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Linking governance storylines with the D-EXPANSE model to explore the power system transition pathways

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Abstract: In 2008 United Kingdom adopted an ambitious target to reduce its greenhouse gas emissions by 80% by 2050, compared to the levels of 1990. This is an unprecedented challenge to the power sector and multiple energy-environment-economic modeling activities have been undertaken to inform the energy policy to deliver this low-carbon transition. The role of governance, choices and strategies of the key actors is increasingly acknowledged as an influential determinant of such transition, but traditional energy-environment-economic models can hardly analyze these aspects. This paper proposes a methodological approach to integrating the governance aspects into energy-environment-economic modeling. In the Realizing Transition Pathways project three qualitative storylines of governance were developed through expert and stakeholder engagement. "Market Rules" storyline envisions that market will deliver low-carbon energy transition. "Central Co-ordination" storyline envisions increased role of the government in shaping this transition. "Thousand Flowers" storyline envisions the wider civic society leading through bottom-up initiatives. These three qualitative storylines are then translated into a range of modeling assumptions for the D-EXPANSE model (Dynamic version of EXploration of PAtterns in Near-optimal energy ScEnarios). D-EXPANSE has the structure of a bottom-up energy-environment-economic model, but is more flexible and allows for systematic exploration of large numbers of power system transition pathways that are cost-optimal and near optimal. Every governance storyline is thus represented by a large number of quantitative pathways and this provides unique insights into the influence of governance on the future UK power system transition.

Keywords: energy transition; quantitative scenarios; storylines; governance; near-optimal

1 INTRODUCTION

In 2008 United Kingdom adopted an ambitious target to reduce its greenhouse gas emissions by 80% by 2050, compared to the levels of 1990. This is an unprecedented challenge to the power sector and multiple energy-environment-economic modeling activities have been undertaken to inform the energy policy to deliver this low-carbon transition (Ekins et al. 2011; Usher and Strachan, 2012). The role of governance, choices and strategies of the key actors is increasingly acknowledged as an influential determinant of such transition (Hughes and Strachan, 2010). However, traditional energy-environment-economic models can hardly analyze these aspects and thus it is essential to adapt these models accordingly. There is a growing interest and some progress in qualitatively deliberating the role of governance (Foxon, 2013) or even modeling decisions and interactions of the key actors, e.g. (Chappin and Afman, 2013; Kwakkel and Yücel, 2012; Madlener and Schmid, 2009). These approaches are not without their own limitations too. First, as the quantitative decision models prescriptively pre-define the types of key actors and their decision rules, they cannot capture the fundamental shifts in governance and society more broadly. Second, deliberative approaches and decision models tend to detach from the energy-environment-economic insights. For example, they often focus on one or two technologies and their deployment, but do not cover the supply-demand constraints, interactions among several technologies and the embedding in the wider environment-economic system. A complete shift from the well-established energy-environment-economic models to decision models or qualitative deliberations may not yield better quality insights. This paper thus argues for combining the strengths of both types of approaches (Alcamo, 2008; Trutnevyte, 2014).

This paper proposes a methodological approach to bringing the governance aspects into energy-environment-economic modeling. This is achieved by linking qualitative governance storylines from the Realising Transition Pathways project (Foxon, 2013) with the energy-environment-economic model D-EXPANSE. These storylines, called “Market Rules”, “Central Co-ordination” and “Thousand Flowers,” were developed through expert and stakeholder engagement and comprise of four to five pages of text on governance and the role of key actors (Transition Pathways, 2012). These storylines are then linked with the D-EXPANSE model (Trutnevyte, 2013a; Trutnevyte and Strachan, 2013). The D-EXPANSE model (Dynamic version of EXploration of PAtterns in Near-optimal energy ScEnarios) has the structure of a bottom-up energy-environment-economic model, but is more flexible as it systematically explores large numbers of energy system transition pathways and can select a smaller set of maximally-different pathways. A single qualitative storyline can mean a large number of very different quantitative representations (Trutnevyte et al. 2012; Trutnevyte, 2014). The challenge is thus to systematically capture all these quantitative representations. The D-EXPANSE model can exactly capture these different representations by selecting a smaller set of maximally-different pathways. This methodological approach is introduced in this paper and then illustrated with the case of the UK power system transition from 2010 until 2050.

2 METHODS

2.1 Overarching approach

The overarching approach to linking governance storylines with the D-EXPANSE model is shown in Figure 1. In the first step, the qualitative governance storylines are ‘translated’ into modeling parameters for D-EXPANSE (Section 2.2). In the second step, D-EXPANSE is used to generate a large set of quantitative power system transition pathways (Section 2.3). From this large set of pathways, a smaller set of maximally-different pathways is extracted in order to understand what types of pathways fall under each storylines. Patterns in the large number of pathways can also be analyzed.

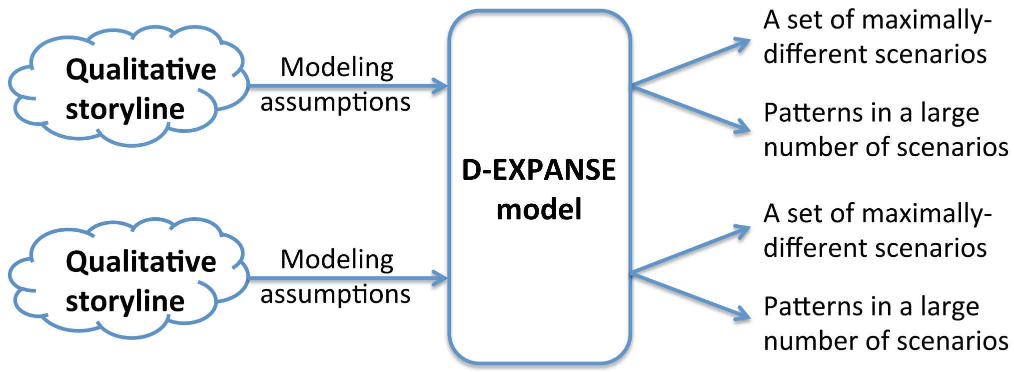

Figure 1. The overarching approach to linking qualitative storylines with the D-EXPANSE model.

2.2 From governance storylines to modeling assumptions

This section introduces the three governance storylines, which are linked with the D-EXPANSE model. The key elements of these storylines were developed in 2008 in a stakeholder workshop of the Transition Pathways project (Foxon, 2013). These Transition Pathways storylines describe the UK power system governance arrangements, choices of the key system actors, key contextual developments and the power system evolution itself from 2008 to 2052. The storylines distinguish between three ideal-types of governance logics:

- "Market Rules" storyline envisions that market-led logic will deliver low-carbon transition with the focus on large-scale low-carbon generation;
- "Central Co-ordination" storyline envisions increased role of the government in shaping this transition through contracts for large-scale low-carbon generation;
- "Thousand Flowers" storyline envisions the wider civic society, including households, communities, local governments and non-governmental organizations, playing a leading role through bottom-up initiatives and focus on smaller-scale generation.

These storylines are four to five pages long; their latest versions are available at (Transition Pathways, 2012). From these four to five pages, key elements are elicited and converted into modeling parameters for the D-EXPANSE model (Table 1). These three storylines envision changes in electricity demand, including the end-use efficiency improvements and uptake of electric heating and electric vehicles. As the D-EXPANSE model does not disaggregate the electricity demand by sectors or uses, the annual electricity demand and the minimum installed capacity requirements are taken as assumptions from (Foxon, 2013). All the three storylines assume that the UK's legally binding emission mitigation target will be met and thus the carbon emission constraints are included in D-EXPANSE too. The key differences in the storylines due to the different governance arrangements are in terms of electricity supply technology choices. Foxon (2013) lists key technologies in every storyline and the uptake of these key technologies is respectively constrained in D-EXPANSE.

Table 1. Systematic 'translation' of governance storylines into modelling parameters

	Market Rules			**Central Co-ordination**			**Thousand Flowers**		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
Minimum installed capacity, GW	106	130	174	103	122	141	107	134	149
Annual electricity generation and import, TWh/year	404	469	560	380	425	448	334	341	328
Share of coal CCS, %	≥10%			≥10%			unconstrained		
Share of gas CCS, %	≥10%			≥10%			unconstrained		
Share of nuclear, %	≥10%			≥10%			unconstrained		
Share of offshore wind, %	≥10%			≥10%			≥10%		
Share of onshore wind, %	unconstrained			unconstrained			≥10%		
Share of solar PV, %	unconstrained			unconstrained			≥5%		
Share of renewable-based CHPs %	unconstrained			unconstrained			≥10%		
Maximum greenhouse gas emissions, gCO_2/kWh	300	70	20	300	70	20	300	70	20

2.3 D-EXPANSE model

The D-EXPANSE model (Trutnevyte and Strachan, 2013) is the dynamic extension of the earlier static EXPANSE model (Trutnevyte, 2013a). D-EXPANSE has the structure of the traditional, bottom-up, technology rich, cost optimization energy system model with perfect foresight. Such bottom-up models form a well established and widely used practice in energy systems modeling. In addition, it has two state-of-the-art features. First, it systematically explores the near-optimal pathways in line with Decarolis (2011) and Chang et al. (1982). Second, it generates large numbers of near-optimal pathways in order to draw patterns in line with McJeon et al. (2011), Gritsevsky and Nakicenovic (2000), and Rozenberg et al. (2010). Instead of using varying input parameters to produce multiple pathways as in the afore-mentioned approaches, D-EXPANSE uses one set of deterministic input parameters. The multiple pathways are generated by allowing a deviation from the cost-optimality assumption. That is, all the pathways generated with D-EXPANSE use the exact same input parameters, but have different total system costs.

The D-EXPANSE model and its mathematical formulation are introduced in detail by Trutnevyte and Strachan (2013). In brief, the D-EXPANSE model firstly is run in cost-optimization mode to find the least cost solution (transition pathway) using a set of technology and cost data as well as the constraints on the annual and peak electricity demand, resource bounds, carbon emission targets and others. The model in run with 5-years time step from 2010 to 2050. Second, the total system costs of the cost-optimal pathway are used as the anchor point for analyzing the near-optimal pathways. A certain deviation in the total system costs is allowed from the optimal level of costs. In this way, costs become a constraint rather than the objective function for the model. The technique of efficient random generation (Chang et al. 1982; Trutnevyte, 2013) is then used to produce a large number (e.g. one thousand) of pathways that all meet the constraint on the near-optimal costs. Third, this large set of near-optimal pathways is analyzed either by eliciting a smaller number of maximally-different pathways or by extracting the patterns in these pathways. The small number of maximally-different pathways is formed by the adapted distance-to-selected technique (Tietje, 2005; Trutnevyte et al. 2012a; Trutnevyte and Strachan, 2013). Alternatively, patterns from the large number of pathways can also be drawn by visually inspecting the results or using statistical techniques.

The D-EXPANSE model is currently set up for analyzing the UK power system transition for the period of 2010-2050 (Trutnevyte and Strachan, 2013). For validation reasons, the D-EXPANSE cost-optimal pathway was compared to the results of the well-established models (Ekins et al. 2011) and matches them with a reasonable level of precision. As compared to a detailed power system model, D-EXPANSE has a relatively coarse representation of the power system. D-EXPANSE has been validated by soft-linking it with the detailed FESA model (Barton et al., 2013). FESA is a single-year UK power generation and demand model, incorporating one-hour time steps for dispatch modeling and using real weather data of temperatures, wind speeds, wave heights and solar radiation. Thus, FESA helped to test whether the pathways generated with D-EXPANSE are technically feasible. D-EXPANSE was also embedded in the multi-model comparison with seven other models (Trutnevyte, 2013a), that ranged from detailed power sector models to economic or environmental impact assessment models. This allowed for validating the other features of D-EXPANSE that could not be covered by FESA.

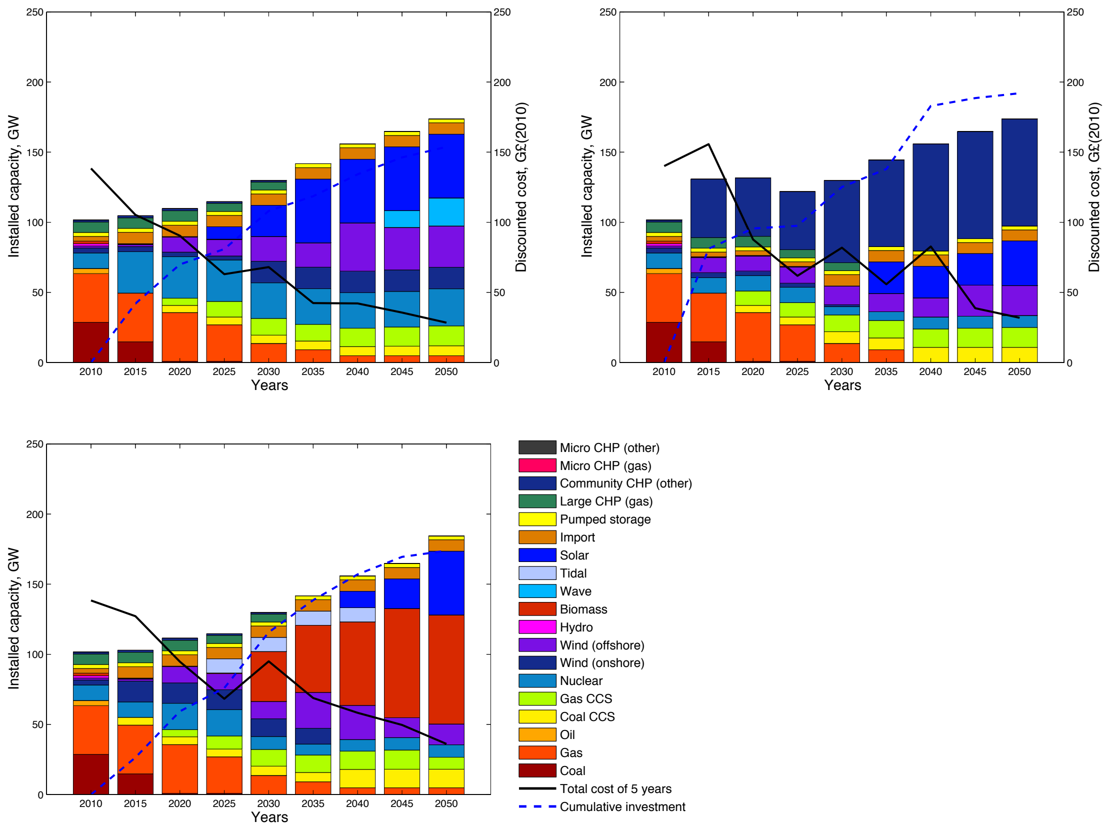

Figure 2. The cost-optimal (top left) and two maximally-different pathways for the “Market Rules” storylines.

3 RESULTS AND DISCUSSION

The analysis presented here was conducted generating one thousand near-optimal pathways, that deviate less than 20% from the cost-optimal pathway in terms of total system costs. Figures 2, 3 and 4 present the cost-optimal and two maximally-different other pathways for the “Market Rules”, “Central

Co-ordination" and "Thousand Flowers" storylines. In terms of technology deployment, the "Market Rules" and "Central Co-ordination" storylines are relatively similar, but this is not surprising due to their focus on the same types of large-scale generation (Table 1). As the electricity generation levels shall be higher in the case of "Market Rules," higher deployment of technologies, such as wave, solar, biomass, tidal or community combined heat and power (CHP), are required as compared to "Central Co-ordination." The "Thousand Flowers" storyline is substantially different both in its story (Foxon, 2013) and in the technology deployment (Figure 4). As compared to the other two storylines, "Thousand Flowers" does not include any carbon capture and storage (CCS), but has higher levels of micro and community CHPs as well as solar power. Figures 2, 3 and 4 present only three maximally-different pathways, but more technology patterns could be elicited when analyzing further pathways.

Figure 5 plots one thousand quantitative pathways in terms of cumulative investment costs, excluding the financing costs, for the three storylines. All of these one thousand pathways deviate 20% or less in terms of total system costs from the cost-optimal pathway for every storyline. As the electricity demand assumptions are different for the three pathways (Foxon, 2013), the investment costs from Figure 5 also differ and thus direct comparison between the governance logics cannot yet be made. Given the assumptions from Table 1, the "Market Rules" storyline leads to the highest level of investment costs, but this is not surprising because the electricity generation levels are the highest in this storyline. Although the "Thousand Flowers" storyline assumes substantially lower electricity demand (Table 1), its investment costs are roughly as high as those of the "Central Co-ordination" indicating of the more expensive technology choices in the "Thousand Flowers" case.

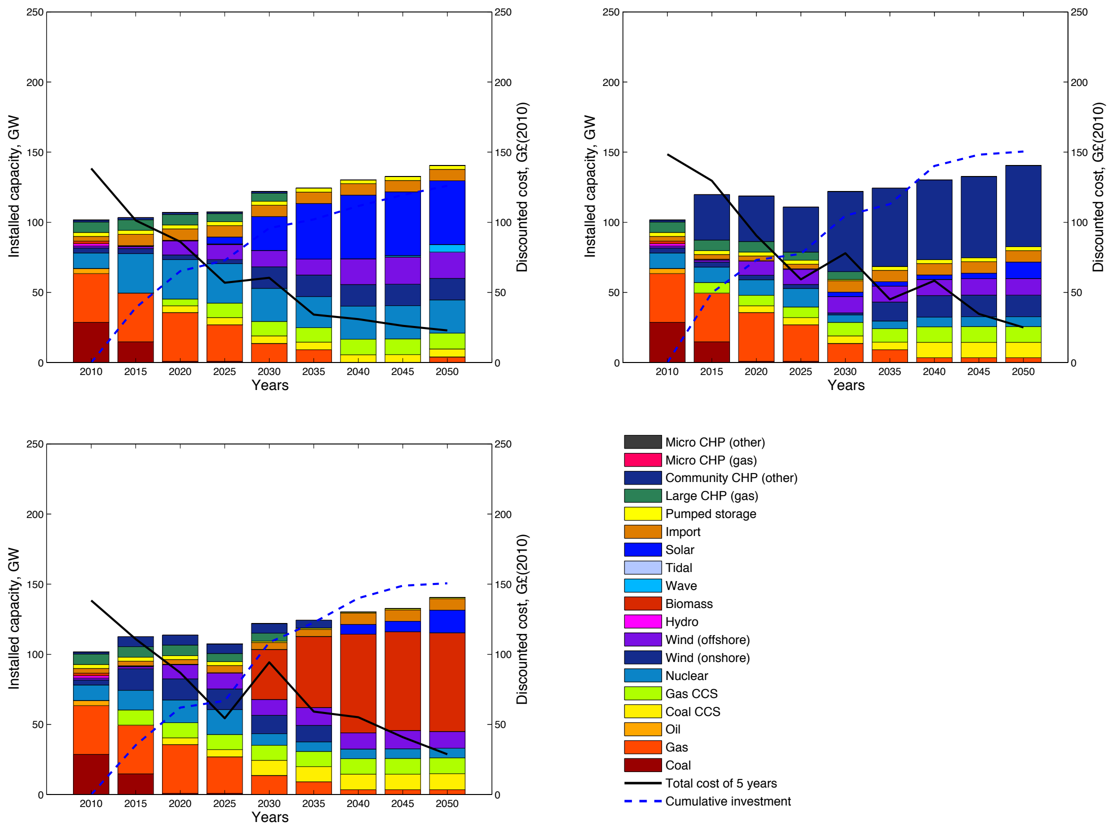

Figure 3. The cost-optimal (top left) and two maximally-different pathways for the "Central Co-ordination" storylines.

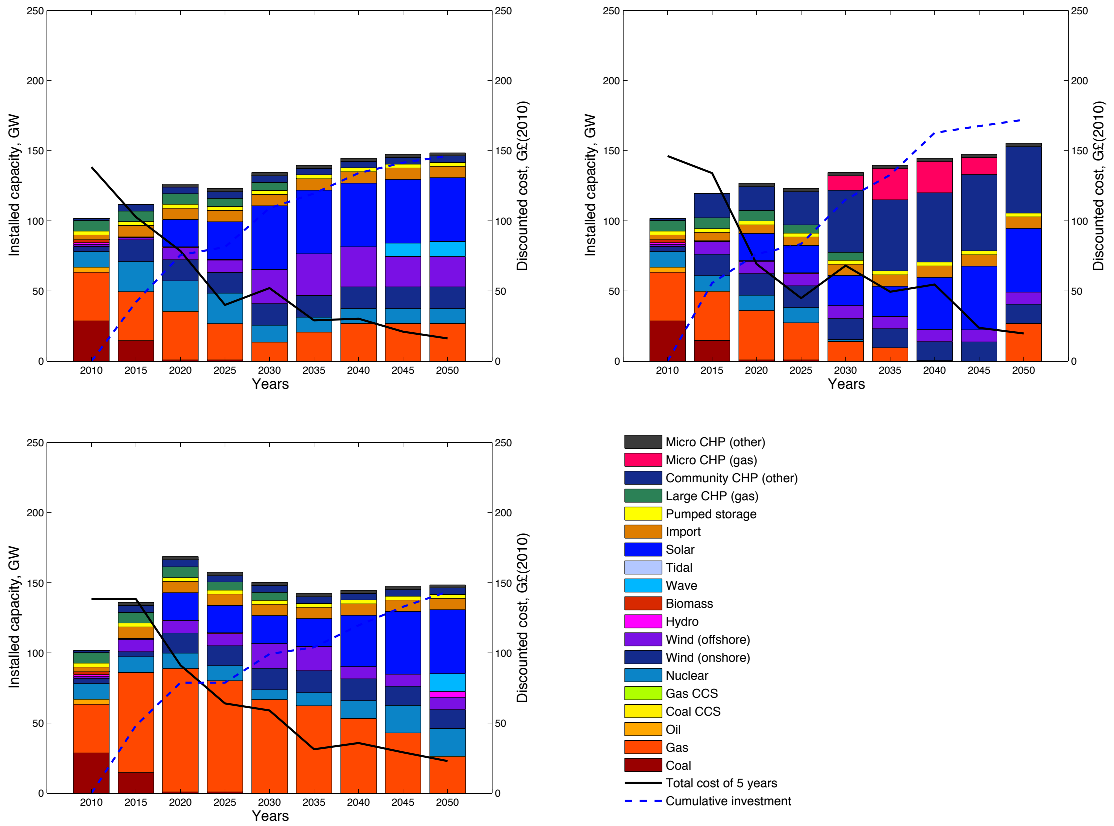

Figure 4. The cost-optimal (top left) and two maximally-different pathways for the “Thousand Flowers” storylines.

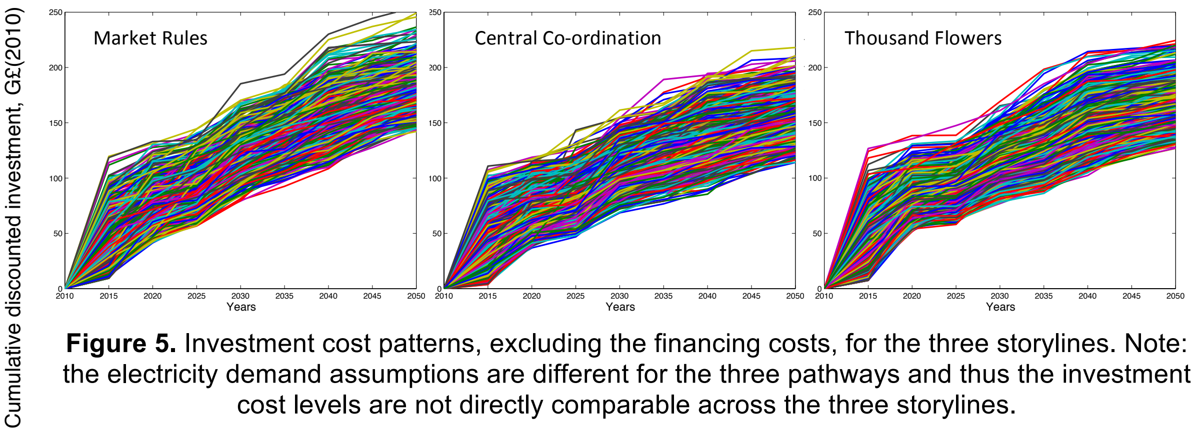

Figure 5. Investment cost patterns, excluding the financing costs, for the three storylines. Note: the electricity demand assumptions are different for the three pathways and thus the investment cost levels are not directly comparable across the three storylines.

4 SUMMARY AND FUTURE RESEARCH NEEDS

In order to capture the role of governance and the choices and strategies of the key actors in shaping the future energy system transition, this paper introduces an approach for linking qualitative governance storylines with quantitative transition pathways, generated with the D-EXPANSE model. The approach is illustrated by analyzing the UK power system transition to low-carbon system from 2010-2050 under market-led, government-led and civic society-led governance logics. The presented work serves as a proof of concept, but already yields novel insights into the three storylines.

Yet, further research is need in three directions: improving the D-EXPANSE model, improving the linkage of D-EXPANSE and storylines, and improving the storylines themselves. With respect to the

D-EXPANSE model, further work is needed to flesh-out in more detail the intra-annual variation of electricity demand and supply. With respect to the linking of D-EXPANSE and the storylines, an even more systematic approach needs to be taken for 'translating' the qualitative storylines into modeling assumptions. Currently, only constraints on technology deployment are included, but other aspects, such as technology costs, could be considered too. With respect to the storylines, the current versions of the storylines were written without taking any economic modeling into account (Foxon, 2013). These storylines are based on expert views about the future and are hardly possible to validate. Further work is thus necessary to address the quality and validation of storylines. In fact, D-EXPANSE could to some extent be used in revising these storylines to make them more consistent with the cost-based rationale, which is the dominant driver of energy system transitions. As D-EXPANSE does not only consider cost-optimal solutions and allows for deviation from cost-optimality, it is especially useful for revising such storylines that acknowledge both cost-based and other drivers.

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