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Facilitating interdisciplinary learning among the Realising Transition Pathways models

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Realising Transition Pathways

Whole systems analysis for a UK more electric low carbon energy future

Realising Transition Pathways

'Realising Transition Pathways' (RTP) is a UK Consortium of engineers, social scientists and policy analysts. The consortium is managed by Professor Geoffrey Hammond of the University of Bath and Professor Peter Pearson of Cardiff University (Co-Leaders). It includes research teams from nine British university institutions: the Universities of Bath, Cardiff, East Anglia, Leeds, Loughborough, Strathclyde, and Surrey, as well as Imperial College London and University College London. The RTP Project [www.realisingtransitionpathways.org.uk] commenced in May 2012 and is sponsored by the 'Engineering and Physical Sciences Research Council' (EPSRC: Grant EP/K005316/1). It is a renewal and development of the earlier 'Transition Pathways' (TP) project, which was initially established in 2008 with the joint sponsorship of E.ON UK (the electricity generator) and the EPSRC. This project addressed the challenge of the so-called energy 'trilemma': the simultaneous delivery of low carbon, secure, and affordable energy services for the electricity sector. It developed and applied a variety of tools and approaches to analyse the technical feasibility, environmental impacts, economic consequences, and social acceptability of three 'transition pathways' towards a UK low carbon electricity system. These pathways explore the roles of market, government and civil society actors in the governance of a low carbon energy transition.

The research within the RTP Project seeks to explore further the constraints and opportunities in realising a low carbon UK energy sector, including those stemming from European developments. This project includes studies on the horizon scanning of innovative energy technologies over the period to 2050, the feasibility of demand responses, uncertainties in economic analysis, the estimation of investment costs of the different pathways, and the implications of markets for investment decisions about energy technologies. Further work is being undertaken on conceptualising, mapping and analysing 'actor dynamics' in the contemporary UK electricity sector, historical transitions and case studies, integrated energy networks modelling and evaluation, and 'whole systems' energy and environmental appraisal of low carbon technologies and pathways. The consortium is also developing their initial work on branching points on pathways, in order to identify and explore other potential branching points on the core transition pathways.

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This document has been prepared to enable results of on-going RTP work to be made rapidly available. It has not necessarily been subject to review and approval, and may not have the authority of a full Research Report or published paper.

1. Abstract

Six quantitative energy models and two appraisal techniques are being developed in the Realising Transition Pathways (RTP) project. All these models and techniques address the UK power system transition until 2050, but differ in their disciplinary perspective, objectives, methodological approaches and parts of the power system addressed. This working paper aims to compare these models to each other in order to facilitate interdisciplinary learning among the models and their developers. First, the RTP models are mapped out in order to understand their overlays and differences. Second, by means of running the models with harmonised assumptions of the "Central Co-ordination" transition pathway, converging and diverging insights of these models are identified. In this way, areas for further development of the models are suggested. This report describes the process and outcomes of this multi-model analysis.

2. Introduction

In autumn 2012 the Realising Transition Pathways (RTP) project leadership envisioned a comparison exercise of six energy models and appraisal techniques that are developed in the RTP project. The key aims of this comparison were:

- Facilitate interdisciplinary learning among the RTP project members about each other's models, their overlays and differences;
- Gather insights into the strengths of every individual model and identify areas for further development that could be undertaken during the RTP project.

This comparison exercise was conducted in several stages from December 2012 to May 2013. First, an internal RTP workshop was organised on 7th December 2012 in order to map the system boundaries, objectives, strengths and weaknesses of the different models. Second, a multi-model analysis of the "Central Co-ordination" transition pathway was conducted in order to compare and contrast the numeric results of the models. The outcomes of this multi-model analysis were presented and discussed in the second internal RTP workshop on 24th April 2013.

This working paper is one of two written outputs, reporting this multi-model analysis. Trutnevyte et al. [1] reflects the feasibility and the prerequisites of the 'Central Co-ordination' pathway from the perspective of these RTP models. This working paper summarises the insights on the strengths and weaknesses of the different models and lists areas for further development of the models. Section 3 of this working paper describes the RTP models. Section 4 describes the process and the results of the multi-model analysis of the "Central Co-ordination" pathway. Section 5 lists the insights for further development of the models.

3. RTP models

Six energy models and two appraisal techniques of the RTP project participated in this multi-model analysis:

1. Energy demand model of the University of Surrey (further called **Demand**)

   This is a bottom-up model of the UK power demand in the domestic and non-domestic sectors. Due to the model's highly disaggregated structure, the influence of parameters, such as the energy service levels, user practices, choices of appliances, building fabric, fuels, deployment of distributed generation and others, can be analysed. The model is based on the synthesis of existing estimates [2-4] and the assumptions from the "Central Co-ordination" narrative.

2. Future Energy Scenario Assessment model of the Loughborough University (**FESA**)

   The Future Energy Scenario Assessment model is a single-year UK power generation and demand model, incorporating one-hour time step for dispatch modelling and using real weather data of temperature, wind speeds, wave height and solar radiation. The model develops scenarios on the basis of the "Central Co-ordination" narrative and technical feasibility constraints.

3. Hybrid Energy System Analysis/Strathclyde UK+ model of the University of Strathclyde (**HESA/UK+**)

   This is a combination of the Hybrid Energy System Analysis tool and the Strathclyde UK+ models [5-7]. Strathclyde UK+ model contains the information about the UK power generation, storage, transmission and distribution with spatial disaggregation (17 onshore, five offshore zones and 39 connections). Strathclyde UK+ model is linked with the HESA model, which optimises the system costs, based on the energy hub concept. The national power demand and generation mix are used as input assumptions.

4. Holistic Approach to Power System Optimisation model by Imperial College London (**HAPSO**)

   This is a bottom-up, cost-minimisation model that determines the optimal generation, storage, transmission and distribution network infrastructure requirements and their associated cost. The objectives of this optimisation are economic efficiency, security and sufficient system controllability. The model optimises simultaneously the long-term investment and short-term operating decisions including hourly generation dispatch, demand side response, storage cycles, and power exchanges [8]. The UK power system is embedded in the European power system that includes UK, Ireland and continental Europe.

5. Behaviour Lifestyles and Uncertainty Energy model with Multi-Level Perspective on transitions of UCL Energy Institute (**BLUE-MLP**)

The BLUE-MLP model is a probabilistic system dynamics simulation that explores the uncertainties due to sector- and actor- specific behavioural elements [9, 10]. 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 [11], 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.

6. Dynamic version of EXploration of PAtterns in Near-optimal energy ScEnarios model of UCL Energy Institute (**D-EXPANSE**)

   The D-EXPANSE model 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 [12-15]. 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 [15].

7. Economic appraisal of the RTP transition pathways by UCL Energy Institute (**EconA**)

   This EconA appraisal aims to evaluate the investment and operational costs as well as the related risks and uncertainties of the transition pathways. This is an appraisal technique; it takes the quantitative representation of the “Central Co-ordination” pathway [16, 17] and appraises it.

8. Environmental and energy appraisal of the RTP transition pathways by the University of Bath (**EEA**)

   The EEA appraisal aims to evaluate the ‘whole system’ (from cradle to gate) greenhouse gas emissions and other environmental impacts, such as human toxicity, particulate matter formation and agricultural land occupation [18, 19]. This is an appraisal technique too as it appraises the “Central Co-ordination” transition pathway, based on its initial quantitative representation [16, 17].

As seen from these descriptions, the RTP models are very diverse in their disciplinary origin, objectives, methodological approaches and parts of the power system covered. In both April and December workshops, it was acknowledged that every model has its strengths and limitations and, thus, has its specific niche or key area of expertise in comparison to the other models. Table 1 attempts to compare the different RTP models and to elicit the individual niche of every model in this landscape of energy models.

Table 1. Comparison of the RTP models

Model	**Demand**	**FESA**	**HESA/UK+**	**HAPSO**	**BLUE-MLP**	**D-EXPANSE**	**EconA**	**EEA**
Energy system boundaries	✓ Residential demand ✓ Non-residential demand ✓ End-use equipment	✓ Residential demand ✓ Non-residential demand ✓ End-use equipment	✓ Total demand	✓ Residential demand ✓ Non-residential demand	✓ Residential demand ✓ Non-residential demand	✓ Total demand	✓ Total demand	✓ Total demand
	✓ Electric demand ✓ Non-electric demand	✓ Electric demand ✓ Non-electric demand	✓ Electric demand ✓ Non-electric demand	✓ Electric demand ✓ Non-electric demand	✓ Electric demand ✓ Non-electric demand	✓ Electric demand	✓ Electric demand	✓ Electric demand
	✓ Small scale CHPs	✓ Large scale electricity generation ✓Decentralised generation ✓Import ✓Export	✓ Large scale electricity generation ✓Decentralised generation ✓Import ✓Export	✓ Large scale electricity generation ✓Decentralised generation ✓Import ✓Export	✓ Large scale electricity generation	✓ Large scale electricity generation ✓Decentralised generation, ✓Import	✓ Large scale electricity generation ✓Decentralised generation, ✓Import	✓ Large scale electricity generation ✓Decentralised generation, ✓Import ✓Export
	✓ Heat supply	✓ Non-electricity supply	✓ Non-electricity supply	✓ Non-electricity supply	✓ Non-electricity supply		✓ Heat supply	
		✓Dispatch ✓Storage ✓ Hydrogen	✓Transmission ✓Distribution	✓Transmission ✓Distribution ✓Dispatch ✓Storage				
Geographical scope	UK	UK	UK	UK, Europe	UK	UK	UK	UK
Spatial disaggregation			17 onshore, 5 offshore	4 UK regions				
Finest temporal resolution	1 year	1 hour	1 year	1 hour	1 year	5 years	1 year	1 year

Model	**Demand**	**FESA**	**HESA/UK+**	**HAPSO**	**BLUE-MLP**	**D-EXPANSE**	**EconA**	**EEA**
How a pathway is constructed?	Calculated based on the assumptions from the 'Central Co-ordination' narrative	Calculated based on the assumptions from the 'Central Co-ordination' narrative and the current merit order	Exogenous input for the supply mix, cost-optimisation for the grid	Cost-optimisation	Probabilistic system dynamics simulation	Cost-optimal pathway and exploration of multiple near-optimal pathways	Exogenous input	Exogenous input
Evaluation of costs			✓Cost-optimisation ✓ Investment, operating and maintenance (O&M), fuel ✓CO_2 price ✓Financial support	✓Cost-optimisation ✓ Investment, O&M, fuel ✓CO_2 price	✓Dynamic simulation, given heterogeneous sensitivity of actors to costs ✓Investment, O&M, fuel ✓Electricity retail price (incl. taxes), CO_2 price, climate change levy ✓Financial support ✓Non-monetary utility	✓Cost constraint, near cost-optimality ✓Investment, O&M, fuel	✓Post hoc assessment ✓ Investment, O&M, fuel	
Evaluation of emissions		✓Post hoc assessment ✓Fuel ✓CO_2	✓Post hoc assessment ✓Fuel ✓CO_2	✓Emission constraint ✓Fuel ✓CO_2	✓Dynamic simulation ✓Fuel only ✓CO_2	✓Emission constraint ✓Fuel ✓CO_2	✓Post hoc assessment ✓Fuel ✓CO_2	✓Post hoc assessment ✓Cradle to gate ✓CO_2eq
Uncertainties				✓ Sensitivity analysis	✓ Probability distributions for multiple	✓ Structural uncertainty around cost-	✓ Ranges in costs	

Model	Demand	FESA	HESA/UK+	HAPSO	BLUE-MLP	D-EXPANSE	EconA	EEA
					parameters	optimisation ✓ Parametric uncertainty accommodated to some extent through near-optimal pathways		
Other aspects addressed		✓ Demand response		✓ Demand response	✓ Behaviour ✓ Multi-level perspective (MLP) to transitions ✓ Heterogeneous actors	✓ Multiple maximally different pathways ✓ Technology interaction patterns	✓Transparency	✓Other environmental impacts, e.g. human toxicity, particulate matter, agricultural land use
Niche/ key field of expertise	✓Bottom-up demand modelling ✓Heating, building refurbishment, end-use equipment	✓Hour-by-hour dispatch ✓Demand response ✓Non-electric demand	✓Transmission, distribution ✓ Non-electric demand, supply and grid ✓ Spatial disaggregation	✓Hour-by-hour dispatch ✓Transmission, distribution ✓Demand response ✓Links to Europe	✓Behaviour ✓Uncertainty ✓MLP perspective ✓Non-electric demand and supply	✓Expanding the range of plausible pathways ✓Technology interaction patterns ✓Uncertainty	✓ Detailed evaluation of costs ✓Transparency	✓ Life cycle emissions and other environmental impacts ✓ RTP Phase I pathways assessed

4. Multi-model analysis of the 'Central Co-ordination' pathway

4.1 Process

In order to compare the six RTP models and two appraisal techniques, all of them were run with harmonised assumptions, reflecting the "Central Co-ordination" pathway [16, 17]. As the narrative of this pathway is very detailed, a smaller number of key aspects were selected. More specifically, the models were tuned to match these harmonised assumptions as closely as possible:

i. Total power demand in the UK:

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

ii. Power generation mix in the UK:

- In 2020, 40% of the produced power comes from low-carbon sources, prioritising coal CCS, nuclear and renewable energy. At least 25% of the produced power comes from renewable sources, such as offshore and onshore wind, wave and tidal energy.
- In 2030, the power generation mix bridges the mixes of 2020 and 2050.
- In 2050, 75% of total produced power comes from large-scale low-carbon sources, such as nuclear, coal and gas CCS, offshore wind, wave and tidal energy. At least, 25% comes from low-carbon decentralised sources, such as onshore wind and biomass combined heat and power (CHP) plants.

iii. Greenhouse gas emissions:

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

iv. Costs:

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

Not all of the RTP models can implement all of these harmonised assumptions. For example, the models that do not consider costs cannot take the discount rate into account. In this case, the models by-passed this assumption. EconA and EEA are appraisal techniques and do not model the power system itself. These appraisals used the initial quantitative representation of the “Central Co-ordination” narrative [16, 17], which is in line with the harmonised assumptions described above.

The participating modelling teams were asked to run their models with this set of harmonised assumptions. The teams gathered insights into the feasibility and the prerequisites of the “Central Co-ordination” pathway, reported in [1], and into the further work needed and planned in the RTP consortium.

4.2 Results

By means of running the RTP models from Table 1 with harmonised assumptions, the converging and diverging insights from these different models were identified and are summarised in Table 2. By analysing the causes of divergence, the areas for further model development were suggested.

Table 2. The converging and diverging insight from the RTP models about the “Central Co-ordination” pathway (model version as of April 2013)

	Converging insights	Diverging insights
Electricity demand in TWh/year	✓ Electricity demand grows to 390-420 TWh/year in 2030 and then at a slower pace to 410-430 TWh/year in 2050 (FESA, HESA/UK+, HAPSO, D-EXPANSE, EconA) ➔*Although this was one of the harmonised assumptions, there is still some minor variation due to slightly different ways the assumptions were implemented in the models.* ✓ The residential share in the total electricity demand is about 35% in 2050 (Demand), but can vary from 10-50% (BLUE-MLP). ➔ *The Demand model analyses only one pathway for the “Central Co-ordination” narrative. Its result of the residential share is embraced by the range of estimates from BLUE.*	✓ BLUE-MLP simulations show that electricity demand will likely grow much more rapidly than the narrative suggests. According to BLUE-MLP, there is 0% chance for the electricity demand to be 410TWh/year in 2050. ➔*The demand assumptions of the “Central Co-ordination” narrative can be wishful thinking, when the behavioural aspects are taken into account.* ➔*BLUE currently does not model refurbishment and the other non-cost driven energy saving measures. This could be the reason why the model is overly pessimistic.* ✓ The estimates of the Demand model are lower (369 TWh/year in 2050) than those of the other models, while the assumptions of EEA are higher (450 TWh/year in 2050). ➔*The way the harmonised assumptions were implemented in the Demand model needs to be crosschecked. The EEA model assumed that the electricity demand of 410* TWh/year does not include electricity imports and the transmission and distribution losses.
Installed electricity generation capacity (GW)	✓ The total installed capacity is about 110-150GW in 2030 and 120-190GW in 2050 (FESA, HAPSO, D-EXPANSE, EconA) ➔*The point estimates of FESA, HAPSO and EconA are covered by the range of modelled pathways by D-EXPANSE.*	✓ HAPSO has a tendency of higher estimates of installed capacity due to the additional OCGT capacity. D-EXPANSE almost embraces the HAPSO values. When compared to FESA, the installed capacity by HAPSO is very similar if OCGT is excluded. ➔ *The difference mostly stems from different reliability assumptions in HAPSO and FESA.*

	Converging insights	Diverging insights
		FESA does not consider availability factors for all types of generation and thus tends to underestimate capacity needs for balancing. This difference between HAPSO and FESA also to some extent is caused by the different assumptions of demand response, curtailment of renewables, storage or emergency electricity cuts. HAPSO cost-optimises the system, while FESA might capture other pathways, which are not cost-optimal, but still feasible. ✓BLUE-MLP has a significantly lower installed capacity of 50GW in 2030 and a fairly high capacity in 2050. ➔*To some extent this is caused by emergency electricity demand cuts, that are analysed in BLUE-MLP, but are not covered by the other models. BLUE-MLP results in much higher estimates of electricity demand in 2050 and thus requires more installed capacity in 2050.*
Electricity supply mix (shares of TWh/year)	✓ The nuclear share in the electricity supply mix (in TWh/year) is high: 20-45% in 2030 and 2050 (FESA, HESA/UK+, HAPSO, BLUE-MLP, EconA, EEA). D-EXPANSE suggests the variation of 5-75% in 2030 and 0-50% in 2050 and thus embraces the variations. ✓ The renewables share is high: 20-35% in 2030 and 30-45% in 2050 (FESA, HESA/UK+, HAPSO, EconA, EEA). D-EXPANSE suggests 0-50% in 2030 and 0-70% in 2050. ✓ The coal and gas CCS share is high: 20-35% in 2030 and 15-20% in 2050 (FESA, HESA/UK+, HAPSO, EconA, EEA). D-EXPANSE suggests 0-60% in 2030 and 0-50% in 2050. ✓ The sum of unabated coal and gas shares are low: 2-7% in 2030 and 0-5% in 2050 (FESA, HESA/UK+, HAPSO, EconA, EEA). D-EXPANSE suggests 0-5% in 2030 and 0-10% in 2050. ✓ The share of electricity import is up to 10% in 2030 and 2050 (FESA, HESA/UK+, HAPSO, EconA, EEA). D-EXPANSE estimates 0-15%. ➔ *The shares in the energy mix by HESA/UK+, EconA and EEA are taken from the initial quantitative representation of the 'Central Co-ordination' narrative. Their insights, naturally, converge.*	✓BLUE-MLP suggests a high share of coal (55%) and a low share of renewable sources (8%) in 2030, compared to the other models. In 2050, it suggests a high share of renewable sources (70%), but a low share of nuclear (20%). D-EXPANSE embraces these values. ➔*To some extent, this is a modelling artefact because BLUE-MLP considers only four technologies and thus the differences in the shares become so pronounced. BLUE-MLP also captures the investment dynamics, when companies deviate from the purely cost-optimal decisions, and thus result in different supply mixes. These mixes are captured by D-EXPANSE, which also analyses near-optimal pathways.* ✓HAPSO models suggests a higher share of electricity import (up to ~20% in both 2030 and 2050) and nuclear (40-50%) than the other models. D-EXPANSE embraces these estimates. ➔*This difference stems from the cost-optimising nature of HAPSO as it glosses other, near-optimal possibilities. Most of the other models, except BLUE-MLP and D-EXPANSE, do not optimise costs. D-EXPANSE still embraces the HAPSO estimates.* ✓FESA, HESA, D-EXPANSE, EconA and EEA included the share of electricity produced in the small scale CHPs into the same mix with the centralised generation.

	Converging insights	Diverging insights
		➔*HAPSO and BLUE-MLP models are more biased towards centralised systems as they exclude small scale CHPs from the consideration.*
Capacity factors, balancing	✓FESA and HAPSO point out that a significant amount of centralised generation operate with low capacity factors in 2050, even with demand side participation. This requires either high curtailment of renewable electricity production or electricity export. ➔*Further analysis is needed to in order to crosscheck the economic feasibility of centralised generators. This is on-going work in EconA.*	✓Compared to the other models, HAPSO has a 2-3 times higher installed capacity of abated and unabated coal and gas power plants (80GW in 2030 and 95GW in 2050). D-EXPANSE also embraces such cases. This capacity, however, does not produce electricity and serves mostly as a reserve capacity. ➔*HAPSO and D-EXPANSE have higher system reliability requirements. But it still needs to be crosschecked to what extent these models overestimate the capacity of fossil fuels-based power plants as a reserve capacity. As FESA does not consider the availability factors for all types of generation, it is likely underestimating the balancing challenge.* ✓HAPSO has a much higher requirement of gas OCGT for balancing (40GW in 2030 and 58GW in2050), compared to FESA and the current "Central Co-ordination" narrative (5GW in 2050). ➔*To some extent this stems from different deployment levels of electricity storage, import and export. This is also an artefact of cost-optimisation, i.e. FESA captures an alternative, more costly pathway with less gas OCGT.*
Costs	✓ The total discounted cumulative investment needed into power plants and interconnectors is £100bn in 2010-2030 and £170bn in 2010-2050 (EconA). This estimate falls under the D-EXPANSE estimates of £50-100bn in 2010-2030, but is higher than £70-130bn for 2010-2050. ➔*This difference likely stems from the fact that EconA analyses a pathway that is not necessarily cost-optimal or near-optimal, while D-EXPANSE includes a constraint that the pathways need to be near cost-optimal.* ✓ The total discounted costs of electricity production, excluding carbon price, are about £30/MWh in 2030 and £12/MWh in 2020 (EconA). According to BLUE-MLP, the estimated electricity retail price (incl. taxes and carbon price) is 40-70£/MWh in 2030 and 5-50£/MWh in 2050. D-EXPANSE results are likely to be very similar (at the moment they are not yet evaluated).	✓ HESA/UK+ estimates the electricity generation costs to be 126£/MWh in 2030 and 130£/MWh in 2050. These estimates are higher than EconA and BLUE-MLP estimates, moreover they do not decrease in time. ➔*It is necessary to check to what extent the HAPSO results are due to higher investment, O&M and fuel costs or higher CO_2 price. Some of the difference may originate in the fact that the costs of HESA/UK+ are not in £(2010). The fact that the costs do not decrease in time is likely caused by non-discounting.*

	Converging insights	Diverging insights
	✓The investment into the distribution and transmission grid, gas OCGT and interconnectors has been estimated by HAPSO only. ➔*The costs are different because they were not discounted and may not be in £(2010).* ✓FESA and HAPSO raise concerns about the economic feasibility of large-scale power plants that work on low load. ➔*Further analysis is needed to crosscheck the economic feasibility of centralised power plants.*	
Emissions	✓The emission target, when considering the CO_2 emissions from fuels only, can be met by 2050 and are only slightly missed by 2030 (FESA, HESA/UK+, HAPSO, EconA). BLUE-MLP, however, estimates only 11% chance of meeting emission target of 80% by 2050.	✓When life-cycle emissions are considered, the target in CO_{2eq}/kWh is not met in both 2030 and 2050. ➔*This is because the emission target refers to operational, rather than life-cycle emissions.* ✓D-EXPANSE shows a range of alternative transition pathways that meet the emission target.

5. Gathered insights for the RTP models

5.1. Developing the RTP models further

Table 1 reveals the diversity of the RTP models: they differ in disciplinary perspectives (technology, economics, environmental research), methodological perspectives (technical simulation, cost optimisation and exploration of near-optimal pathways, probabilistic simulation, post hoc assessment) and system boundaries. Thus, the diverging insights from the different models in Table 2 do not necessarily originate from the weaknesses of the models. These diverging insights can also be the results of the different system boundaries, alternatives analysed, different methods and so on. Instead of aiming to align the results of the different models into the same numeric values, Table 2 rather attempts to map out the diversity of the modelling results and questions the origins of these differences.

Yet, on the basis of Table 2 minor mistakes can be eliminated and the early versions of the models can be improved. Several cases are already highlighted with respect to supply-demand balance modelling, reserve capacity assumptions, demand evolution and centralised generation bias. Based on Table 2, the RTP modelling teams are invited to further investigate the origins of the diverging results and reflect whether their models need to be revised.

In the April workshop, the ideas for further development of the RTP models were discussed and synthesised into common themes:

- Electricity supply technologies considered: the RTP models already have a fairly consistent list of electricity supply technologies that they consider. Yet, it should be questioned whether there are further alternatives that might be meaningful to consider, e.g. biomass CCS.
- Decentralised generation: Most of the current RTP models primarily consider the centralised generation alternatives. It remains unclear to what extent the RTP modelling results are thus biased towards the centralised generation and exclude the decentralised generation.
- Future work: The RTP modelling teams in the first workshop identified their priorities for further development of the models. These priorities could be formed into clusters for future work in RTP:
    - Economic considerations and insights from cost-optimisation (FESA, HESA/UK+, D-EXPANSE, EconA);
    - Uncertainty (HAPSO/UK+, BLUE-MLP, EconA, D-EXPANSE);
    - Behaviour, social aspects (HAPSO, BLUE-MLP, Demand);
    - Spatial disaggregation (Demand, FESA, EconA);
    - Technology learning (Demand, HESA/UK+, EEA);
    - Grid representation (FESA, EconA).

5.2. Mapping the potential bilateral model linkages

The diversity of the RTP models (Table 1) also offers opportunities for soft-linking the models or sharing the data in order to achieve new insights. Figure 1 maps the potential bilateral collaborations between the RTP models. These collaborations can take the form of:

- Data sharing: For example, the Demand model shares the heat and electricity demand estimates with FESA.
- Post-run evaluation of another model: For example, EconA could be used to evaluate the costs of the pathways, generated by FESA or HESA/UK+ .
- Additional insights: For example, the life-cycle emissions by EEA could be used by the other models.

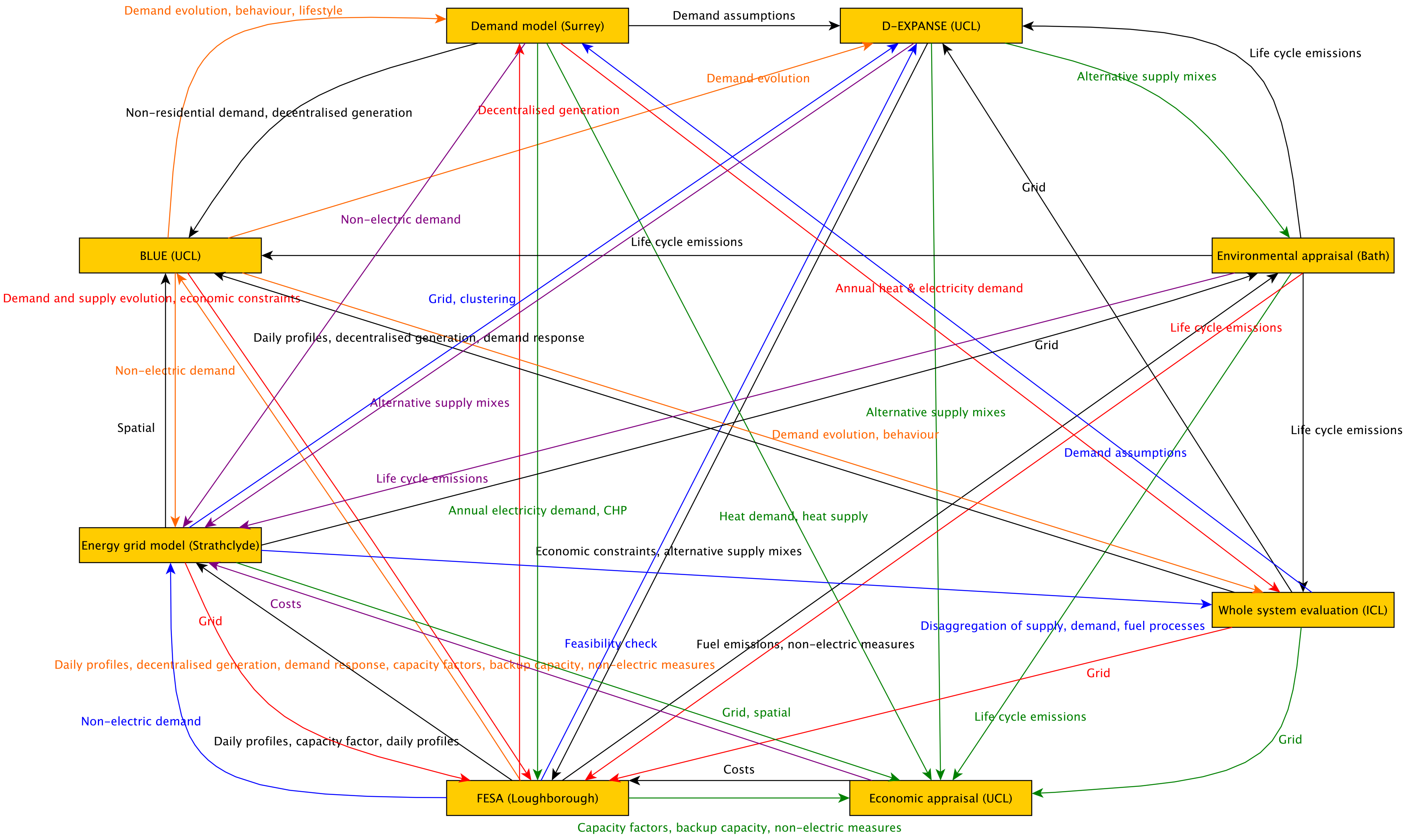

Figure 1. The map of the potential bilateral collaboration between the RTP models (Note: Colours of the arrows have no meaning)

6. Conclusions

This working paper reported an attempt to initiate and to facilitate interdisciplinary learning among six energy models and two appraisal techniques of the Realising Transition Pathways (RTP) project. This facilitation included two internal RTP workshops and a multi-model analysis of the 'Central Co-ordination" pathway. It led to two written outputs. This RTP working paper summarised insights for further development and collaboration of the RTP models. Trutnevyte et al. [1] described multi-model insights on the feasibility and prerequisites of the 'Central Co-ordination' narrative.

Since April 2013, this initiative has already led to concrete examples of the RTP models being developed further and collaborating. These examples are:

- BLUE-MLP model was updated in August 2013 based on comparing its results with the results of the other models (Table 2);
- D-EXPANSE model is being updated at the moment on the same grounds (Table 2);
- The complementary results from EconA and HAPSO models are being combined at the moment in order to improve the economic appraisal of the RTP transition pathways;
- D-EXPANSE model is being combined with the statistical methods used at the University of Strathclyde;
- Collaboration between the Demand, FESA and BLUE-MLP models is being discussed.

This list of examples proves that this initiative succeeded in encouraging and facilitating the interdisciplinary learning among the RTP models. Further examples may arise in the future too, as the project progresses.

7. References

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