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Linking a storyline with multiple models: a cross-scale study of the UK power system transition

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<http://dx.doi.org/10.1016/j.techfore.2014.08.018>

PUBLISHER

© Elsevier

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

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REPOSITORY RECORD

Trutnevyte, Evelina, John P. Barton, Aine O'Grady, Damiete Emmanuel-Yusuf, Danny Pudjianto, and Elizabeth M. Robertson. 2019. "Linking a Storyline with Multiple Models: A Cross-scale Study of the UK Power System Transition". figshare. <https://hdl.handle.net/2134/25320>.

Manuscript Number: TFSC-13-417R2

Title: Linking a storyline with multiple models: a cross-scale study of the UK power system transition

Article Type: Research Article

Keywords: Scenarios; storylines; cross-scale; quantitative models; simulation; energy; environment; climate change; transition pathways

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Abstract: State-of-the-art scenario exercises in the energy and environment 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 a cross-scale study of 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 on power system targets for the models. Then, a new concept called the landscape of models is introduced. This landscape helps to map the key fields of expertise of individual models, including their temporal, spatial and disciplinary foci. The storyline is then assessed based on the cross-scale modelling results. While the storyline is important for transmitting information about governance and the choices of key actors, many targets aspired in it are inconsistent with modelling results. The storyline overestimates demand reduction levels, uptake of marine renewables and irreplaceability of carbon capture and storage. It underestimates the supply-demand balancing challenge, the need for back-up capacity and the role of nuclear power and interconnectors with Europe. Thus, iteratively linking storylines and models is key.

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London, 23 August 2014

Linking a storyline with multiple models: a cross-scale study of the UK power system transition

Dear Prof Phillips,

Thank you for your positive feedback to our manuscript. As recommended by the third reviewer, we now added a sentence explaining our definition of “cross-scale” study. Please find the manuscript and a short response to the reviewer’s comment attached.

We look forward to hearing from you.

With best wishes on behalf of all co-authors,
Dr Evelina Trutnevyte

Point-by-point response to the reviewers' comments

The original comments of the reviewers are typeset in Bold.
Our answers are typeset in Roman.

Reviewer #3

This is a significantly revised paper which I was seeing for the first time. Reading it "raw" I thought that it was original with a very clear exposition and useful implied recommendations for both analysts and policymakers. I looked back at the original reviewers' constructive comments and would say that the authors have responded fully and without any degree of push-back. I unreservedly recommend this for publication (almost) "as is". One tiny point - on p.6 they introduce the term "cross-scale" (apparently to replace "interdisciplinary" in the original submission). The term is not explicitly defined or exemplified, though I can guess the meaning from earlier references to temporal and spatial aspects. Just one additional sentence would clarify the exposition. We think it is indeed a good idea to clearly define what we mean by the 'cross-scale' term. As suggested by the reviewer, we add an explanation on page 6:

114 models to each [41]. Thus, a new approach has to be developed for linking
115 detailed storylines with multiple, cross-scale models, which have different
116 spatial, temporal and disciplinary foci. This paper proposes such an approach.
117 There is a growing number of interdisciplinary projects in energy, climate

Evelina Trutnevite 23/8/14 13:13
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Highlights

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

Figure 1

Figure 2

Central Co-ordination storyline

Figure 3

Annual power generation, TWh/year

- Imports
- Solar
- Total marine
- Biomass
- Hydro
- Offshore wind
- Onshore wind
- Nuclear
- CHP - Total
- Gas OCGT
- Gas CCGT with CCS
- Coal with CCS
- Oil without CCS
- Gas CCGT without CCS
- Coal without CCS

Figure 4

Demand

FESA

D-EXPANSE

EconA

BLUE-MLP

EEA

HESA/UK+

HAPSO

Detailed modelling
(key field of expertise)

Stylised modelling

Exogenous assumptions

Vitae

- Dr Evelina Trutnevyte works as a Research Associate at the University College London (UCL) Energy Institute. Her research focuses on the development of context-specific, spatially differentiated energy strategies that combine insights from multiple disciplines and stakeholder engagement. She received her PhD at the Institute for Environmental Decisions, ETH Zurich, and her Master's degree in Power Engineering from Vilnius Gediminas Technical University. She strengthened her expertise during studies and fellowships at Aalborg University (Denmark), Lithuanian Energy Institute, Power Systems Laboratory at ETH Zurich (Switzerland), University of Oslo (Norway), and during two years of engineering consulting in Lithuania.
- Dr John Barton is a Research Associate at Loughborough University's Centre for Renewable Energy Systems Technology (CREST). He also received his PhD and Master's degree at Loughborough University. His 7 years of post-doctoral research includes energy storage, whole energy system modelling, distributed generation, demand response, condition monitoring of wind turbines and public engagement with renewable energy. John is also an energy consultant and company director, previously working with Bryte Energy Ltd on hydrogen technologies and now working with Air Fuel Synthesis Ltd making synthetic liquid transport fuels. John co-created and then developed the FESA model.
- Áine O'Grady is a Research Officer at the University of Bath where she is part of the Sustainable Energy Research Team in the Department of Mechanical Engineering. Previously, Áine worked at Aquamarine Power, and carried out a life-cycle assessment of its wave energy device prototype, and contributed to environmental design improvements. Her current research involves the technology assessment of energy systems using a set of appraisal techniques from engineering, environmental sciences and strategic thinking (such as environmental life-cycle assessment, thermodynamic analysis, horizon scanning and other future-oriented technology analysis).

- Damiete Ogunkunle is a Research Officer at the Centre for Environmental Strategy, University of Surrey, where she obtained her Masters' degree in Environmental Management. She has worked in a range of research projects since 2008 including the sustainability assessment of UK bioenergy supply chains. Currently, she is involved in the development of the energy demand models as part of the Realising Transitions Pathways consortium. She is also working part time towards completing her PhD degree.
- Dr Danny Pudjianto is a Research Fellow at Imperial College London with the expertise in power system modelling and optimization, power system economics, regulation, system operation, strategic planning, system security, and technology evaluations from power system perspective including smart grids, active network management, demand response, distributed generation, energy storage, and energy networks. He holds degrees in Economics (BA) and Electronics (BSc), and Power System (MSc and PhD). He has published more than 40 technical papers.
- Elizabeth Robertson is a Research Assistant at the University of Strathclyde's Institute of Energy and Environment. She received her MPhys (Hons) from the University of York, UK in 2008 and is currently pursuing a PhD at the University of Strathclyde. Her research interests include combined energy system modelling and the interaction of physically connected, but individually operated energy markets.

Supplementary Files with no Changes Marked

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1 **Linking a storyline with multiple models: a cross-scale**
2 **study of the UK power system transition**

3

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9 **Abstract**

10 State-of-the-art scenario exercises in the energy and environment fields argue
11 for combining qualitative storylines with quantitative modelling. This paper
12 proposes an approach for linking a highly detailed storyline with multiple,
13 diverse models. This approach is illustrated through a cross-scale study of the UK
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15 linked with insights from six power system models and two appraisal
16 techniques. First, the storyline is ‘translated’ into harmonised assumptions on
17 power system targets for the models. Then, a new concept called the landscape
18 of models is introduced. This landscape helps to map the key fields of expertise
19 of individual models, including their temporal, spatial and disciplinary foci. The
20 storyline is then assessed based on the cross-scale modelling results. While the
21 storyline is important for transmitting information about governance and the
22 choices of key actors, many targets aspired in it are inconsistent with modelling
23 results. The storyline overestimates demand reduction levels, uptake of marine
24 renewables and irreplaceability of carbon capture and storage. It underestimates
25 the supply-demand balancing challenge, the need for back-up capacity and the
26 role of nuclear power and interconnectors with Europe. Thus, iteratively linking
27 storylines and models is key.

29 **Keywords**

30 Scenarios, storylines, cross-scale, quantitative models, simulation, energy,
31 environment, climate change, transition pathways

34 **Highlights**

- 35 • Linking a qualitative storyline with multiple, diverse quantitative models
- 36 • Landscape of models for mapping the fields of expertise of individual
- 37 models
- 38 • Cross-scale analysis of the UK power system transition until 2050

39

40 **Graphical abstract**

41 *Insert the Graphical abstract about here*

42

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, such as governance, institutional changes or energy-related behaviour, 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, 19]. Despite the current research on formal techniques for developing better storylines [20-23], these limitations still remain.

Quantitative models-based scenarios are produced by a single or multiple models, such as in the ADAM [24], Energy Modelling Forum [25], Low Carbon Society modelling [26] and NEEDS [27] 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, 13, 15]. Models are based on the empirical data, physical laws, 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, and environmental aspects. But they still have difficulty in capturing the afore-mentioned softer and subtler aspects. The research priorities are towards developing more detailed models and including softer aspects, such as behaviour and governance, into models [17, 28]. Yet, even better models alone can hardly offer the breadth and engaging nature of the storyline-based scenarios. For example, the models cannot picture organisational and institutional change needed to deliver a wanted transition, even if these elements are important for decision makers to envision and manage this transition.

In light of these strengths and weaknesses of storylines and quantitative models, state-of-the-art scenario studies argue for combining them [1-5]. In order to complement the models, storylines can reflect such aspects, like (i) exogenous context in which the modelled system is embedded into, (ii) exogenous modelling assumptions, such as drivers for change, or (iii)

93 aspirational targets for the future system. Many recent scenario exercises
94 already have the elements of both storylines and models: storylines include
95 numbers, while modelling outputs are described in short qualitative narratives.
96 Several scenario exercises explicitly combine the storylines and the quantitative
97 models in an iterative manner [6, 10, 11, 29-31]. Examples of these include key
98 international scenario exercises: the integrated climate change scenarios of the
99 Intergovernmental Panel of the Climate Change [32, 33], the scenarios of
100 ecosystem services in the Millennium Ecosystem Assessment [34] and of the
101 global environment in the Global Environmental Outlook [35].

102 Despite the fact that the combination of storylines and quantitative
103 models has emerged as an established practice in the technology- and
104 environment-related fields [1-6], existing literature runs short in providing
105 methodological insights for how to link detailed storylines, which are developed
106 through stakeholder and expert engagement, with multiple quantitative models.
107 First, if the storylines are very detailed, then numerous additional assumptions
108 are needed to 'translate' them into model parameters. Second, multiple diverse
109 models may be needed to model detailed storylines with various spatial and
110 temporal foci, disciplinary perspective (technical feasibility, economic or
111 environmental appraisal), model objective, and the parts of the system
112 addressed. This diversity is valuable because the storylines can be addressed
113 from multiple angles and across scales, but it is challenging to relate such diverse
114 models to each [36]. Thus, a new approach has to be developed for linking
115 detailed storylines with multiple, cross-scale models, which have different
116 spatial, temporal and disciplinary foci. ~~and~~ This paper proposes such an
117 approach. There is a growing number of interdisciplinary projects in energy,

climate change and other technology- and environment-related studies. It can be expected that many of these projects will attempt to develop cross-scale scenarios by linking storylines with multiple models and will require such an approach.

The proposed approach is illustrated with the cross-scale analysis of the UK power system transition until 2050 as a part of the Realising Transition Pathways (RTP) consortium project. A detailed storyline, called the *Central Co-ordination*, was developed in the preceding Transition Pathways project [37-39] and is used for the cross-scale analysis with six quantitative power system models and two quantitative appraisal techniques. The idea for this analysis arose from discussions at RTP consortium workshops. The authors of this paper took the analysis forward and its results will be an input to further development of the consortium's research.

This paper is laid out as follows: Section 2 proposes a general methodological approach; Section 3 gives an example of linking the *Central Co-ordination* storyline with eight RTP models, present and discusses the findings; Section 4 discusses the general approach; and Section 5 concludes.

2. Proposed approach for linking storylines with multiple models

This section describes the proposed process (Figure 1) of linking a detailed storyline with the insights from multiple diverse models. First of all, one of the biggest challenges in cross-scale scenario studies is ability to systematically combine insights from multiple cross-scale models. Understanding and mapping the breadth and depth of the expertise of every

individual model is challenging, especially given a diverse set of models. This paper proposes mapping this expertise in two complementary ways:

- (i) List the key characteristics of the models and elicit the **key fields of expertise**. These key fields of expertise reflect the types of insights that a particular model analyses in most depth, as compared to the other models. This concept of the key field of expertise thus appreciates the distinct value of every model in a multi-model analysis. 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.
- (ii) Prepare a visual map, called the **landscape of models**. This map shall summarise the information about the breadth and depth of the analysis, done by every model, and show how these afore-mentioned fields of expertise overlap between the models. This mapping can be done on the basis of the parts of the system addressed and/or other thematic considerations addressed by the models. The mapping characteristics will likely differ from one set of models to another. The depth of analysis can then be defined in three categories: detailed modelling (the key field of expertise), stylised modelling and exogenous assumptions only.

Insert Figure 1 about here

Figure 1. The iterative process of linking storylines with multiple cross-scale quantitative models

Both concepts of the model's key field of expertise and the landscape of models help to grasp, where models differ or overlap. If models overlap, then they can validate each other and help cross-check the results. Every model, however, likely has at least one area where it outperforms the other models in depth or breadth as there is no single best model that covers all aspects in depth and across all the relevant scales.

As shown in Figure 1, in order to link a detailed storyline with insights from multiple models, the qualitative storyline is first 'translated' into a set of harmonised assumptions that are necessary for conducting the model runs, specifically tailored for the storyline (Step 1 in Figure 1). Such a 'translation' is a challenging task. On the one hand, these harmonised assumptions will already be a narrower representation of the 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 models used for cross-scale analyses are often 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.

After the models are run with these harmonised assumptions, the statements of the storyline are checked for their consistency with the modelling results (Step 2 in Figure 1). The storyline can then be revised. The landscape of models plays an important role here as it highlights 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

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 1 is repeated iteratively for updating the storyline.

3. The case of the UK power system transition

This section provides a cross-scale example of linking a very detailed storyline of the UK power sector transition until 2050 with insights from six power system models and two appraisal techniques. The section starts by describing the UK power sector and the context of the storyline (Section 3.1), then moves to the description of the models (Section 3.2), the process of linking a storyline with multiple models (Section 3.3), and finishes with summarising and discussing the findings.

3.1. UK power system and the Central Co-ordination storyline

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 [39, 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 in the preceding Transition Pathways project: *Central Co-ordination*, *Market Rules* and *Thousand Flowers* [39, 45]. Compared to other scenario exercises in the UK [7-9, 46] 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 or drivers such as population growth, technological development and others, c.f. [32, 34, 35, 47]. The RTP storylines explicitly focus on the uncertainty around governance 'logics' and the choices of actors and how this could affect the power system transitions. In order to achieve this, the RTP storylines combine all three afore-mentioned elements of storylines: exogenous context, transition drivers and – mostly – targets for the future power system.

The process of developing these three storylines is described in detail in [39]. 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 [45] and shorter summaries are published in [39]. 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 [39]. This process was partly informed by insights from three power system models, but none of these models were informed by economic considerations [39]. 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.

The *Central Co-ordination* storyline, analysed in this paper, is one of the three storylines of the RTP project. These storylines picture three ideal types of governance ‘logics’ in the UK power system (Figure 2): government, market and civil society ‘logics’. In these storylines, the views that the government, market or civil society actors respectively need to lead the low-carbon transition emerge as the ‘zeitgeist’ of the time [39]. In the case of the *Central Co-ordination* storyline, the central UK government successfully establishes the dominant role by direct co-ordination to deliver the energy policy goals. In the *Market Rules* storyline, the market actors successfully 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 society at large shall take an active role in delivering the low-carbon transition as small-scale solutions, especially, but not only 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 [48]. Since the power market liberalisation in 1990s, the market ‘logic’ has been dominating in the UK,

but the influence of the government ‘logic’ has been increasing in 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.

Insert Figure 2 about here

Figure 2. The three ideal types of governance ‘logics’ in the UK power system transition. Source: J. Burgess and T. Hargreaves. The figure is reproduced from [39].

The *Central Co-ordination* storyline includes five pages of narrative and here only the key points are summarised. The central UK government is assumed to actively shape the power system transition through the establishment of a new 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 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 any 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 for power generation. As noted, society at large 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, interventions on lifestyles and behaviour will be undertaken by the government, especially through smart metering and demand side response measures. The key risks, identified in the storyline for the realisation of this transition, are (i) the 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.

In addition to the qualitative narrative, the *Central Co-ordination* storyline was already assigned an initial quantitative representation (Figure 3), developed in an iterative process by the Transition Pathways Technical Elaboration Working Group. This quantitative representation served both as an example of how the power sector may look in detail and as a basis for conducting further quantitative research on the storyline (for instance, for environmental or economic appraisals).

Insert Figure 3 about here

Figure 3. The initial quantitative representation of the *Central Co-ordination* storyline. Source: Transition Pathways project. The figure is reproduced from [39].

3.2. Landscape of the RTP models

This section describes the six power system models and two appraisal 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 cross-scale aspects [16]. The RTP leadership envisioned a multi-model analysis, expecting that this analysis, rather than results of a single model, will have 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 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 [49-51] and the assumptions from the *Central Co-ordination* storyline.
- **FESA:** The Future Energy Scenario Assessment model [52, 53], developed at the Loughborough University, is a single-year UK power generation and demand model, incorporating one-hour time steps for dispatch modelling and using 2001 Met Office weather data on 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, 31, 54, 55]. 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 [55].

- **EconA:** The Economic Appraisal (EconA), conducted by University College London, aims to systematically calculate and compare total investment costs and total system costs for power generation, transmission and distribution for the three transition pathways. The results are disaggregated for the different power generation technologies, which allows for economic feasibility assessment. The EconA is an appraisal technique; it takes the quantitative representation (Figure 3) of the *Central Co-ordination* storyline and calculates the power system costs for it. In this paper, the EconA 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 [56, 57]. 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 [58], 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 a life cycle assessment (LCA) of the UK power system carried out by the University of Bath [59, 60]. Over 18 environmental impacts were evaluated from cradle to gate, accounting for all upstream and operational activities. Impacts covered in this assessment include climate change, which is quantified through greenhouse gas emissions, and other environmental impacts, such as fossil fuel depletion, human toxicity, particulate matter formation and agricultural land occupation. Similar to the EconA, the EEA framework is a model, which appraises the *Central Co-ordination* storyline, based on its initial quantitative representation (Figure 3).

- 415 • **HESA/UK+**: This is a combination of the Hybrid Energy System

416 Analysis tool (HESA) and the Strathclyde UK+ models that were

417 developed at the University of Strathclyde [61-63]. The Strathclyde

418 UK+ model contains all the information for the transition pathways

419 scenarios with spatial disaggregation (17 onshore, five offshore zones

420 and 39 connections) of generation, storage, transmission and

421 distribution. It is linked to the HESA model, which cost-optimises the

422 system, based on the energy hub concept [64, 65]. The national power

423 demand and generation mix are used as input assumptions.
- 424 • **HAPSO**: The Holistic Approach to Power System Optimisation model

425 (HAPSO) is developed at the Imperial College London. It is a bottom-

426 up, cost-minimisation model that determines the optimal generation,

427 energy storage, transmission, and distribution network infrastructure

428 requirements and their associated cost to achieve three objectives:

429 economic efficiency, security, and sufficient system controllability. The

430 model optimises simultaneously the long-term investment and short-

431 term operating decisions including hourly generation dispatch,

432 Demand Side Response, storage cycles, and power exchanges taking

433 into account the impact of decisions across all sectors in the power

434 system [66]. The UK power system is embedded in the European

435 power system including UK, Ireland and continental Europe and thus

436 allows for modelling of the power exchange across these regions.

437

438 The fields of expertise of the individual models are mapped in Table 1 and

439 Figure 4. The landscape of the RTP models is prepared 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). Both Table 1 and Figure 4 help to show that the eight models, used in this analysis, cover a broad spectrum of cross-scale insights across time, space, system boundaries and disciplines.

449 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); storage (stylised)	Storage (stylised)	Dispatch (stylised); Demand response	Storage (stylised)	Dispatch; Storage	Dispatch; Demand response; Storage
-- Trans-mission and distribution						Transmission and distribution	Transmission and distribution	Transmission and distribution

Model	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
-- Inter-connectors to Europe		Import; Export	Import	Import		Import	Import; Export	Import; Export; UK embedding in the European system
-- Non-electric parts of the energy system	Non-electric heating	Non-electric heating; Non-electric transport; Non-electric industrial and commercial uses			Non-electric heating; Non-electric transport; Non-electric industrial and commercial uses		Non-electric heating	
Modelling method	Deterministic simulation	Deterministic simulation	Cost-optimisation and evaluation of maximally different near-optimal pathways	Appraisal of exogenous scenarios	Dynamic simulation	Appraisal of exogenous scenarios	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

Model	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
Environmental considerations		Post hoc assessment; Operational emissions (from primary energy use); Only CO ₂ emissions	Emission constraint; Operational emissions; Only CO ₂ emissions	Exogenous assumptions	Post hoc assessment; Operational emissions; Only CO ₂ emissions	Post hoc assessment; 'Whole system' (LCA) environmental impacts, including upstream and operational impacts; Greenhouse gas emissions (CO _{2eq}); Fossil fuel depletion; Human toxicity; Particulate matter; Agricultural land occupation	Post hoc assessment; Operational emissions; Only CO ₂ emissions	Emission constraint; Operational emissions; Only CO ₂ emissions
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			

450

451

Model	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
<i>Key field of expertise</i>	<i>Demand</i>	<i>Dispatch, demand response and storage; Generation</i>	<i>Maximally different alternatives; Uncertainty</i>	<i>Economic appraisal</i>	<i>Uncertainty; Behaviour and heterogeneity of the actors</i>	<i>Energy and environmental appraisal</i>	<i>Transmission and distribution; Generation; Spatial disaggregation</i>	<i>Dispatch and demand response; Generation; Transmission and distribution; Interconnectors</i>

Insert Figure 4 about here

Figure 4. The landscape of models (model versions as of April 2013)

3.3. Process of linking the storyline with multiple models

For translating the *Central Co-ordination* storyline into the harmonised modelling assumptions, several key aspects of this storyline are taken. In contrast to the typical story-and-simulation approach, such as [32, 33], where storyline describes the drivers of future transition, the *Central Co-ordination* storyline includes multiple targets for the future power system that should be met under the increased role of government. The targets that are chosen as harmonised modelling assumptions 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.

- 477 ii. Power generation mix in the UK:
- 478 - In 2020, 40% of the produced power comes from low-carbon sources,
- 479 prioritising coal CCS, nuclear and renewable sources. At least 25% of
- 480 the produced power comes from renewable sources, such as offshore
- 481 and onshore wind, wave, tidal barrage and tidal stream.
- 482 - In 2030, the power generation mix bridges the mixes of 2020 and
- 483 2050.
- 484 - In 2050, 75% of total produced power comes from large-scale low-
- 485 carbon sources, such as nuclear, coal and gas CCS, offshore wind,
- 486 wave, tidal barrage and tidal stream. At least, 25% comes from low-
- 487 carbon decentralised sources, such as onshore wind and biomass
- 488 combined heat and power (CHP) plants.

- 489 iii. Greenhouse gas emissions:
- 490 - In 2020, the average carbon intensity in the whole UK power system is
- 491 300 gCO₂/kWh of power produced;
- 492 - In 2030, this value drops to 30 gCO₂/kWh;
- 493 - In 2050, it is as low as 20 gCO₂/kWh.

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

496

497 Not all of the eight models can implement all of these harmonised

498 assumptions. First, the Demand, FESA models and EEA cannot consider the last

499 assumption about the discount rate as they do not consider costs at all. They,

500 therefore, by-passed this assumption, but implemented the remaining

501 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 3), which is in line with the harmonised assumptions described above.

The qualitative statements from the *Central Co-ordination* storyline are then scrutinised from the perspective of the outputs of every model. The storyline pictures the contextual information, such as the governance arrangements and the role of the different actors. These aspects can hardly be interrogated by the models. But the description of the targets, that are aspired in the storyline as a result of the governance arrangements and the actors' decisions, can be 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" [45, 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" [45, p. 3] is interrogated by the eight models.

3.4. Results and discussion on 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 power system targets to be delivered by the governance

arrangements and actor choices, specified in the storyline, is compared and contrasted with the modelling results.

Robust elements of the storyline

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.

Divergence on demand reduction levels

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

551 saving behaviour and efficiency improvements. However, the BLUE-MLP model
552 shows that, when the economic drivers of energy demand and the heterogeneity
553 of the behaviour of the different actors is considered, maintaining slow power
554 demand growth through the entire model horizon appears rather wishful
555 thinking. This finding is in line with the common observation that technically and
556 economically sensible energy demand reduction measures may not be taken up
557 in reality [67]. Storylines developed by the various stakeholders and experts—
558 even more than models—tend to be overly optimistic and fragile from the
559 modelling perspective [10, 11]. This remark is also consistent with a broader
560 argument that failures of effectively mitigating climate change can be expected
561 [68]. The *Central Co-ordination* storyline envisions a passive role of the civic
562 society. Without the active energy saving action of the society at large, drastic
563 demand reduction may be challenging to achieve. The UK government could only
564 enforce some types of measures for mitigating the power demand, such as smart
565 meters, efficient domestic appliances or refurbishment of buildings. Thus, the
566 expectation from the storyline about the demand needs to be revisited.

567 568 *Divergence on back-up capacity*

569 The *Central Co-ordination* storyline aspired to the retirement of existing
570 coal and gas power plants by 2037 and their replacement with low-carbon
571 technologies, such as renewable energy sources or gas and coal with CCS.
572 However, both the D-EXPANSE, BLUE-MLP and HAPSO models, which also model
573 the demand response potential, show that this aspiration is challenged by the
574 dispatch (supply-demand balancing) constraint. According to the models, for the
575 aspired high deployment of intermittent renewable energy sources there will be

a need for significant levels of back-up capacity, mostly flexible gas OCGT power plants. The D-EXPANSE model, which explores the many 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. Most importantly, the HAPSO model, whose key field of expertise is dispatch modelling due to its one-hour temporal resolution and detailed assessment of supply 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 supply 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 4, 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.

Divergence on emission mitigation levels

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 gCO₂/kWh in the storyline, the modelling outcomes range from 33 gCO₂/kWh to 56 gCO₂/kWh for CO₂ for operational emissions and equals 120 gCO_{2eq}/kWh for the 'whole system' (cradle to gate) emissions. The D-EXPANSE model shows a number of power generation mixes, which are not necessarily the same as modelled in other seven models, but are still consistent with the harmonised assumptions of the storyline. Some of these mixes could meet the target of 30 gCO₂/kWh, but these mixes are different from the mixes evaluated

by the other models. Thus, while reaching the emission target can be technically feasible, it may not be realistic via the means that the storyline describes. According to the EEA, which has the most detailed accounting of the operational and ‘whole system’ emissions as its key field of expertise, the emissions 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.

Divergence on power generation mix

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 [39]. 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 to lack of market integration and lack of interconnectors between the UK and continental Europe. This significant curtailment would reduce the economic feasibility of renewable 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. The EEA model highlighted that the deployment of coal CCS is likely to provide almost a quarter less carbon emission mitigation than is normally assumed on a whole system basis. 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.

Divergence on the key risk

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; near-optimal scenarios are defined as scenarios that have up to 30% higher total cumulative system costs by 2050 than the least cost scenario. Many of these scenarios do not have CCS, even if the carbon price rise to £207.5/tonne CO_{2eq} by 2050 is assumed in line with [69]. 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 coal 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, even with the carbon price increase up to £600/tonne CO_{2eq} by 2050. 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, as it describes high levels of intermittent renewable sources and inflexible power plants with CCS, which are challenging to combine. At the same time, the storyline does not refer to the necessary flexible generation and demand response measures that would guarantee simultaneous integration of CCS and renewable sources into the system. 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 2 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.

Under-represented aspects of the storyline

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 4). 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. All these aspects are often forgone not only in the Transition Pathways storylines, but also in wider energy policy discourses. Yet, the future power system transition requires a portfolio of measures on the power demand, generation, transmission and distribution sides. These aspects need to be considered, when developing the next version of the storyline.

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

Some of the relevant quotes from the storyline, taken from [45]. 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								

The key risk is that “Carbon capture and storage turns out to be technologically or economically unfeasible”			(Not key risk)					
The key risk is that “Higher energy service costs resulting from high levels of low-carbon investment.”								

4. Discussion on the general approach

This section critically reflects the proposed approach for linking detailed storylines with multiple models, based on the case of the *Central Co-ordination* storyline.

Development of storylines

In scenario processes, storylines are often very detailed because they aim 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 under the typical story-and-simulation approach [2] or when using such detailed storylines as in the RTP projects, the internal consistency of this storyline becomes at risk. For example, the comparison of the *Central Co-ordination* storyline with the outputs of the eight RTP models reveals several inconsistencies. The storyline describes the role of society at large as passive, while the envisioned substantial decrease in the energy service demand may not be feasible without concerted efforts to reduce demand for energy services. In order to avoid such cases, it seems likely that the development of internally consistent, stakeholder-based storylines, facilitated by formal techniques such as formative scenario analysis or cross-impact balance [5, 20-23, 70, 71], would increase the robustness of the qualitative storyline itself.

Second, some internal inconsistencies as well as other mistakes due to the lack of analytical foundation can be eliminated by comparing the storyline with

models (given that these models are available), as done in this paper. This is essential because the power system transition is inherently complex and the 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 [70]. 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 leaving the power system description to the multiple models.

‘Translation’ of storylines into model assumptions

The way a qualitative storyline is ‘translated’ into the assumptions for the quantitative models (Step 1 in 1) 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 storyline and the multiple targets, aspired by the stakeholders, could be tested in light of modelling results. This can be a useful and creative learning exercise for the stakeholders [10, 11]. At the same time, the RTP project seeks to better grasp a wide range of plausible future power system developments, if the central UK government plays a more active role in shaping the power sector transition. Thus, models with different rationales could help capturing a wider range of these plausible futures. If too many assumptions would be used, this variety of plausible futures would be lost. For example, in the case of the RTP models, 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 of the study, presented in Section 3. 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.

Mapping the expertise of models

The landscape of models (Table 1 and Figure 4) proved to be a useful approach for understanding and mapping the fields of expertise of the eight, very diverse cross-scale models as in 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 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 and scales 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 RTP models proved to be useful for assessing the storyline from different cross-scale perspectives on space, time, system boundaries, discipline and even technique (Table 1).

However, this landscape of RTP models for revising the *Central Coordination* storyline 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 RTP 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 [46, 72] 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 [73] and thus, together with the landscape of models, it could improve the analytical assessment of the qualitative storylines.

Two-way reflexive collaboration

The iterative loop in Figure 1 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 inconsistencies between the storyline and the models. 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 inconsistencies in the storyline. Unpacking the underlying mechanisms of this divergence (as already reported in Section 3.4) is thus essential for understanding why this divergence appears and, if necessary, revising the storyline and/or the models. The next step of this process would be a collaborative, reflexive effort between the storyline developers and the modellers. In this way, improved versions of the storyline and the models could be developed.

The iterative loop in Figure 1 is a two-way reflexive collaboration between the storyline and the models [36]. 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, 54, 55, 74-76]. Such process could be organised similar to the process of Figure 1, but it would start with the modelling exercise.

5. Conclusions

849 This paper extends the current state-of-the-art approach for linking
850 qualitative storylines with quantitative, cross-scale models. An approach is
851 proposed for linking a very detailed storyline, which describes the governance
852 'logics' and the choices of key system actors, with multiple, very diverse
853 quantitative models. This approach is especially relevant because a growing
854 number of interdisciplinary projects worldwide tend to bring together social
855 scientists with modellers. Most of these models already exist before the projects
856 and differ substantially in their spatial and temporal foci, disciplinary
857 perspective, model objective, system boundaries and the format of inputs and
858 outputs. Cross-comparison of such models is a challenge in itself. In the proposed
859 approach, the comparison of the models is based on a new concept called the
860 landscape of models. Moreover, this paper goes further by linking these multiple,
861 diverse cross-scale models with qualitative storyline. Therefore, the described
862 approach is a novel contribution to the existing literature.

863 In the frame of the Realising Transition Pathways project, the proposed
864 approach is illustrated by revising the *Central Co-ordination* storyline, developed
865 in the earlier Transition Pathways project, for exploring the UK power system
866 transition until 2050. This storyline describes the governance 'logics' and the
867 choices of the key system actors, when the UK central government should take a
868 more active role in shaping the power system transition. Such contextual
869 considerations as governance and the actors' choices can hardly be modelled in
870 the current RTP models; this highlights the value of the storyline. This qualitative
871 storyline is addressed through the perspective of six, very diverse models and
872 two appraisal techniques: Demand, FESA, D-EXPANSE, EconA, BLUE-MLP, EEA,
873 HESA/UK+ and the HAPSO models. These models and appraisals revealed the

874 fragile nature of the storyline. From the perspective of the model, the storyline
875 tended to wishfully overestimate the power demand reduction potential and the
876 uptake of marine renewables. The necessity for CCS to meet long-term stringent
877 greenhouse gas emissions targets was also overestimated. But it underestimated
878 the supply-demand balancing challenge, the need for gas power plants as a back-
879 up capacity, the role of nuclear power and interconnectors with Europe, and the
880 challenge of meeting the stringent emissions targets. Thus, the combination of
881 the qualitative storyline and its revisions from the perspective of multiple,
882 diverse models is key for developing robust future scenarios and transition
883 pathways. An iterative process for this purpose has been proposed in this paper.

884 For the RTP consortium, the interpretation of the results of this analysis
885 and their implications for the future development of both the storylines and the
886 models will be the subject of further debate, research and papers.

887 888 **Acknowledgements**

889 This work was conducted as a part of the Realising Transition Pathways
890 consortium project, supported by the UK Engineering and Physical Sciences
891 Research Council (Grant EP/K005316/1). The authors are solely responsible for
892 the analysis and views in this paper.

893 The authors thank the other members of the Realising Transition
894 Pathways project and the preceding Transition Pathways project, who developed
895 the *Central Co-ordination* storyline and participated in the workshops that led to
896 the development of this paper (a full list of the consortium members is available
897 at [77]). The substantial contributions of Neil Strachan and other contributions
898 of Graham Ault, Stuart Galloway, Geoff Hammond, Matt Leach, Goran Strbac and

Murray Thomson in guiding the development and analysis of the models are also acknowledged. The authors especially value the extensive critical review by Geoff Hammond, Peter Pearson and the anonymous reviewers that helped to considerably improve the manuscript.

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1175

1 **Linking a storyline with multiple models: a cross-scale**
2 **study of the UK power system transition**

3

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9 **Abstract**

10 State-of-the-art scenario exercises in the energy and environment fields argue
11 for combining qualitative storylines with quantitative modelling. This paper
12 proposes an approach for linking a highly detailed storyline with multiple,
13 diverse models. This approach is illustrated through a cross-scale study of the UK
14 power system transition until 2050. The storyline, called *Central Co-ordination*, is
15 linked with insights from six power system models and two appraisal
16 techniques. First, the storyline is ‘translated’ into harmonised assumptions on
17 power system targets for the models. Then, a new concept called the landscape
18 of models is introduced. This landscape helps to map the key fields of expertise
19 of individual models, including their temporal, spatial and disciplinary foci. The
20 storyline is then assessed based on the cross-scale modelling results. While the
21 storyline is important for transmitting information about governance and the
22 choices of key actors, many targets aspired in it are inconsistent with modelling
23 results. The storyline overestimates demand reduction levels, uptake of marine
24 renewables and irreplaceability of carbon capture and storage. It underestimates
25 the supply-demand balancing challenge, the need for back-up capacity and the
26 role of nuclear power and interconnectors with Europe. Thus, iteratively linking
27 storylines and models is key.

29 **Keywords**

30 Scenarios, storylines, cross-scale, quantitative models, simulation, energy,
31 environment, climate change, transition pathways

34 **Highlights**

- 35 • Linking a qualitative storyline with multiple, diverse quantitative models
- 36 • Landscape of models for mapping the fields of expertise of individual
- 37 models
- 38 • Cross-scale analysis of the UK power system transition until 2050

39

40 **Graphical abstract**

41 *Insert the Graphical abstract about here*

42

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, such as governance, institutional changes or energy-related behaviour, 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, 19]. Despite the current research on formal techniques for developing better storylines [20-23], these limitations still remain.

Quantitative models-based scenarios are produced by a single or multiple models, such as in the ADAM [24], Energy Modelling Forum [25], Low Carbon Society modelling [26] and NEEDS [27] 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, 13, 15]. Models are based on the empirical data, physical laws, 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, and environmental aspects. But they still have difficulty in capturing the afore-mentioned softer and subtler aspects. The research priorities are towards developing more detailed models and including softer aspects, such as behaviour and governance, into models [17, 28]. Yet, even better models alone can hardly offer the breadth and engaging nature of the storyline-based scenarios. For example, the models cannot picture organisational and institutional change needed to deliver a wanted transition, even if these elements are important for decision makers to envision and manage this transition.

In light of these strengths and weaknesses of storylines and quantitative models, state-of-the-art scenario studies argue for combining them [1-5]. In order to complement the models, storylines can reflect such aspects, like (i) exogenous context in which the modelled system is embedded into, (ii) exogenous modelling assumptions, such as drivers for change, or (iii)

93 aspirational targets for the future system. Many recent scenario exercises
94 already have the elements of both storylines and models: storylines include
95 numbers, while modelling outputs are described in short qualitative narratives.
96 Several scenario exercises explicitly combine the storylines and the quantitative
97 models in an iterative manner [6, 10, 11, 29-31]. Examples of these include key
98 international scenario exercises: the integrated climate change scenarios of the
99 Intergovernmental Panel of the Climate Change [32, 33], the scenarios of
100 ecosystem services in the Millennium Ecosystem Assessment [34] and of the
101 global environment in the Global Environmental Outlook [35].

102 Despite the fact that the combination of storylines and quantitative
103 models has emerged as an established practice in the technology- and
104 environment-related fields [1-6], existing literature runs short in providing
105 methodological insights for how to link detailed storylines, which are developed
106 through stakeholder and expert engagement, with multiple quantitative models.
107 First, if the storylines are very detailed, then numerous additional assumptions
108 are needed to ‘translate’ them into model parameters. Second, multiple diverse
109 models may be needed to model detailed storylines with various spatial and
110 temporal foci, disciplinary perspective (technical feasibility, economic or
111 environmental appraisal), model objective, and the parts of the system
112 addressed. This diversity is valuable because the storylines can be addressed
113 from multiple angles and across scales, but it is challenging to relate such diverse
114 models to each [36]. Thus, a new approach has to be developed for linking
115 detailed storylines with multiple, cross-scale models, which have different
116 spatial, temporal and disciplinary foci. This paper proposes such an approach.
117 There is a growing number of interdisciplinary projects in energy, climate

change and other technology- and environment-related studies. It can be expected that many of these projects will attempt to develop cross-scale scenarios by linking storylines with multiple models and will require such an approach.

The proposed approach is illustrated with the cross-scale analysis of the UK power system transition until 2050 as a part of the Realising Transition Pathways (RTP) consortium project. A detailed storyline, called the *Central Co-ordination*, was developed in the preceding Transition Pathways project [37-39] and is used for the cross-scale analysis with six quantitative power system models and two quantitative appraisal techniques. The idea for this analysis arose from discussions at RTP consortium workshops. The authors of this paper took the analysis forward and its results will be an input to further development of the consortium's research.

This paper is laid out as follows: Section 2 proposes a general methodological approach; Section 3 gives an example of linking the *Central Co-ordination* storyline with eight RTP models, present and discusses the findings; Section 4 discusses the general approach; and Section 5 concludes.

2. Proposed approach for linking storylines with multiple models

This section describes the proposed process (Figure 1) of linking a detailed storyline with the insights from multiple diverse models. First of all, one of the biggest challenges in cross-scale scenario studies is ability to systematically combine insights from multiple cross-scale models. Understanding and mapping the breadth and depth of the expertise of every

individual model is challenging, especially given a diverse set of models. This paper proposes mapping this expertise in two complementary ways:

- (i) List the key characteristics of the models and elicit the **key fields of expertise**. These key fields of expertise reflect the types of insights that a particular model analyses in most depth, as compared to the other models. This concept of the key field of expertise thus appreciates the distinct value of every model in a multi-model analysis. 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.
- (ii) Prepare a visual map, called the **landscape of models**. This map shall summarise the information about the breadth and depth of the analysis, done by every model, and show how these afore-mentioned fields of expertise overlap between the models. This mapping can be done on the basis of the parts of the system addressed and/or other thematic considerations addressed by the models. The mapping characteristics will likely differ from one set of models to another. The depth of analysis can then be defined in three categories: detailed modelling (the key field of expertise), stylised modelling and exogenous assumptions only.

Insert Figure 1 about here

Figure 1. The iterative process of linking storylines with multiple cross-scale quantitative models

Both concepts of the model's key field of expertise and the landscape of models help to grasp, where models differ or overlap. If models overlap, then they can validate each other and help cross-check the results. Every model, however, likely has at least one area where it outperforms the other models in depth or breadth as there is no single best model that covers all aspects in depth and across all the relevant scales.

As shown in Figure 1, in order to link a detailed storyline with insights from multiple models, the qualitative storyline is first 'translated' into a set of harmonised assumptions that are necessary for conducting the model runs, specifically tailored for the storyline (Step 1 in Figure 1). Such a 'translation' is a challenging task. On the one hand, these harmonised assumptions will already be a narrower representation of the 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 models used for cross-scale analyses are often 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.

After the models are run with these harmonised assumptions, the statements of the storyline are checked for their consistency with the modelling results (Step 2 in Figure 1). The storyline can then be revised. The landscape of models plays an important role here as it highlights 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

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 1 is repeated iteratively for updating the storyline.

3. The case of the UK power system transition

This section provides a cross-scale example of linking a very detailed storyline of the UK power sector transition until 2050 with insights from six power system models and two appraisal techniques. The section starts by describing the UK power sector and the context of the storyline (Section 3.1), then moves to the description of the models (Section 3.2), the process of linking a storyline with multiple models (Section 3.3), and finishes with summarising and discussing the findings.

3.1. UK power system and the Central Co-ordination storyline

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 [39, 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 in the preceding Transition Pathways project: *Central Co-ordination*, *Market Rules* and *Thousand Flowers* [39, 45]. Compared to other scenario exercises in the UK [7-9, 46] 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 or drivers such as population growth, technological development and others, c.f. [32, 34, 35, 47]. The RTP storylines explicitly focus on the uncertainty around governance 'logics' and the choices of actors and how this could affect the power system transitions. In order to achieve this, the RTP storylines combine all three afore-mentioned elements of storylines: exogenous context, transition drivers and – mostly – targets for the future power system.

The process of developing these three storylines is described in detail in [39]. 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 [45] and shorter summaries are published in [39]. 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 [39]. This process was partly informed by insights from three power system models, but none of these models were informed by economic considerations [39]. 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.

The *Central Co-ordination* storyline, analysed in this paper, is one of the three storylines of the RTP project. These storylines picture three ideal types of governance ‘logics’ in the UK power system (Figure 2): government, market and civil society ‘logics’. In these storylines, the views that the government, market or civil society actors respectively need to lead the low-carbon transition emerge as the ‘zeitgeist’ of the time [39]. In the case of the *Central Co-ordination* storyline, the central UK government successfully establishes the dominant role by direct co-ordination to deliver the energy policy goals. In the *Market Rules* storyline, the market actors successfully 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 society at large shall take an active role in delivering the low-carbon transition as small-scale solutions, especially, but not only 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 [48]. Since the power market liberalisation in 1990s, the market ‘logic’ has been dominating in the UK,

but the influence of the government ‘logic’ has been increasing in 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.

Insert Figure 2 about here

Figure 2. The three ideal types of governance ‘logics’ in the UK power system transition. Source: J. Burgess and T. Hargreaves. The figure is reproduced from [39].

The *Central Co-ordination* storyline includes five pages of narrative and here only the key points are summarised. The central UK government is assumed to actively shape the power system transition through the establishment of a new 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 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 any 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 for power generation. As noted, society at large 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, interventions on lifestyles and behaviour will be undertaken by the government, especially through smart metering and demand side response measures. The key risks, identified in the storyline for the realisation of this transition, are (i) the 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.

In addition to the qualitative narrative, the *Central Co-ordination* storyline was already assigned an initial quantitative representation (Figure 3), developed in an iterative process by the Transition Pathways Technical Elaboration Working Group. This quantitative representation served both as an example of how the power sector may look in detail and as a basis for conducting further quantitative research on the storyline (for instance, for environmental or economic appraisals).

Insert Figure 3 about here

Figure 3. The initial quantitative representation of the *Central Co-ordination* storyline. Source: Transition Pathways project. The figure is reproduced from [39].

3.2. Landscape of the RTP models

This section describes the six power system models and two appraisal 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 cross-scale aspects [16]. The RTP leadership envisioned a multi-model analysis, expecting that this analysis, rather than results of a single model, will have 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 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 [49-51] and the assumptions from the *Central Co-ordination* storyline.
- **FESA:** The Future Energy Scenario Assessment model [52, 53], developed at the Loughborough University, is a single-year UK power generation and demand model, incorporating one-hour time steps for dispatch modelling and using 2001 Met Office weather data on 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, 31, 54, 55]. 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 [55].

- **EconA:** The Economic Appraisal (EconA), conducted by University College London, aims to systematically calculate and compare total investment costs and total system costs for power generation, transmission and distribution for the three transition pathways. The results are disaggregated for the different power generation technologies, which allows for economic feasibility assessment. The EconA is an appraisal technique; it takes the quantitative representation (Figure 3) of the *Central Co-ordination* storyline and calculates the power system costs for it. In this paper, the EconA is also considered as a model in a broader sense.

- 391 • **BLUE-MLP:** The BLUE-MLP model (Behaviour Lifestyles and
392 Uncertainty Energy model with Multi-Level Perspective on
393 transitions) is a probabilistic systems dynamic simulation that
394 explores the uncertainties due to sector- and actor- specific
395 behavioural elements [56, 57]. These behavioural elements include
396 market heterogeneity, intangible costs and benefits, hurdle rates,
397 replacement and refurbishment rates and demand elasticities. In
398 addition, the model links these behavioural uncertainties with the
399 multi-level perspective to transitions [58], where landscape
400 (government decisions and the international context), regime (the
401 current UK power system structure and its regulation) and niche
402 innovations (lifestyle influenced changes in demand) interact with
403 each other.
- 404 • **EEA:** The Energy and Environmental Appraisal (EEA) is a life cycle
405 assessment (LCA) of the UK power system carried out by the
406 University of Bath [59, 60]. Over 18 environmental impacts were
407 evaluated from cradle to gate, accounting for all upstream and
408 operational activities. Impacts covered in this assessment include
409 climate change, which is quantified through greenhouse gas emissions,
410 and other environmental impacts, such as fossil fuel depletion, human
411 toxicity, particulate matter formation and agricultural land
412 occupation. Similar to the EconA, the EEA framework is a model,
413 which appraises the *Central Co-ordination* storyline, based on its initial
414 quantitative representation (Figure 3).

- 415 • **HESA/UK+**: This is a combination of the Hybrid Energy System

416 Analysis tool (HESA) and the Strathclyde UK+ models that were

417 developed at the University of Strathclyde [61-63]. The Strathclyde

418 UK+ model contains all the information for the transition pathways

419 scenarios with spatial disaggregation (17 onshore, five offshore zones

420 and 39 connections) of generation, storage, transmission and

421 distribution. It is linked to the HESA model, which cost-optimises the

422 system, based on the energy hub concept [64, 65]. The national power

423 demand and generation mix are used as input assumptions.
- 424 • **HAPSO**: The Holistic Approach to Power System Optimisation model

425 (HAPSO) is developed at the Imperial College London. It is a bottom-

426 up, cost-minimisation model that determines the optimal generation,

427 energy storage, transmission, and distribution network infrastructure

428 requirements and their associated cost to achieve three objectives:

429 economic efficiency, security, and sufficient system controllability. The

430 model optimises simultaneously the long-term investment and short-

431 term operating decisions including hourly generation dispatch,

432 Demand Side Response, storage cycles, and power exchanges taking

433 into account the impact of decisions across all sectors in the power

434 system [66]. The UK power system is embedded in the European

435 power system including UK, Ireland and continental Europe and thus

436 allows for modelling of the power exchange across these regions.

437

438 The fields of expertise of the individual models are mapped in Table 1 and

439 Figure 4. The landscape of the RTP models is prepared 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). Both Table 1 and Figure 4 help to show that the eight models, used in this analysis, cover a broad spectrum of cross-scale insights across time, space, system boundaries and disciplines.

449 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); storage (stylised)	Storage (stylised)	Dispatch (stylised); Demand response	Storage (stylised)	Dispatch; Storage	Dispatch; Demand response; Storage
-- Trans-mission and distribution						Transmission and distribution	Transmission and distribution	Transmission and distribution

Model	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
-- Inter-connectors to Europe		Import; Export	Import	Import		Import	Import; Export	Import; Export; UK embedding in the European system
-- Non-electric parts of the energy system	Non-electric heating	Non-electric heating; Non-electric transport; Non-electric industrial and commercial uses			Non-electric heating; Non-electric transport; Non-electric industrial and commercial uses		Non-electric heating	
Modelling method	Deterministic simulation	Deterministic simulation	Cost-optimisation and evaluation of maximally different near-optimal pathways	Appraisal of exogenous scenarios	Dynamic simulation	Appraisal of exogenous scenarios	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

Model	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
Environmental considerations		Post hoc assessment; Operational emissions (from primary energy use); Only CO ₂ emissions	Emission constraint; Operational emissions; Only CO ₂ emissions	Exogenous assumptions	Post hoc assessment; Operational emissions; Only CO ₂ emissions	Post hoc assessment; 'Whole system' (LCA) environmental impacts, including upstream and operational impacts; Greenhouse gas emissions (CO _{2eq}); Fossil fuel depletion; Human toxicity; Particulate matter; Agricultural land occupation	Post hoc assessment; Operational emissions; Only CO ₂ emissions	Emission constraint; Operational emissions; Only CO ₂ emissions
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			

450

451

Model	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
<i>Key field of expertise</i>	<i>Demand</i>	<i>Dispatch, demand response and storage; Generation</i>	<i>Maximally different alternatives; Uncertainty</i>	<i>Economic appraisal</i>	<i>Uncertainty; Behaviour and heterogeneity of the actors</i>	<i>Energy and environmental appraisal</i>	<i>Transmission and distribution; Generation; Spatial disaggregation</i>	<i>Dispatch and demand response; Generation; Transmission and distribution; Interconnectors</i>

452 *Insert Figure 4 about here*

453
454 Figure 4. The landscape of models (model versions as of April 2013)

455
456 *3.3. Process of linking the storyline with multiple models*

457 For translating the *Central Co-ordination* storyline into the harmonised
458 modelling assumptions, several key aspects of this storyline are taken. In
459 contrast to the typical story-and-simulation approach, such as [32, 33], where
460 storyline describes the drivers of future transition, the *Central Co-ordination*
461 storyline includes multiple targets for the future power system that should be
462 met under the increased role of government. The targets that are chosen as
463 harmonised modelling assumptions are: (i) a mild growth of the power demand
464 due to the incentives for end-use energy efficiency, (ii) the increased use of large-
465 scale low-carbon technologies, especially of those where UK industry could take
466 a global lead, and a medium uptake of decentralised generation, (iii) the
467 achievement of the emission mitigation goals and (iv) low risk of investment due
468 to the tenders for tranches, issued by the Strategic Energy Agency. More
469 specifically, the models are tuned to match these harmonised assumptions as
470 closely as possible:

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

- 477 ii. Power generation mix in the UK:
- 478 - In 2020, 40% of the produced power comes from low-carbon sources,
- 479 prioritising coal CCS, nuclear and renewable sources. At least 25% of
- 480 the produced power comes from renewable sources, such as offshore
- 481 and onshore wind, wave, tidal barrage and tidal stream.
- 482 - In 2030, the power generation mix bridges the mixes of 2020 and
- 483 2050.
- 484 - In 2050, 75% of total produced power comes from large-scale low-
- 485 carbon sources, such as nuclear, coal and gas CCS, offshore wind,
- 486 wave, tidal barrage and tidal stream. At least, 25% comes from low-
- 487 carbon decentralised sources, such as onshore wind and biomass
- 488 combined heat and power (CHP) plants.

- 489 iii. Greenhouse gas emissions:
- 490 - In 2020, the average carbon intensity in the whole UK power system is
- 491 300 gCO₂/kWh of power produced;
- 492 - In 2030, this value drops to 30 gCO₂/kWh;
- 493 - In 2050, it is as low as 20 gCO₂/kWh.

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

496

497 Not all of the eight models can implement all of these harmonised

498 assumptions. First, the Demand, FESA models and EEA cannot consider the last

499 assumption about the discount rate as they do not consider costs at all. They,

500 therefore, by-passed this assumption, but implemented the remaining

501 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 3), which is in line with the harmonised assumptions described above.

The qualitative statements from the *Central Co-ordination* storyline are then scrutinised from the perspective of the outputs of every model. The storyline pictures the contextual information, such as the governance arrangements and the role of the different actors. These aspects can hardly be interrogated by the models. But the description of the targets, that are aspired in the storyline as a result of the governance arrangements and the actors' decisions, can be 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" [45, 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" [45, p. 3] is interrogated by the eight models.

3.4. Results and discussion on 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 power system targets to be delivered by the governance

arrangements and actor choices, specified in the storyline, is compared and contrasted with the modelling results.

Robust elements of the storyline

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.

Divergence on demand reduction levels

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

551 saving behaviour and efficiency improvements. However, the BLUE-MLP model
552 shows that, when the economic drivers of energy demand and the heterogeneity
553 of the behaviour of the different actors is considered, maintaining slow power
554 demand growth through the entire model horizon appears rather wishful
555 thinking. This finding is in line with the common observation that technically and
556 economically sensible energy demand reduction measures may not be taken up
557 in reality [67]. Storylines developed by the various stakeholders and experts—
558 even more than models—tend to be overly optimistic and fragile from the
559 modelling perspective [10, 11]. This remark is also consistent with a broader
560 argument that failures of effectively mitigating climate change can be expected
561 [68]. The *Central Co-ordination* storyline envisions a passive role of the civic
562 society. Without the active energy saving action of the society at large, drastic
563 demand reduction may be challenging to achieve. The UK government could only
564 enforce some types of measures for mitigating the power demand, such as smart
565 meters, efficient domestic appliances or refurbishment of buildings. Thus, the
566 expectation from the storyline about the demand needs to be revisited.

567 568 *Divergence on back-up capacity*

569 The *Central Co-ordination* storyline aspired to the retirement of existing
570 coal and gas power plants by 2037 and their replacement with low-carbon
571 technologies, such as renewable energy sources or gas and coal with CCS.
572 However, both the D-EXPANSE, BLUE-MLP and HAPSO models, which also model
573 the demand response potential, show that this aspiration is challenged by the
574 dispatch (supply-demand balancing) constraint. According to the models, for the
575 aspired high deployment of intermittent renewable energy sources there will be

a need for significant levels of back-up capacity, mostly flexible gas OCGT power plants. The D-EXPANSE model, which explores the many 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. Most importantly, the HAPSO model, whose key field of expertise is dispatch modelling due to its one-hour temporal resolution and detailed assessment of supply 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 supply 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 4, 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.

Divergence on emission mitigation levels

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 gCO₂/kWh in the storyline, the modelling outcomes range from 33 gCO₂/kWh to 56 gCO₂/kWh for CO₂ for operational emissions and equals 120 gCO_{2eq}/kWh for the 'whole system' (cradle to gate) emissions. The D-EXPANSE model shows a number of power generation mixes, which are not necessarily the same as modelled in other seven models, but are still consistent with the harmonised assumptions of the storyline. Some of these mixes could meet the target of 30 gCO₂/kWh, but these mixes are different from the mixes evaluated

by the other models. Thus, while reaching the emission target can be technically feasible, it may not be realistic via the means that the storyline describes. According to the EEA, which has the most detailed accounting of the operational and ‘whole system’ emissions as its key field of expertise, the emissions 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.

Divergence on power generation mix

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 [39]. 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 to lack of market integration and lack of interconnectors between the UK and continental Europe. This significant curtailment would reduce the economic feasibility of renewable 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. The EEA model highlighted that the deployment of coal CCS is likely to provide almost a quarter less carbon emission mitigation than is normally assumed on a whole system basis. 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.

Divergence on the key risk

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; near-optimal scenarios are defined as scenarios that have up to 30% higher total cumulative system costs by 2050 than the least cost scenario. Many of these scenarios do not have CCS, even if the carbon price rise to £207.5/tonne CO_{2eq} by 2050 is assumed in line with [69]. 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 coal 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, even with the carbon price increase up to £600/tonne CO_{2eq} by 2050. 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, as it describes high levels of intermittent renewable sources and inflexible power plants with CCS, which are challenging to combine. At the same time, the storyline does not refer to the necessary flexible generation and demand response measures that would guarantee simultaneous integration of CCS and renewable sources into the system. 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 2 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.

Under-represented aspects of the storyline

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 4). 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. All these aspects are often forgone not only in the Transition Pathways storylines, but also in wider energy policy discourses. Yet, the future power system transition requires a portfolio of measures on the power demand, generation, transmission and distribution sides. These aspects need to be considered, when developing the next version of the storyline.

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

Some of the relevant quotes from the storyline, taken from [45]. 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								

The key risk is that “Carbon capture and storage turns out to be technologically or economically unfeasible”			(Not key risk)					
The key risk is that “Higher energy service costs resulting from high levels of low-carbon investment.”								

699

4. Discussion on the general approach

This section critically reflects the proposed approach for linking detailed storylines with multiple models, based on the case of the *Central Co-ordination* storyline.

Development of storylines

In scenario processes, storylines are often very detailed because they aim 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 under the typical story-and-simulation approach [2] or when using such detailed storylines as in the RTP projects, the internal consistency of this storyline becomes at risk. For example, the comparison of the *Central Co-ordination* storyline with the outputs of the eight RTP models reveals several inconsistencies. The storyline describes the role of society at large as passive, while the envisioned substantial decrease in the energy service demand may not be feasible without concerted efforts to reduce demand for energy services. In order to avoid such cases, it seems likely that the development of internally consistent, stakeholder-based storylines, facilitated by formal techniques such as formative scenario analysis or cross-impact balance [5, 20-23, 70, 71], would increase the robustness of the qualitative storyline itself.

Second, some internal inconsistencies as well as other mistakes due to the lack of analytical foundation can be eliminated by comparing the storyline with

models (given that these models are available), as done in this paper. This is essential because the power system transition is inherently complex and the 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 [70]. 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 leaving the power system description to the multiple models.

'Translation' of storylines into model assumptions

The way a qualitative storyline is 'translated' into the assumptions for the quantitative models (Step 1 in 1) 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 storyline and the multiple targets, aspired by the stakeholders, could be tested in light of modelling results. This can be a useful and creative learning exercise for the stakeholders [10, 11]. At the same time, the RTP project seeks to better grasp a wide range of plausible future power system developments, if the central UK government plays a more active role in shaping the power sector transition. Thus, models with different rationales could help capturing a wider range of these plausible futures. If too many assumptions would be used, this variety of plausible futures would be lost. For example, in the case of the RTP models, 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 of the study, presented in Section 3. 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.

Mapping the expertise of models

The landscape of models (Table 1 and Figure 4) proved to be a useful approach for understanding and mapping the fields of expertise of the eight, very diverse cross-scale models as in 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 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 and scales 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 RTP models proved to be useful for assessing the storyline from different cross-scale perspectives on space, time, system boundaries, discipline and even technique (Table 1).

However, this landscape of RTP models for revising the *Central Coordination* storyline 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 RTP 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 [46, 72] 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 [73] and thus, together with the landscape of models, it could improve the analytical assessment of the qualitative storylines.

Two-way reflexive collaboration

The iterative loop in Figure 1 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 inconsistencies between the storyline and the models. 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 inconsistencies in the storyline. Unpacking the underlying mechanisms of this divergence (as already reported in Section 3.4) is thus essential for understanding why this divergence appears and, if necessary, revising the storyline and/or the models. The next step of this process would be a collaborative, reflexive effort between the storyline developers and the modellers. In this way, improved versions of the storyline and the models could be developed.

The iterative loop in Figure 1 is a two-way reflexive collaboration between the storyline and the models [36]. 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, 54, 55, 74-76]. Such process could be organised similar to the process of Figure 1, but it would start with the modelling exercise.

5. Conclusions

849 This paper extends the current state-of-the-art approach for linking
850 qualitative storylines with quantitative, cross-scale models. An approach is
851 proposed for linking a very detailed storyline, which describes the governance
852 'logics' and the choices of key system actors, with multiple, very diverse
853 quantitative models. This approach is especially relevant because a growing
854 number of interdisciplinary projects worldwide tend to bring together social
855 scientists with modellers. Most of these models already exist before the projects
856 and differ substantially in their spatial and temporal foci, disciplinary
857 perspective, model objective, system boundaries and the format of inputs and
858 outputs. Cross-comparison of such models is a challenge in itself. In the proposed
859 approach, the comparison of the models is based on a new concept called the
860 landscape of models. Moreover, this paper goes further by linking these multiple,
861 diverse cross-scale models with qualitative storyline. Therefore, the described
862 approach is a novel contribution to the existing literature.

863 In the frame of the Realising Transition Pathways project, the proposed
864 approach is illustrated by revising the *Central Co-ordination* storyline, developed
865 in the earlier Transition Pathways project, for exploring the UK power system
866 transition until 2050. This storyline describes the governance 'logics' and the
867 choices of the key system actors, when the UK central government should take a
868 more active role in shaping the power system transition. Such contextual
869 considerations as governance and the actors' choices can hardly be modelled in
870 the current RTP models; this highlights the value of the storyline. This qualitative
871 storyline is addressed through the perspective of six, very diverse models and
872 two appraisal techniques: Demand, FESA, D-EXPANSE, EconA, BLUE-MLP, EEA,
873 HESA/UK+ and the HAPSO models. These models and appraisals revealed the

874 fragile nature of the storyline. From the perspective of the model, the storyline
875 tended to wishfully overestimate the power demand reduction potential and the
876 uptake of marine renewables. The necessity for CCS to meet long-term stringent
877 greenhouse gas emissions targets was also overestimated. But it underestimated
878 the supply-demand balancing challenge, the need for gas power plants as a back-
879 up capacity, the role of nuclear power and interconnectors with Europe, and the
880 challenge of meeting the stringent emissions targets. Thus, the combination of
881 the qualitative storyline and its revisions from the perspective of multiple,
882 diverse models is key for developing robust future scenarios and transition
883 pathways. An iterative process for this purpose has been proposed in this paper.

884 For the RTP consortium, the interpretation of the results of this analysis
885 and their implications for the future development of both the storylines and the
886 models will be the subject of further debate, research and papers.

887 888 **Acknowledgements**

889 This work was conducted as a part of the Realising Transition Pathways
890 consortium project, supported by the UK Engineering and Physical Sciences
891 Research Council (Grant EP/K005316/1). The authors are solely responsible for
892 the analysis and views in this paper.

893 The authors thank the other members of the Realising Transition
894 Pathways project and the preceding Transition Pathways project, who developed
895 the *Central Co-ordination* storyline and participated in the workshops that led to
896 the development of this paper (a full list of the consortium members is available
897 at [77]). The substantial contributions of Neil Strachan and other contributions
898 of Graham Ault, Stuart Galloway, Geoff Hammond, Matt Leach, Goran Strbac and

Murray Thomson in guiding the development and analysis of the models are also acknowledged. The authors especially value the extensive critical review by Geoff Hammond, Peter Pearson and the anonymous reviewers that helped to considerably improve the manuscript.

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