Linking storylines with multiple models: an interdisciplinary analysis of the UK power system transition

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Abstract

State-of-the-art scenario exercises in the energy and climate change fields argue for combining qualitative storylines with quantitative modelling. This paper proposes an approach for linking a highly detailed storyline with multiple, diverse models. This approach is illustrated through an interdisciplinary analysis of the increased role of the government in shaping the UK power system transition until 2050. The storyline, called *Central Co-ordination*, is linked with insights from six power system models and two appraisal techniques. First, the storyline is 'translated' into harmonised assumptions that can be used by these models. Then, the concept, called the landscape of models, is introduced. This landscape helps to map the key fields of expertise of individual models. The storyline is then assessed based on the results of the models and appraisals. It is shown that the storyline is important for transmitting information about the governance arrangements and the choices of key actors. However, the storyline is fragile in light of modelling results and can be improved on this basis. To the best of the authors' knowledge, this is the first structured attempt to bring together such diverse range of models for fleshing out a storyline. The proposed approach could thus be useful for other interdisciplinary analyses.

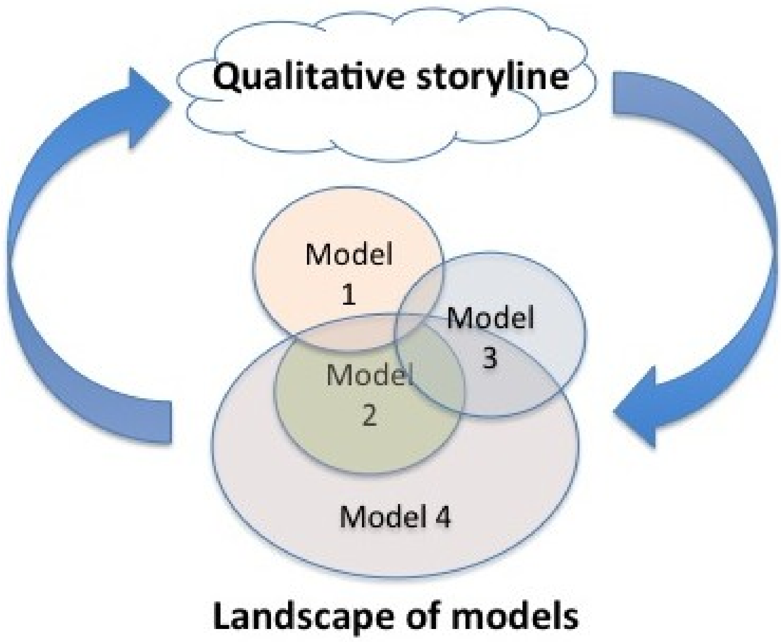
Keywords

Scenarios, storylines, quantitative models, energy, climate change, interdisciplinary, transition pathways

Highlights

- Linking qualitative storylines with multiple, diverse quantitative models
- Landscape of models for mapping the fields of expertise of individual models
- Interdisciplinary analysis of the UK power system transition until 2050

Graphical abstract



1. Introduction

Scenario exercises in energy, climate change and other technology- and environment-related studies are based on qualitative storylines, quantitative models or, often, on a combination of both [1-6]. Storyline-based scenarios are expressed as qualitative narratives that in length may range from brief titles to very long and detailed descriptions. Examples of such scenarios are the Tyndall decarbonisation scenarios [7, 8], the CLUES decentralised energy scenarios [9] or the energy visions in Switzerland [10, 11]. The value of such storylines is threefold [2, 4, 12-14]. First, when these storylines are developed through engagement of experts and stakeholders, they combine multiple perspectives and sources of expertise [2]. They may lead to novel and creative ways of thinking about the future that go beyond modelling insights. Second, storylines are key for communicating the results of scenario exercises. Due to their qualitative nature, they are accessible and memorable to a broad range of audiences. When developed through stakeholder engagement, they are likely to be accepted, supported and used more often [15]. Third, storylines represent a much broader picture than quantitative models and encapsulate a number of softer and subtler aspects that cannot yet be modelled [16]. Storylines thus can form the input assumptions to the quantitative models and embed these models into a bigger picture [17, 18]. However, storylines have two key limitations. First, storylines alone at times may be detached from reality as even experts can have a limited understanding of whether a particular storyline is feasible [10, 11, 15]. Second, as storylines are developed by combining multiple views of experts and stakeholders, they can be considered biased, not reproducible and not transparent [2]. Despite the current research on formal techniques for developing better storylines [5, 12, 19-21], these limitations still remain.

Quantitative models-based scenarios are produced by a single or multiple models, such as in the ADAM [22], Energy Modelling Forum [23], Low Carbon Society modelling [24] and NEEDS [25] projects. The key strength of these scenarios is that they satisfy the inherent need for numeric values in the technology- and environment-related fields [2, 10, 14, 15]. Models are based on the actual data, laws of physics, principles of economics and state-of-the-art knowledge about the technology and environmental processes. Thus, peer-reviewed, transparently documented models provide rigorous, internally consistent scenarios. However, models can address only a limited number of aspects, such as technology, economic, environmental aspects. But they still have difficulty in capturing the afore-mentioned softer and subtler aspects. The key research tendencies are towards developing more detailed models and including softer aspects, such as behaviour and governance, into models [17, 26]. Yet, even better models alone can hardly offer the breadth and engaging nature of the storyline-based scenarios.

In light of these strengths and weaknesses of storylines and quantitative models, state-of-the-art scenario studies argue for combining them [1-6]. Many recent scenario exercises already have the elements of both: storylines include numbers, while modelling outputs are described in short qualitative narratives. Several scenario exercises explicitly combine the storylines and the quantitative models in an iterative manner [6, 10, 11, 27-29]. Examples of these include key international scenario exercises: the integrated climate change scenarios of the Intergovernmental Panel of the Climate Change [30, 31], the scenarios of ecosystem services in the Millennium Ecosystem Assessment [32] and of the global environment in the Global Environmental Outlook [33]. This approach is thus also used for analysing the UK power system transition pathways until 2050 in the Realising Transition Pathways (RTP) project.

The RTP project is a continuation of the original Transition Pathways project. Grounded in the conceptual framework of socio-technical transitions [34], the original Transition Pathways project combined historical and future-oriented, technical, environmental and social perspectives into an interdisciplinary analysis of the future UK power system transition [35-37]. Three transition pathways—*Central Co-ordination*, *Market Rules* and *Thousand Flowers*—were elaborated in this preceding project [37, 38]. Every of the three transition pathways encapsulated a storyline (or a narrative), its quantitative representation (a scenario) as well as a range of additional analyses, such as the analyses of branching points and actors' choices and power system modelling. In the succeeding RTP project, a structured process was envisioned and implemented for linking these original storylines with the insights from multiple models, available in the RTP project. This process is reported here for one of these storylines, namely *Central Co-ordination*.

Despite the fact that combination of storylines and quantitative models starts emerging as an established practice in the technology- and environment-related fields [1-6], existing literature runs short in providing methodological insights for how to link such storylines with multiple models. First, the RTP storylines are very detailed (four to five pages) and numerous additional assumptions are needed to 'translate' them into model parameters. Second, there are six power system models and two appraisal techniques available in the project. They are very diverse and differ in their disciplinary perspective (technical feasibility, economic or environmental appraisal), model objective, the parts of the power system addressed and the format of inputs and outputs. This diversity is valuable because the storylines can be addressed from multiple angles, but it is challenging to relate such diverse models to each. Thus, a new approach had to be developed for linking such detailed storylines with multiple, very diverse models. To the best of the authors' knowledge, this is the first structured attempt to bring together such diverse range of models for fleshing out a storyline. Although it is the first attempt, it is highly relevant. There is a growing number of similar interdisciplinary projects, like the RTP project [39]. It can be expected that many of these projects will attempt to develop scenarios by linking storylines with multiple models. Pulling together a number of existing models is a challenge in itself, in addition to their linking with the storylines. This paper provides some methodological insights for organising these processes.

This paper is laid out as follows: Section 2 provides the essential background about the UK power system, the RTP project, the *Central Co-ordination* storyline and the models and appraisals; Section 3 introduces the process used for linking the storyline with the multiple models; Section 4 discusses the results and the process; Section 5 concludes.

2. The case of the UK power system transition

2.1. UK power system and the RTP storylines

In the 1990s the UK underwent a major process of liberalisation of its power market and privatisation of its companies [40, 41]. With about three quarters of power produced in fossil fuel-based plants, this market-led approach came under significant pressure in the last decade due to growing climate change concerns. The UK government undertook several key interventions. In 2008 the UK adopted the Climate Change Act, supported by all major political parties, which sets a legally binding target to cut the country's greenhouse gas emissions by 80% by 2050 as compared to the emission levels of 1990. In line with [42], the major decarbonisation of the power sector, together with substantial levels of electric heating and transport, are seen as the key measures to reach this target. However, replacement of the aging coal and nuclear power plants and significant investments in transmission and distribution requires massive investment. An increased deployment of renewable energy sources raises concerns over their intermittency and, thus, supply security. Therefore, this decarbonisation challenge does not stand alone and is a part of the so-called energy policy 'trilemma' of decarbonisation, affordability and supply security [37, 43]. The Energy Bill, released in 2012, and especially its part on Electricity Market Reform, attempts to mediate between these three corners of the 'trilemma' [44]. The Energy Bill aims to set a policy framework for the power system transition that meets the 'trilemma.'

In light of these developments, the RTP project aims to shed light on the potential transition pathways of the UK power system until 2050. Three transition pathways were developed: *Central Co-ordination*, *Market Rules* and *Thousand Flowers* [37, 38]. Compared to other scenario exercises in the UK [7-9, 45] and elsewhere, these pathways are novel because they include storylines that specifically focus on the role of governance 'logics' and multiple actors in actively shaping the power system transition. Traditionally in scenario studies, storylines are used for representing key uncertainties such as population growth, technological development and others, c.f. [30-33]. The RTP storylines explicitly focus on the uncertainty around governance 'logics' and the choices of actors.

The process of developing of these three storylines is described in detail in [37]. In brief, the first version of the storylines was developed in the original

Transition Pathways project in a stakeholder workshop in 2008. The technical feasibility, social acceptability and the sustainability of the first version of the storylines were then interrogated in further workshops with experts and key stakeholders, who represented energy companies, policy-makers and non-governmental organisations. This interrogation led to the revised version 2.1 of the pathways, which is currently the latest version. The complete storylines are available online at [38] and shorter summaries are published in [37]. Every storyline consists of four to five pages of qualitative description, a list of key risks for the realisation of the specific storyline and an overview table. Afterwards, a Transition Pathways Technical Elaboration Working Group was set up from the experts in the project in order to assign a quantitative representation for every storyline. This quantitative representation shows the numeric values of the total UK power demand and the power generation mix until 2050 [37]. This process, however, was partly informed by insights from three models, but none of these models were informed by economic considerations [37]. In the succeeding RTP project, there are more models available, of which some include the economic considerations. Therefore, a more structured process was undertaken for linking the storylines with insights from multiple models. In so doing it will show how iteration between storylines and models can fruitfully enhance the process of developing and analysing the broader transition pathways.

2.2. The Central Co-ordination storyline

The *Central Co-ordination* storyline, analysed in this paper, is one of the three storylines of the RTP project: *Central Co-ordination*, *Market Rules* and *Thousand Flowers*. These storylines respectively picture three ideal types of governance 'logics' in the UK power system (Figure 1): government, market and civil society 'logics'. The different groups of actors are assumed to frame their view and enrol the other actors into their 'logic' [37]. In the case of the *Central Co-ordination* storyline, the central UK government argues for the dominant role of the direct co-ordination and the national government actors to deliver the energy policy goals. In the *Market Rules* storyline, the market actors argue that the energy 'trilemma' is best achieved by the large power companies and other market actors, freely interacting with the policy framework. The investment, made by the large power companies on the basis of investment return (including carbon price effects), available knowledge, regulatory framework and incentives set by the government, will determine the power system transition. The *Thousand Flowers* storyline argues that civil society shall take an active role in delivering the low-carbon transition as small-scale solutions through community-led initiatives and energy service companies (ESCOs). The key recent developments in the UK power sector are described as a hybrid between the *Central Co-ordination* and the *Market Rules* storylines [46]. Since the power market liberalisation in 1990s, the market 'logic' has been dominating in the UK, but the influence of the government 'logic' is increasing in the recent years, especially after the adoption of the legally binding emissions target. The *Central Co-ordination* storyline is therefore chosen for in-depth analysis in this paper.

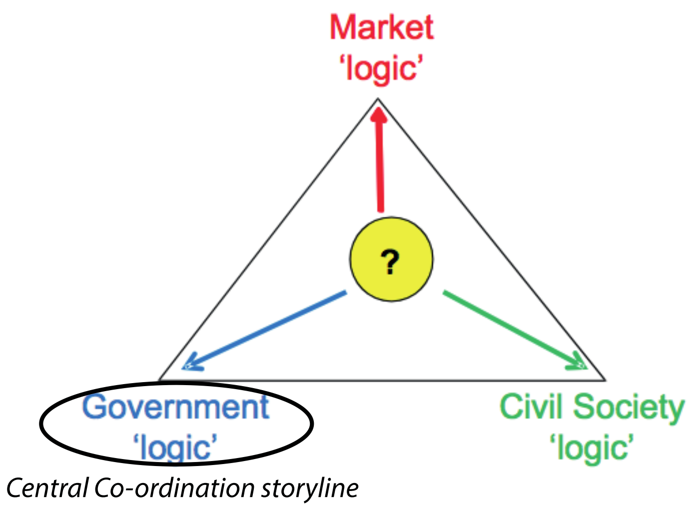


Figure 1. The three ideal types of governance 'logics' in the UK power system transition. Source: J. Burgess and T. Hargreaves. The figure is reproduced from [37].

In the *Central Co-ordination* storyline, the central UK government will actively shape the power system transition through the establishment of Strategic Energy Agency. This agency will issue tenders for tranches (central contracts) for particular types of low-carbon generation and develop 'technology push' programmes for low-carbon technologies. In order to promote UK industry, the agency will primarily support those technologies where the UK has a potential to become a global leader: marine renewables (offshore wind, wave and tidal power), carbon capture and storage (CCS) and electric vehicles. This strong government commitment will underwrite the investment risks for the large power companies. These companies will invest according to the government's plans and deliver the transition, dominated by large-scale power generation. The government will focus on removing the system-wide blockages, such as the lack of transmission capacity, planning issues, supply chains and skills. As a result, the emission mitigation target of 80% by 2050, as compared to the year 1990, will be achieved. As noted, civil society will remain a relatively passive player in this storyline. Initially, only non-behavioural measures of demand response will be used, such as increased efficiency standards for appliances and newly built buildings. Later, with the increased industrial and climate benefits, the interventions on the lifestyles and behaviour will be undertaken by the government. The key risks, identified in the storyline for the realisation of this transition, are the (i) technical and economic feasibility of CCS, (ii) public opposition to costly low-carbon investment due to increased household expenditure, (iii) little effort to incentivise behaviour change of the energy users. The more detailed storyline is also provided in Table 2, where this storyline is linked with six models and two appraisals. In addition to the qualitative narrative, the *Central Co-ordination* storyline was already assigned an initial quantitative representation (Figure 2), developed in an iterative process by the Transition Pathways Technical Elaboration Working Group.

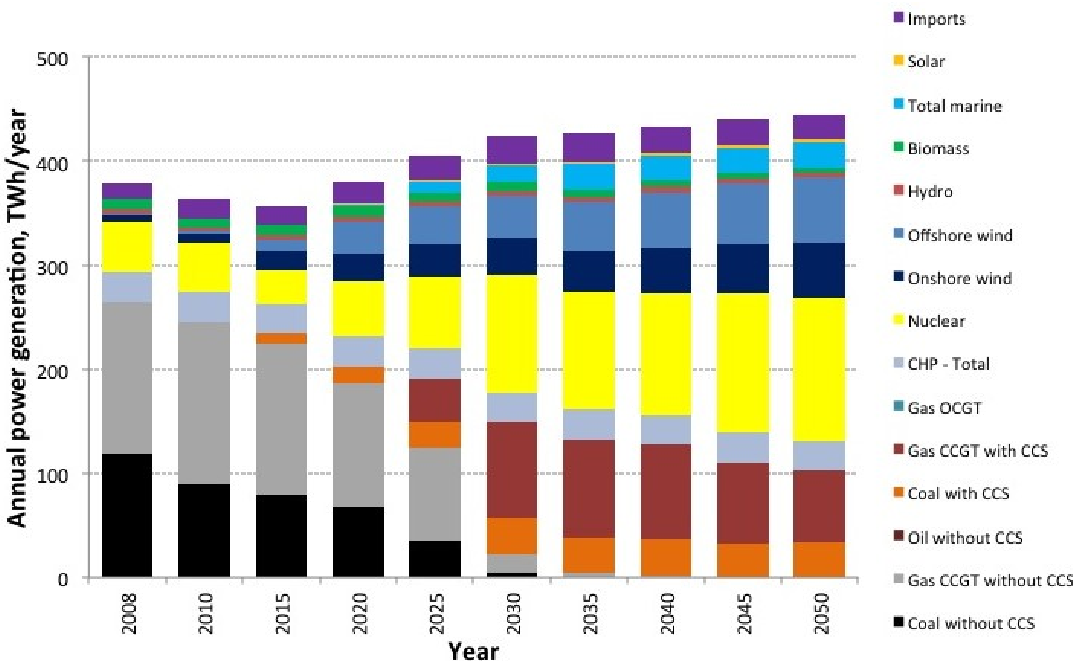


Figure 2. The initial quantitative representation of the *Central Co-ordination* storyline. Source: Transition Pathways project. The figure is reproduced from [37].

2.3. Eight models of the RTP project

This section describes the six power system models and two appraisal frameworks (also called 'models') that were linked in this paper to the *Central Co-ordination* storyline. These models are very diverse and this diversity is a strong point as there is not a single best model or methodology that encapsulates all the relevant aspects [16]. The RTP leadership envisioned a multi-model analysis, expecting that this analysis, rather than results of a single model, has potential to provide a broader spectrum of insights.

The eight models used are (in the order of the breadth of the power system boundaries):

- **Demand**: The energy demand model, developed at the University of Surrey, is a bottom-up model of the UK power demand in the domestic and non-domestic sectors. Due to its highly disaggregated structure, the influence of a range of parameters can be modelled, such as the energy service levels, user practices, choices of appliances, building fabric, fuels, deployment of distributed generation and others. The model is based on the synthesis of existing estimates [47-49] and the assumptions from the *Central Co-ordination* storyline.

- **FESA:** The Future Energy Scenario Assessment model [50, 51], developed at the Loughborough University, is a single-year UK power generation and demand model, incorporating one-hour time step for dispatch modelling and using real weather data of temperature, wind speeds, wave height and solar radiation. The model develops scenarios on the basis of the *Central Co-ordination* storyline and technical feasibility constraints.
- **D-EXPANSE**: The D-EXPANSE model (Dynamic version of EXploration of PAtterns in Near-optimal energy ScEnarios), developed at the University College London, has the structure of a bottom-up power system model. In addition to the cost optimisation, D-EXPANSE systematically explores the maximally different near-optimal pathways [15, 29, 52, 53]. In this way, D-EXPANSE aims to open up the understanding of the fundamentally different ways how the UK power system could evolve. By allowing the deviation from the cost-optimal pathway, D-EXPANSE also explores the structural uncertainty around the concept of rationality and cost-optimisation. The D-EXPANSE model has been validated by comparing its outputs with the results of existing, well-established whole system models and cost estimates for the UK [53].
- **EconA**: The Economic Appraisal (EconA), conducted by University College London, aims to evaluate the investment needed, costs, benefits and the related risks and uncertainties of the transition pathways. The EconA is an appraisal technique; it takes the quantitative representation (Figure 2) of the *Central Co-ordination* storyline and appraises it. In this paper, the Econ A is also considered as a model in a broader sense.
- **BLUE-MLP**: The BLUE-MLP model (Behaviour Lifestyles and Uncertainty Energy model with Multi-Level Perspective on transitions) is a probabilistic systems dynamic simulation that explores the uncertainties due to sector- and actor- specific

behavioural elements [54, 55]. These behavioural elements include market heterogeneity, intangible costs and benefits, hurdle rates, replacement and refurbishment rates and demand elasticities. In addition, the model links these behavioural uncertainties with the multi-level perspective to transitions [34], where landscape (government decisions and the international context), regime (the current UK power system structure and its regulation) and niche innovations (lifestyle influenced changes in demand) interact with each other.

- **EEA**: The Energy and Environmental Appraisal (EEA) is conducted by the University of Bath [56, 57]. It aims to evaluate the 'whole system' (from cradle to gate) greenhouse gas emissions and other environmental impacts, such as human toxicity, particulate matter formation and agricultural land occupation. Similarly to the EconA, the EEA framework is a model in a broader sense as it appraises the *Central Co-ordination* storyline, based on its initial quantitative representation (Figure 2).
- **HESA/UK+**: This is a combination of the Hybrid Energy System Analysis tool (HESA) and the Strathclyde UK+ models that were developed at the University of Strathclyde [58-60]. Strathclyde UK+ model contains all the information for the transition pathways scenarios with spatial disaggregation (17 onshore, five offshore zones and 39 connections) of generation, storage, transmission and distribution. It is linked to the HESA model, which cost-optimises the system, based on the energy hub concept [61, 62]. The national power demand and generation mix are used as input assumptions.
- **HAPSO**: The Holistic Approach to Power System Optimisation model (HAPSO) is developed at the Imperial College London. It is a bottom-up, cost-minimisation model that determines the optimal generation, energy storage, transmission, and distribution network infrastructure requirements and their associated cost to achieve the objectives: economic efficiency, security, sufficient system controllability. The model optimises simultaneously the long-term investment and short-

term operating decisions including hourly generation dispatch, Demand Side Response, storage cycles, and power exchanges taking into account the impact of decisions across all sectors in power system [63]. The UK power system is embedded in the European power system including UK, Ireland and continental Europe and thus allows for modelling of the power exchange across these regions.

Understanding and mapping the breadth and depth of the expertise of every individual model in a multi-model analysis is challenging, especially given such a diverse set of models. Here this mapping is attempted in two ways. First, Table 1 lists the key characteristics of the models. Based on that, the ***key field of expertise*** is identified for every model. This key field of expertise is the types of insights that a particular model analyses in most depth, as compared to the other seven models. This concept of the key field of expertise thus appreciates the distinct value of every model in this multi-model analysis.

Second, Figure 3 provides a visual mapping of the eight models; this map is called the ***landscape of models***. It aims to summarise the information about the breadth and depth of the analysis, done by every model, and to show how these fields of expertise overlap between the models. This mapping is done on the basis of the parts of the power system addressed (demand; generation; dispatch, demand response and storage; transmission and distribution; and interconnectors with Europe) and other thematic considerations addressed by the model (analysis of the maximally different alternatives; uncertainty; behaviour and heterogeneity of actors; economic considerations; environmental considerations; and spatial disaggregation). These thematic considerations are specific to this analysis and might differ for analyses with other sets of models. The depth of analysis is defined in three categories: detailed modelling (the key field of expertise), stylised modelling and exogenous assumptions only.

Both Table 1 and Figure 3 help to show that the eight models, used in this analysis, cover a broad spectrum of insights. To some extent these models overlap. If models overlap, then they can validate each other and help cross-checking the results. Every model, however, always has at least one area where it outperforms the other models in depth or breadth. And this shows that there is no single best model that covers all the aspects in depth; all of the eight models are useful as none of them alone covers all the relevant aspects in depth. The concept of the key field of expertise of every model is thus especially useful here. It shows which conclusions of which model shall be prioritized over the conclusions of other models. The conclusions that are derived from the key fields of expertise of a specific model shall be weighted more than the conclusions on the same topic of the other models.

Table 1. Summary of the eight models (model versions as of April 2013)

Model	**Demand**	**FESA**	**D-EXPANSE**	**EconA**	**BLUE-MLP**	**EEA**	**HESA/UK+**	**HAPSO**
Spatial scope	UK, single region	UK, single region	UK, single region	UK, single region	UK, single region	UK, single region	UK, 17 onshore and 5 offshore regions	UK, 5 regions Europe, incl. UK, Ireland and continental Europe
Finest temporal resolution	1 year	1 hour	5 years	1 year	1 year	1 year	1 year	1 hour
Parts of the power system addressed								
--Power demand	Total demand; Demands by users, energy services, end-use equipment	Total demand; Demands by users, energy services, end-use equipment	Total demand	Total demand	Total demand; Demands by users and energy services	Total demand	Total demand	Total demand; Demands by users and energy services
-- Power generation	Decentralised generation	Large-scale generation; Decentralised generation	Large-scale generation; Decentralised generation	Large-scale generation; Decentralised generation	Large-scale generation	Large-scale generation; Decentralised generation	Large-scale generation; Decentralised generation	Large-scale generation; Decentralised generation
-- Dispatch, demand response and storage		Dispatch; Demand response; Storage, incl. hydrogen	Dispatch (stylised)		Dispatch (stylised); Demand response		Dispatch; Storage	Dispatch; Demand response; Storage
-- Trans-mission and distribution						Transmission and distribution	Transmission and distribution	Transmission and distribution
-- Inter-connectors to Europe		Import; Export	Import	Import		Import	Import; Export	Import; Export; UK embedding in the European

Model	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
								system
-- Non-electric parts of the energy system	Non-electric heating	Non-electric heating; Non-electric transport			Non-electric heating; Non-electric transport; Non-electric industrial and commercial uses		Non-electric heating	
Method for constructing alternative pathways (scenarios)	Modifying the assumptions according to the storylines	Modifying the assumptions according to the storylines; Merit order of power generation	Cost-optimisation and evaluation of maximally different near-optimal pathways	Input from other models	Dynamic simulation	Input from other models	Cost-optimisation	Cost-optimisation
Economic considerations			Cost-optimisation; Exploration of near-optimal pathways	Post hoc assessment	Dynamic simulation, given the heterogeneous sensitivity of the different actors to costs		Cost-optimisation	Cost-optimisation
Environmental considerations		Post hoc assessment; Operational emissions (from primary energy use); Only CO_2 emissions	Emission constraint; Operational emissions; Only CO_2 emissions	Input from other models	Post hoc assessment; Operational emissions; Only CO_2 emissions	Post hoc assessment; 'Whole system' emissions (upstream and operational); Greenhouse gas emissions (CO_{2eq}); Human toxicity; Particulate matter; Agricultural land occupation	Post hoc assessment; Operational emissions; Only CO_2 emissions	Emission constraint; Operational emissions; Only CO_2 emissions

Model	**Demand**	**FESA**	**D-EXPANSE**	**EconA**	**BLUE-MLP**	**EEA**	**HESA/UK+**	**HAPSO**
Treatment of uncertainty			Structural uncertainty around cost-optimisation; Parametric uncertainty accommodated to some extent through maximally different, near-optimal pathways	Parametric uncertainty considered through ranges for uncertain parameters	Parametric uncertainty considered through probabilistic modelling			Parametric uncertainty considered through sensitivity analysis
Treatment of behaviour and heterogeneity of actors			Considered to some extent through deviations from cost-optimal pathway		Detailed modelling			
Key field of expertise	***Demand***	***Dispatch, demand response and storage; Generation***	***Maximally different alternatives; Uncertainty***	***Economic appraisal***	***Uncertainty; Behaviour and heterogeneity of the actors***	***Energy and environmental appraisal***	***Transmission and distribution; Generation; Spatial disaggregation***	***Dispatch and demand response; Generation; Transmission and distribution; Interconnectors***

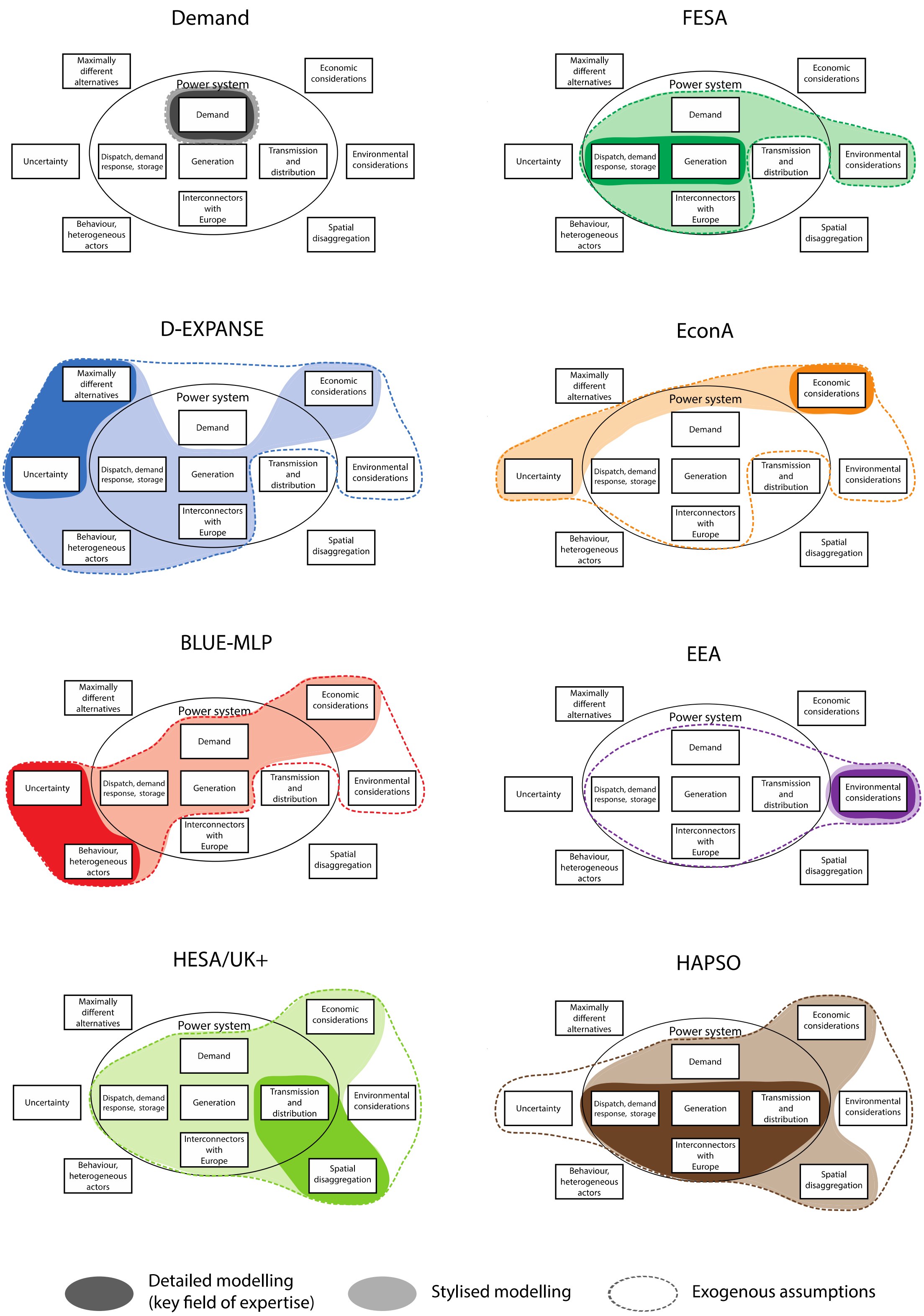


Figure 3. The landscape of models (model versions as of April 2013)

3. The process of linking the storyline with the multiple models

This Section describes the process (Figure 4) of linking the *Central Co-ordination* storyline with the insights from the eight models. First, the qualitative storyline is ‘translated’ into a set of harmonised assumptions that are necessary for conducting the model runs, specifically tailored for this storyline (Section 3.1). The models are then run with these harmonised assumptions. Second, the outputs from the models are used for revisiting the qualitative statements of the storyline (Section 3.2). Generally, neither the storyline nor the multiple models are fixed; they are all being updated given the new developments in the real world, new data sources, feedback from peer review and so on. Thus, in line with [2], the process from Figure 4 is repeated iteratively for updating the storyline.

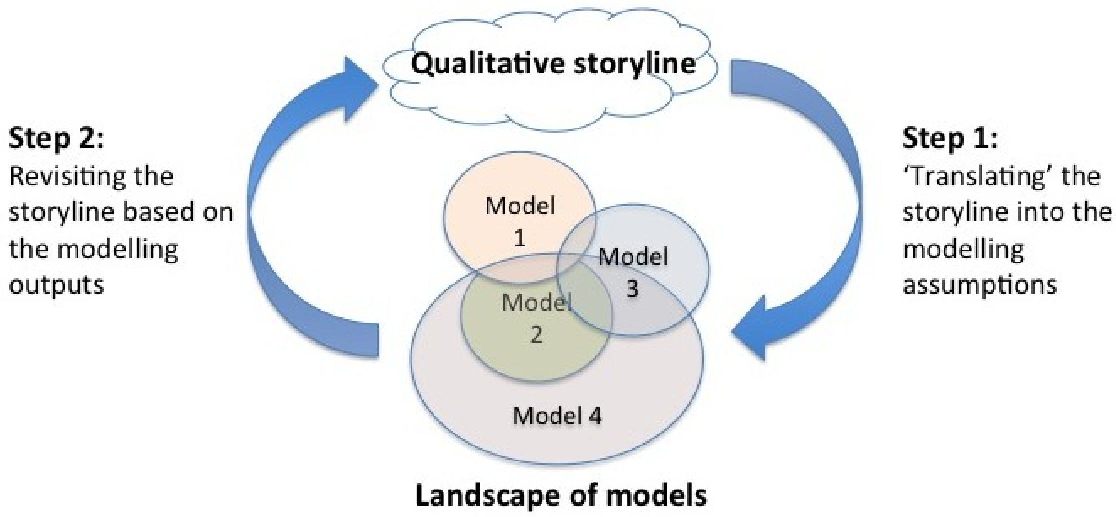


Figure 4. The iterative process of linking storylines with multiple quantitative models

3.1. Step 1: ‘Translating’ the storyline into the modelling assumptions

‘Translating’ such a detailed storyline *Central Co-ordination* [37, 38] into a set of harmonised assumptions that will be used by the models is a challenging task. On the one hand, these harmonised assumptions will already be a narrower representation of this qualitative storyline that is rich in detail. This is reasonable as quantitative models always represent only a part of the bigger, qualitative picture [10]. On the other hand, these quantitative assumptions should not be too narrow and should allow enough flexibility for the quantitative models to express their perspective and to make their distinct contributions. Every model has a broad range of other, model-specific assumptions. As the multiple models used for this analysis are very diverse, it is desirable to harmonise the list of the assumptions so that they could be implemented in all of the models. As a result, there are a lot of possible variations and a certain share of subjectivity involved in the process how a storyline is 'translated' into the model assumptions.

For translating the *Central Co-ordination* storyline into the harmonised modelling assumptions, several key aspects of this storyline are taken. These aspects are: (i) a mild growth of the power demand due to the incentives for end-use energy efficiency, (ii) the increased use of large-scale low-carbon technologies, especially of those where UK industry could take a global lead, and a medium uptake of decentralised generation, (iii) the achievement of the emission mitigation goals and (iv) low risk of investment due to the tenders for tranches, issued by the Strategic Energy Agency. More specifically, the models are tuned to match these harmonised assumptions as closely as possible:

i. Total power demand in the UK:
   - In 2020, the total power demand, including losses, stabilises at 350 TWh/year;
   - In 2030, it increases to 390 TWh/year due to increased electric heating and electric vehicles;
   - In 2050, it is equal to 410 TWh/year.

ii. Power generation mix in the UK:
   - In 2020, 40% of the produced power comes from low-carbon sources, prioritising coal CCS, nuclear and renewable sources. At least 25% of the produced power comes from renewable sources, such as offshore and onshore wind, wave, tidal barrage and tidal stream.
   - In 2030, the power generation mix bridges the mixes of 2020 and 2050.
   - In 2050, 75% of total produced power comes from large-scale low-carbon sources, such as nuclear, coal and gas CCS, offshore wind, wave, tidal barrage and tidal stream. At least, 25% comes from low-

carbon decentralised sources, such as onshore wind and biomass combined heat and power (CHP) plants.

iii. Greenhouse gas emissions:
   - In 2020, the average carbon intensity in the whole UK power system is 300 gCO_2/kWh of power produced;
   - In 2030, this value drops to 30 gCO_2/kWh;
   - In 2050, it is as low as 20 gCO_2/kWh.

iv. Investment:
   - Social discount rate of 3.5% is used for the calculation.

Not all of the eight models can implement all of these harmonised assumptions. First, the Demand, FESA models and EEA cannot consider the last assumption about the discount rate as they do not consider costs at all. They, therefore, by-passed this assumption, but implemented the remaining assumptions. Second, the EconA and EEA are appraisal techniques and require inputs about the whole power demand structure and generation mix rather than modelling assumptions. Thus, the EconA and EEA are conducted on the basis of the initial quantitative representation of the storyline (Figure 2), which is in line with the harmonised assumptions described above.

3.2. Step 2: Revisiting the storyline based on the modelling outputs

The qualitative statements from the *Central Co-ordination* storyline are scrutinised from the perspective of the outputs of every model. The storyline pictures the governance arrangements and the role of the different actors and these can hardly be interrogated by the models. But the description of the outputs of these different governance arrangements and the actors' decisions is analysed. For example, the statement "In the financial budget statement in April 2009, the UK Government formally adopts carbon budgets for the periods 2008-12, 2013-17 and 2018-22 based on a 34% reduction in greenhouse gas (GHG) emissions by 2020 from 1990 levels" [38, p. 1] is not analysed as it describes the intention of the government. But, the statement "This is realised by the achievement of 25% of electricity to be generated from renewables by 2020" [38, p. 3] is interrogated by the eight models. The landscape of models (Figure 4) plays an important role here as it helps to highlight the key fields of expertise of every model. In this way, it becomes possible to prioritise the models in scrutinising the specific aspects of the storyline, such as the demand, generation, economic appraisal and so on.

4. Results and discussion

4.1. Revisiting the Central Co-ordination storyline

Table 2 presents the summarized results of revisiting the *Central Co-ordination* storyline from the perspective of the eight RTP models; detailed results are available in the Electronic Supplementary Material. Every qualitative statement about the outcomes of the governance and actor choices, specified in the storyline, is compared and contrasted with the modelling results.

From the perspective of these eight models, the *Central Co-ordination* storyline is fairly robust (as there are few red cells in Table 2). It can be seen that the storyline is almost completely supported by the Demand, FESA and HESA/UK+ models. This is no surprise because these three models specialise in technical feasibility assessment of the power system transitions. These models can be tailored to mimic the storyline and identify only the key mistakes of technical feasibility. Moreover, the researchers, who work with these models, played an active role in the Technical Elaboration Working Group in the original Transition Pathways project. Thus, the storyline is already partly informed by these models and it is not surprising that there is no divergence. The majority of the diverging insights come from the BLUE-MLP, HAPSO and D-EXPANSE models. These models include a broader range of considerations than technical feasibility (Table 1): heterogeneous behaviour of the key actors, uncertainty, detailed dispatch modelling and maximally different alternatives. Thus, naturally these models question the *Central Co-ordination* storyline more.

Although the results from the eight models are in line with most statements of the *Central Co-ordination* storyline, several clusters of diverging insights are identified. First, the storyline described only a mild increase in the total power demand (20% higher in 2050 as compared to 2008) due to energy saving behaviour and efficiency improvements. However, the BLUE-MLP model shows that, when the heterogeneity of the behaviour of the different actors is considered, maintaining slow power demand growth through the entire model horizon appears rather wishful thinking. Storylines developed by the various stakeholders and experts often tend to be overly optimistic and fragile from the modelling perspective [10, 11]. This remark is also consistent with a broader argument that failures of effectively mitigating climate change can be expected [64]. The *Central Co-ordination* storyline envisions a passive role of the civic society. Without the voluntary energy saving action of the civil society, drastic demand reduction may be challenging to achieve. The UK government could enforce some types of measures for mitigating the power demand, such as smart meters, efficient domestic appliances or refurbishment of buildings. But in a democratic society, a rapid and massive implementation of such measures may be problematic. Thus, the expectation from the storyline about the demand needs to be revisited.

The *Central Co-ordination* storyline aspired to the retirement of existing coal and gas power plants by 2037 and their replacement with low-carbon technologies, such as renewable energy sources or gas and coal with CCS. However, both the D-EXPANSE, BLUE-MLP and HAPSO models, which also model the demand response potential, show that this aspiration is challenged by the dispatch (supply-demand balancing) constraint. According to the models, for the aspired high deployment of renewable energy sources there will be a need for significant levels of back-up capacity, mostly gas OCGT power plants. D-EXPANSE model, which explores the maximally different pathways, shows that at least 15 GW of gas power plants would be required. The power generation mixes of BLUE-MLP also include 15 GW of gas or coal power plants. The HAPSO model, which evaluates the cost-optimal pathway while taking into account energy security requirements, proposes 50GW of gas OCGT. The value is higher than the one suggested by the D-EXPANSE and BLUE-MLP models because the HAPSO model assumes higher supple security requirements. Overall, the complete retirement of fossil fuel based power plants is questionable and the results suggest that the storyline needs to include more of that type of plant. As highlighted in Figure 2, the dispatch modelling is the key field of expertise of the

HAPSO model. Thus, its conclusion about the 50GW of gas OCGT by 2037 shall be prioritized over the D-EXPANSE and the BLUE-MLP conclusions.

The FESA, BLUE-MLP, EEA, HESA/UK+ and HAPSO models all agree that the target of the greenhouse gas emissions in 2035 would not be met. Instead of the aspired 30 gCO_2/kWh in the storyline, the modelling outcome range from 33 gCO_2/kWh to 54 gCO_2/kWh for CO_2 for operational emissions and equals to 120 gCO_{2eq}/kWh for the 'whole system' (cradle to gate) emissions. The D-EXPANSE model shows a number of power generation mixes that could meet the target of 30 gCO_2/kWh, but these mixes are different from the mixes evaluated by the other models. Thus, while reaching the emission target can be technically feasible, this may not be realistic via the means that the storyline describes. According to the EEA, if the 'whole system' emissions were considered, then the target would also be missed (although a different target for the 'whole system' emissions could be expected). Thus, either the achieved levels of emissions or the measures (power demand and generation mix) need to be revisited in the storyline.

When the *Central Co-ordination* storyline was initially developed in the Transition Pathways project, it had little insights from the experts and models, informed by the economic considerations [37]. This is reflected in the points of divergence between the models and the storyline about the power generation mix. The D-EXPANSE, BLUE-MLP and HAPSO models, which include information about costs, the cost-optimal and near-optimal decisions of actors, both include more nuclear power than anticipated by the storyline. The D-EXPANSE model prioritises onshore and offshore wind power as renewable energy sources rather than wave and tidal power, as envisioned in the storyline. The BLUE-MLP model includes a much more significant deployment of nuclear power due to its costs and emissions performance. The HAPSO model raises concerns about significant curtailment of the power produced by the renewable energy sources due lack of market integration and subsequent development of interconnectors between the UK and the continental Europe. This significant curtailment would reduce the economic feasibility of these sources. While the storyline also describes a high deployment of gas and coal CCS, the D-EXPANSE model shows that many of the cost-optimal and near-optimal pathways could have no CCS in the generation mix. The HAPSO model also questions the large deployment of CCS because, from the dispatch perspective, these plants would run on a low capacity factor (24% to 36%) and thus their economic feasibility is challenged. In brief, these results suggest that a revised version of the *Central Co-ordination* storyline should consider a higher share of nuclear and wind power, but a more pessimistic deployment of coal and gas CCS and other types of renewable energy sources.

The *Central Co-ordination* storyline identifies the technical and economic feasibility of CCS as one of the key risks for implementing the storyline. While most of the eight models include a share of coal and gas CCS, the D-EXPANSE model shows that this is not a prerequisite. D-EXPANSE generates a large number of maximally different cost-optimal and near-optimal scenarios (30% deviation from the least cost scenario). Many of these scenarios do not have CCS. This means that the coal and gas CCS are not prerequisites for implementing the *Central Co-ordination* storyline, as it is described in the harmonised assumptions. As coal and gas CCS is a relatively costly technology, it appears seldom in the cost-optimal and near-optimal scenarios. In the D-EXPANSE modelling outputs, the environmental gains of the coal and gas CCS are rather replaced by the deployment of other low-carbon technologies (renewable sources and nuclear power), while the role of back-up capacity of coals and gas CCS power plants is compensated by coal and gas plants without CCS. The BLUE-MLP model also provides a range of power generation mixes without CCS. Thus, instead of suggesting the feasibility of CCS as the key risk, these results seem to imply that *Central Co-ordination* storyline shall consider other risks that are highlighted by diverging insights from the eight models. One of these key risks is the supply-demand balancing challenge. As the HAPSO, D-EXPANSE and BLUE-MLP models show, supply-demand balancing may be a big challenge in the *Central Co-ordination* storyline and this may cause public concerns over supply security. Another key risk is the failure to meet the greenhouse gas emissions target. The results of these multiple models from Table 1 already show that the target might be missed in 2035. This failure would become even more likely if, in order to meet the balancing challenge, the needed gas power plants would be installed as the back-up capacity. The third key risk is the need for nuclear power, which—as the recent years show—may cause a high public resistance.

Despite the fact that the *Central Co-ordination* storyline is very detailed, it seems to miss or under-represent several aspects that are analysed in the eight models (Figure 3). The storyline does not describe any arrangements regarding power import and export as well as the relations with the other European countries, as modelled by the HAPSO and D-EXPANSE models. The storyline does not discuss the governance arrangements and the choices of actors about the power transmission and distribution grid, covered by the HESA/UK+ and HAPSO models. The demand response levels, important for the dispatch modelling by the FESA, HAPSO and other models, have also been only described to a limited extent. The D-EXPANSE and BLUE-MLP models analyse the influence of parametric and structural uncertainty on the power system transition, but these insights are so far not incorporated into the storyline. The above-listed aspects could be considered, when developing the next version of the storyline.

Table 2. Revisiting the storyline with the multiple models (detailed documentation is available in the Electronic Supplementary Material). **Green** colour means that the model outputs are in line with the storyline, **yellow** – that there is a minor divergence, **red** – that the storyline statement contradicts the model outputs, **white** – the particular statement is not addressed in the model.

Some of the relevant quotes from the storyline, taken from [38]. The complete list of quotes is available in the Electronic Supplementary Material	**Demand**	**FESA**	**D-EXPANSE**	**EconA**	**BLUE-MLP**	**EEA**	**HESA/ UK+**	**HAPSO**
2008 -2022								
"By 2020, the energy efficiency measures have led to the stabilisation of electricity demand."								
"This policy involves a risk being passed to consumers of experiencing higher than average electricity costs, if the price of natural gas does not rise significantly."								
"By 2020, <…> the relative decarbonisation of electricity supply has led to the achievement of the carbon budget of a 34% reduction in CO_2 emissions, compared to 1990 levels."								
"This is realised by the achievement of 25% of electricity to be generated from renewables by 2020."								
"High levels of deployment for onshore (8GW) and offshore wind, (10GW) which operates at over 40% capacity factor; the first operational CCS coal plant; and four new (1.6 GW) nuclear power stations."								
2023 -2037								
"Remaining other coal and gas power stations are retired as they reach the end of their life."								
"This leads to the further penetration of onshore and offshore wind (though at a lower rate of deployment than in earlier periods) and scaling up of wave and tidal power schemes, as a result of experience gained through earlier demonstration projects."								
"The commercial viability of CCS increases, thanks to earlier investment in demonstration projects and a high carbon price."								
"A total of 12 new (1.7 GW) nuclear power stations being in operation by 2030"								
"Energy service demand reduces, thanks to household and industrial energy efficiency measures"								
"The [electric vehicle] fleets are coordinated to allow a proportion of them at any time to act as system regulators, to facilitate the penetration of high levels of inflexible generation. This system is having a major positive impact on grid management by distribution network operators by the 2030s."								

"Domestic electricity demand rises due to the adoption of electric heating for 60% of domestic heating systems"								
"Overall, electricity demand only rises by just over 10% from 2020 to 2035"								
[From 2020 to 2035] "The carbon intensity of electricity generation improves significantly to less than 30 gCO_2/kWh (though higher when calculated on a life-cycle basis)"								
2038-2052								
"So, total electricity demand in 2050 is only 20% higher than in 2008."								
"The deployment of both domestic and non-domestic distributed generation increases, meeting around a quarter of total demand by 2050, with significant shares from onshore wind and biomass CHP systems."								
"The centralised generation system is now almost totally decarbonised, with eighteen large nuclear power plants with a total of 30 GW capacity providing the largest share of generation. There is significant further investment in CCS systems, resulting in 10GW of coal with CCS and 20 GW of gas with CCS by 2050. Overall, 65 GW of renewables capacity is installed, mainly onshore and offshore wind and wave and tidal power."								
"The average carbon intensity of electricity generation has now been reduced to below 20 gCO_2/kWh by 2050, resulting in the almost complete decarbonisation of power generation, though carbon emissions are significantly higher when calculated on a life-cycle basis."								
Key risks								
"Carbon capture and storage turns out to be technologically or economically unfeasible"								
"Higher energy service costs resulting from high levels of low-carbon investment."								

4.2. Discussion on the generalised process

In the Section 4.1 the limitations of the *Central Co-ordination* storyline were identified from the perspective of eight models (Figure 3). This Section 4.2 critically reflects the reported process of linking the storyline with the multiple models in the RTP project and highlights procedural insights, relevant for the general approach (Figure 2).

The starting point of this analysis was the *Central Co-ordination* storyline that was developed in the original Transition Pathways project [37, 38]. This storylines is lengthy (five pages) as it aimed to richly represent the complex power system transition. The storyline also aimed to encapsulate numerous details, coming from the different parts of the power system, viewpoints (government, power companies, consumers etc.), stakeholder and expert inputs. Such a process, however, has shortcomings. First, when so many diverse inputs are brought into one storyline, the internal consistency of this storyline becomes at risk. The comparison of the storyline with the outputs of the eight models revealed several inconsistencies. For example, the storyline describes the role of civil society as passive, while the envisioned substantial decrease in the energy service demand may not be feasible without voluntary action of energy consumers. In order to avoid such cases, it seems likely that the development of internally consistent, stakeholder-based storylines, facilitated by formal techniques such as cross-impact balance or formative scenario analysis [5, 12, 19-21], would increase the robustness of the qualitative storyline itself.

Second, some of such internal inconsistencies as well as other mistakes due to the lack of analytical foundation can be eliminated by comparing the storyline with the models (given that these models are available), as done in this paper. This is essential because the power system transition is inherently complex and qualitative storylines-based approach on its own cannot capture this complexity [11]. The afore-mentioned cross-impact balance or formative scenario analysis can be used for mediating among the diverging perspectives of the experts. The insights from the multiple models could thus perhaps be brought into these analyses too in order to derive storylines that are informed by multiple models and multiple stakeholder views simultaneously.

Third, lengthy and detailed storylines may be easier for the audience to imagine, but they also lead to overconfidence about how realistic they are [12]. This is problematic because such exercises distract the attention of the audience from other, as likely or as desirable, scenarios. The scenario approach is expected, however, to expand rather than narrow down the understanding about the plausible futures. Therefore, there is a threshold for how long and detailed the storyline shall be. When storylines are combined with the multiple models as in this paper, a meaningful approach would be to keep in the storyline the details about the governance and the choices of the actors, while leave the power system description to the multiple models.

The way a qualitative storyline is 'translated' into the assumptions for the quantitative models (Step 1 in Figure 2) is decisive for the comparison of the storyline and the modelling results. There is a trade-off between the number of assumptions and how much flexibility the models have to express their perspective. If a large number of assumptions is used, the models would be tailored to mimic the storyline almost completely. In this way, the added value of models, which have different rationales than described in the storyline, would be ignored. For example, the cost-optimising models, like HAPSO or D-EXPANSE, could be tailored to produce the results, similar to the storyline if there are no major inconsistencies in the storyline. But this would gloss over the fact that the cost-optimal and near-optimal—thus, perhaps more realistic pathways—may be very different than the one described in the storyline. The modelling assumptions thus shall better allow more flexibility for the models to express their perspective. However, it is challenging to define what the optimal number and type of assumptions are. Moreover, one qualitative statement might have a range of quantitative representations which need to be captured systematically [10, 11]. The 'translation' procedure, used in this paper, is acknowledged as one of the weaknesses. To some extent, this fragility arose because only one storyline was analysed through the perspective of the eight models. If all three storylines of the RTP project were analysed (*Central Co-ordination*, *Market Rules* and *Thousand Flowers*), this problem could be resolved to some extent, as a unified framework for the 'translation' of these storylines into modelling assumptions would need to be defined. By comparing three storylines, a more robust framework could be developed.

The landscape of models (Table 2 and Figure 3) proved to be a useful approach for understanding and mapping the fields of expertise of the eight, very diverse models of the RTP project. This landscape helped to understand where the models overlap and where they have their key, individual fields of expertise as compared to the other seven models. In line with [16], this landscape approach assumes that the usefulness of the model is the local matter. There is no single best model that covers all the relevant aspects in sufficient depth and breadth. The usefulness of the model depends on the model's suitability to answer the specific question at hand and to fill a gap among the other existing models. In the reported process, due to their different key fields of expertise, all eight models proved to be useful for assessing the storyline (Table 2). However, this landscape of models is not complete because not all of the qualitative statements in the storyline could be assessed. First, the statements about wider developments of industry and the national economy could not be addressed. For this purpose, a macro-economic model or a whole energy system model would be needed in the landscape. This whole energy system model would need to be broader than the already used HAPSO model, which addresses only the power system. This model would need to have as wide system boundaries as UK MARKAL or TIMES [45, 65] and to address the whole supply chain of the whole energy system (not only the power system) and energy-economy interactions.

Second, assuming a substantial deployment of distributed generation, there would be a need for improved modelling of local voltage control and two-way power flows. This problem would increase even more if the *Thousand Flowers* storyline would be analysed, because this storyline pictures a significant uptake of decentralised generation. A model that addresses these issues would need to be added to the landscape of models too.

Third, the storyline raised issues about public acceptability of rising energy prices or, as suggested by the models, possibly decreasing supply security due to the deployment of intermittent renewable energy sources. While the public acceptability issues are challenging to model, they are of high relevance for the future transitions. Therefore, in parallel to the modelling-based assessment of the storyline, a social scientific assessment is required. This social scientific analysis already took place in the Transitions Pathways project [66] and thus, together with the landscape of models, it could improve the analytical assessment of the qualitative storylines.

The iterative loop in Figure 2 would be completely closed by revising the qualitative storyline on the basis of the results of the eight models. The exercise, reported in Table 2, helped to identify the points of fragility of the storyline. The diversity of the eight models here proved to be especially useful as the results of the different models were at times diverging. While some models were in line with all or almost all storyline statements, there was almost always at least one model that diverged from the storyline. Any of these divergences can have credible reasons leading to the fragility of the storyline. Unpicking the underlying mechanisms of this divergence (as already reported in Section 4.1.) is thus essential for understanding why this divergence appears and, if necessary, revising the storyline. The next step of this process would be a collaborative, reflexive effort between the storyline developers and the modellers. In this way, an improved storyline version could be developed.

The iterative loop in Figure 2 is a two-way reflexive collaboration between the storyline and the models. In this paper, a storyline-led approach is reported. The storyline was developed first and then was assessed from the perspective of the different models, at the same time reflecting on the potentially relevant models that were missing from the analysis. Models alone can hardly capture the broader picture, covered in the storyline, such as the power system governance 'logics' and the choices of the key actors. As these aspects are very challenging to model, it is meaningful to use a storyline-led approach. However, an alternative, modelling-led approach could also be used to derive storylines too. This could be based on the generation of a large number of scenarios with multiple models and extracting a smaller range of scenarios with fundamentally-different structures and describing them in storylines. Some research in this direction is already reported in [6, 11, 52, 53, 67-69]. Such process could be organised similar to the process of Figure 2, but it would start with the modelling exercise.

5. Conclusions

This paper extends the current state-of-the-art approach for linking qualitative storylines with quantitative models. An approach is proposed for linking a very detailed storyline, which describes the governance 'logics' and the choices of key system actors, with multiple, very diverse quantitative models. This approach is especially relevant because a growing number of interdisciplinary projects worldwide tend to bring together social scientists with modellers. Most of these models already exist before the projects and differ substantially is their disciplinary perspective, model objective, system boundaries and the format of inputs and outputs. Cross-comparison of such models is a challenge in itself. In the proposed approach, the comparison of the models is based on the concept, called the landscape of models. Even more, this paper goes further by linking these multiple, diverse models with qualitative storyline. Therefore, the described approach is a novel contribution to the existing literature.

In the frame of the Realising Transition Pathways project, the proposed approach is illustrated by revising the *Central Co-ordination* storyline, developed in the earlier Transition Pathways project, for exploring the UK power system transition until 2050. This storyline describes the governance 'logics' and the choices of the key system actors, when the UK central government takes a more active role in shaping the power system transition. Such soft considerations as governance and the actors' choices can hardly be modelled in the current RTP models; this highlights the value of the storyline. This qualitative storyline is addressed through the perspective of six, very diverse models and two appraisal techniques: Demand, FESA, D-EXPANSE, EconA, BLUE-MLP, EEA, HESA/UK+ and the HAPSO models. These models and appraisals revealed the fragile nature of the storyline. The storyline tended to overestimate the power demand reduction potential, the uptake of marine renewables and the importance of CCS feasibility. But it underestimated the supply-demand balancing challenge, the need for gas power plants as a back-up capacity, the role of nuclear power and interconnectors with Europe, and the challenge of meeting the long-term stringent greenhouse gas emissions targets. Thus, the combination of the qualitative storyline and its revisions from the perspective of multiple, diverse models is key for developing robust future scenarios and transition pathways. An iterative process for this purpose has been proposed in this paper.

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