bridging in early steps (when socio-technical pathway ideas led to changes in model parameters, which changed the initial ‘neutral’ scenario into pathway A and B) to empirical bridging in later steps. For these later steps, we conclude that the identification of ‘transition bottlenecks’ and their use to develop socio-technical scenarios provided a productive medium for dialogue, because they both involved innovation-oriented bridging efforts between *future*-oriented model-based scenarios and *contemporary* MLP-dynamics at niche and regime levels. The dialogue was not always easy, because scholars from both communities had different interests and scientific vocabularies. But repeated interactions in the 3-year PATHWAYS project build trust and stimulated learning and mutual understanding.

On the one hand, socio-technical transition scholars came to appreciate the role of models in analyzing ‘whole system’ transitions. Focusing on single innovations, transition scholars would sometimes criticize modelers for optimistic assumptions (e.g. with regard to nuclear power or CCS), and argue for down-scaled projections. But to reach the 2 °C target, models would then automatically increase the deployment of other innovations (e.g. onshore wind), which introduced other optimistic assumptions. This dialogue between modelers and transition scholars improved the latter's awareness of ‘whole system’ challenges and the need to go beyond purely critical discussions of models (which characterizes many environmental social scientists). The dialogue also increased awareness of the high plasticity of computer models and the degree to which parameters can be adjusted (what modelers in meetings called ‘kicking the models’) to achieve particular pathways.

On the other hand, discussions about the transition bottlenecks and socio-technical scenarios increased the reflexivity of modelers about the importance of analyzing a wider range of factors beyond techno-economic parameters. In particular, the socio-technical storylines showed that many social, political, and cultural changes are required to actually realize the model-generated pathways. Additionally, the socio-technical scenarios showed that new policy instruments or approaches cannot be implemented ‘out of the blue’, but actually require much preparation and appropriate contexts (e.g. building support coalitions, learning processes, public sense of urgency).

These experiences and reflections reinforce the wider point that debates about low-carbon transition pathways are likely to be more fruitful when academic silos are broken down and different epistemic communities come to better understand each other's logics of reasoning and inquiry.

8. Conclusions

We have developed and illustrated a methodological procedure that facilitates dialogue and bridging between computer models and the MLP, which resulted in socio-technical scenarios that help explore problems of social acceptance and political feasibility in low-carbon transitions. This is important because these problems are not well addressed in model-based scenarios, and because real-world transitions are increasingly encountering these problems. We introduced ‘transition bottlenecks’ as a methodological aid to identify these problems and facilitate dialogue about them between modelers and socio-technical transition scholars. The transition bottlenecks also guided the development of socio-technical scenarios and discussion of policy implications. These socio-technical scenarios qualified model-based outcomes by exploring pathways for the societal embedding of low-carbon innovations that resulted from social interactions and endogenous changes in discourses, preferences, support coalitions and policies. Because social acceptance and political feasibility are shaped by social interactions, our policy discussion focused more on policy approaches and governance styles than on specific policy instrument settings.

We demonstrated our methodological procedure for low-carbon transitions in UK electricity generation, developing socio-technical storylines for various innovations in two scenarios, which differed in terms of lead actors, depth of change and governance styles. We conclude that the procedure and ‘transition bottlenecks’ concept facilitated productive dialogue and produced new and interesting socio-technical scenarios, but also note that the cross-community dialogue required mutual learning and trust. The broader message is that policies and analysis of low-carbon transition pathways should not only focus on techno-economic dimensions, but also address socio-cultural and political dimensions. Without the latter, UK implementation of low-carbon innovations (e.g. biomass, BECCs, onshore wind, grid improvement) is likely to face protests and delays, which would jeopardize reaching the 2 °C target.

As the two communities become more accustomed to analytical bridging, we may expect further mutual learning and methodological elaborations of the socio-technical scenario approach. First, to extend the learning opportunities, it may be productive to include stakeholders in the process, as has been done in previous foresight and scenario exercises. Second, future research could try to include ‘wildcard’ events and ‘landscape’ processes in the methodology and socio-technical scenarios. Third, the approach could be broadened to better accommodate demand and lifestyle changes.

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