Investment appraisal of cost-optimal and near-optimal pathways for the UK electricity sector transition to 2050

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Abstract

Deep decarbonisation of the electricity sector is central to achieving the United Kingdom's (UK) climate policy targets for 2050 and meeting its international commitments under the Paris Agreement. While the overall strategy for decarbonising the energy system has been well established in previous studies, there remain deep uncertainties around the total investment cost requirements for the power system. The future of the power system is of critical importance because low carbon electricity may create significant opportunities for emissions reduction in buildings and transport. A key policy application of quantitative analysis using models is to explore how much investment needs to be mobilised for the energy transition. However, past estimates of energy transition costs for the UK power sector have focused only on 2030 rather than 2050 and consider a relatively narrow range of uncertainties. This paper addresses this important research gap. The UK government's main whole system energy economy model is linked to a power system model that employs an advanced approach to uncertainty analysis, combining Monte Carlo simulation with Modelling-to-Generate Alternatives (MGA), producing 800 different scenario pathways. These pathways simultaneously consider uncertainties in policy, technology and costs. The results show that with *No Climate Policy*, installed generation capacities in 2050 are found in the range 60-75GW, while under an *80% Reduction in GHG Emissions*, between 100GW and 130GW of plant are required. Meeting climate targets for 2050 is also found to increase the investment requirements for new electricity generation. The interquartile range for cumulative investments in new generation under the *No Climate Policy* scenario ranges from £60bn to £75bn, while under an *80% Reduction in GHG Emissions*, investment requirements approximately double to £110bn - £140bn. The exercise demonstrates the importance of uncertainty analysis to policy evaluation, yielding insights for future research practice both in the UK and internationally.

Keywords

Highlights

- 800 future transition pathways for the UK power sector explored under uncertainty
- Analysis combines Monte Carlo simulation and Modelling-to-Generate-Alternatives (MGA)
- Many technologically diverse pathways are found to incur similar overall costs
- Meeting climate targets may require an additional 25GW – 70GW of power capacity
- Achieving climate targets may require additional investments of £35bn-£80bn

1.0 Introduction: Investment needs and the key uncertainties facing the UK electricity sector

The Paris Agreement commits signatories from 175 states to limiting anthropogenic global warming below 2°C above pre-industrial levels [1]. Achieving this objective will require large-scale decarbonisation of the global energy system through actions taken at the level of individual countries. Under Article 4, more developed countries are expected to take a leading role. Examples of deep decarbonisation analysis can be found for multiple countries, including China [2,3] , the United States [4], Germany [5], Denmark [6], Ireland [7] , Switzerland [8], Portugal [9] , and the United Kingdom [10,11]. The United Kingdom (UK) is one example of an advanced economy which is already committed to ambitious long-term decarbonisation targets. These targets are enshrined in law under the Climate Change Act 2008 [12], and are implemented as a series of carbon budgets subject to monitoring by an independent regulator [13].

Whole system analyses of long-term climate mitigation strategies for the UK that simultaneously evaluate options for buildings, industry, transport and energy supply have shown the critical role of decarbonising the UK electricity sector [14,15]. Most modelled UK low-carbon pathways that achieve climate targets for 2050 rely on the rapid decarbonisation of electricity generation before the 2030s in order to later electrify large fractions of building heating and road transport [16]. Model-based insights have led to the decarbonisation of the power sector and the electrification of heating and transport becoming key pillars of the UK government's greenhouse gas (GHG) emissions reduction strategy [17–19]. However, while the strategic direction of travel is clear, the level of investment costs required to mobilise the energy transition remains an important unresolved area for policymakers.

Previous analyses have evaluated the investment costs associated with a handful of potential electricity sector pathways out to the 2030s [20,21]. However, these pathways accounted for only a limited set of uncertainties and did not include an outlook to 2050 (Section 3.0). The willingness of investors to finance new low-carbon

generation remains a major uncertainty [22]. The 2008 financial crisis left many traditional financing sources, such as banks, in a weakened state and recent "Electricity Market Reform" measures have been designed to attract investment from a wider range of financial institutions [23]. However, empirical research suggests that institutional investors are currently deterred from placing funds into low-carbon infrastructures because of the perceived high risks caused by the Government's uncertain strategic intentions [24]. It remains to be seen whether the UK's current institutional and governance arrangements will be fit for purpose and deliver the required investment levels, or whether other alternatives may need to be pursued. Research has explored market-, state- and civic-led pathways for the electricity sector [25], but it remains far from clear what the most effective governance arrangements could be to drive the desired transition.

Another key uncertainty is the timing for the commercial availability and deployment of key low-carbon generation technologies and their future costs in the period to 2050 [22,26]. For example, new nuclear power has received significant policy support in the UK, but attracting investment for the first new plant, Hinkley Point C, has been an extremely challenging process [27]. The UK has historically been a strong proponent of nuclear power despite vociferous opposition from various political and civil society groups [28]. Nuclear power is not the only low-carbon power technology that potentially faces deep uncertainties and an uphill struggle. Fossil-fuelled plants fitted with Carbon Capture and Storage (CCS) have been identified as key to enabling an affordable transition towards UK climate targets [13,14,29]. Although pilot and demonstration projects are essential for the eventual commercialisation of CCS [30,31], in 2016 the UK Government cancelled its support for a CCS demonstration programme for the second time in 5 years [32]. This again increases uncertainties about the future costs and availability of CCS in the UK.

Other key uncertainties highlighted in both expert elicitations and model-based analyses include the influence of economic growth, population demographics [26], and long-term shifts in energy demand resulting from changes to behaviour and lifestyles [33]. The costs of fossil fuels, for which the UK is a net importer, are uncertain and could be highly significant for the future transition [15,26,34]. The future availability of bioenergy resources is another widely-acknowledged uncertainty [35–37]. Bioenergy may be central for decarbonising many UK economic sectors such as industry, heating and transport. It could also be particularly important in electricity generation, especially when used in conjunction with CCS technology to achieve negative emissions [15]; though this is considered by many to be a controversial strategy [38].

Finally, there are large uncertainties associated with the socio-political dimension to energy policy [22]. The UK Climate Change Act enjoyed broad cross-party political support when it was implemented in 2008, but the political appetite to strive for extremely challenging climate targets has yet to be seriously tested [39]. The new administration which came into power in July 2016 has taken the step of abolishing the UK Department of Energy and Climate Change (DECC), potentially signalling that environmental issues are falling down the policy priority scale. It remains to be seen whether an electorate that can vote out unpopular governments will be willing to bear the increased and sustained costs of any future energy transition [40].

2.0   Study objectives

Deep decarbonisation of the electricity system is central to achieving the UK's climate targets for 2050. While the critical role of the power sector in enabling emissions reductions has become broadly accepted in the energy policy community, critical details for implementing this strategy such as understanding the total costs involved remain underexplored. The costs of meeting the decarbonisation challenge are subject to multiple uncertainties that make investment appraisals difficult. This study aims to review past investment analyses (Section 3.0), evaluate the current state-of-the-art in energy modelling and uncertainty analysis (Section 4.0), and conduct an original UK electricity sector investment appraisal for the period 2010-2050 under a broad spectrum of policy, technology and cost uncertainties (Sections 5.0 and 6.0). Finally, the implications for UK and international energy policy and research into energy systems decarbonisation using quantitative models is explored (Sections 7.0 and 8.0).

3.0   Review of existing estimates of the UK electricity sector investment requirements

Before presenting our own analysis in Sections 5.0 and 6.0, we first present a review of past estimates of the investment costs required to transform the UK electricity sector. In line with earlier overviews by Blyth et al. [41] and Trutnevyte et al. [20], a range of first-order estimates for investment costs from a variety of sources is shown in Figure 1. To enable cross-comparison across different time horizons, investment costs are expressed in terms of annual capital expenditure.

Figure 1 – Existing estimates of the UK electricity sector investment requirements from various industry, academic, and government sources [20,23,42–50]
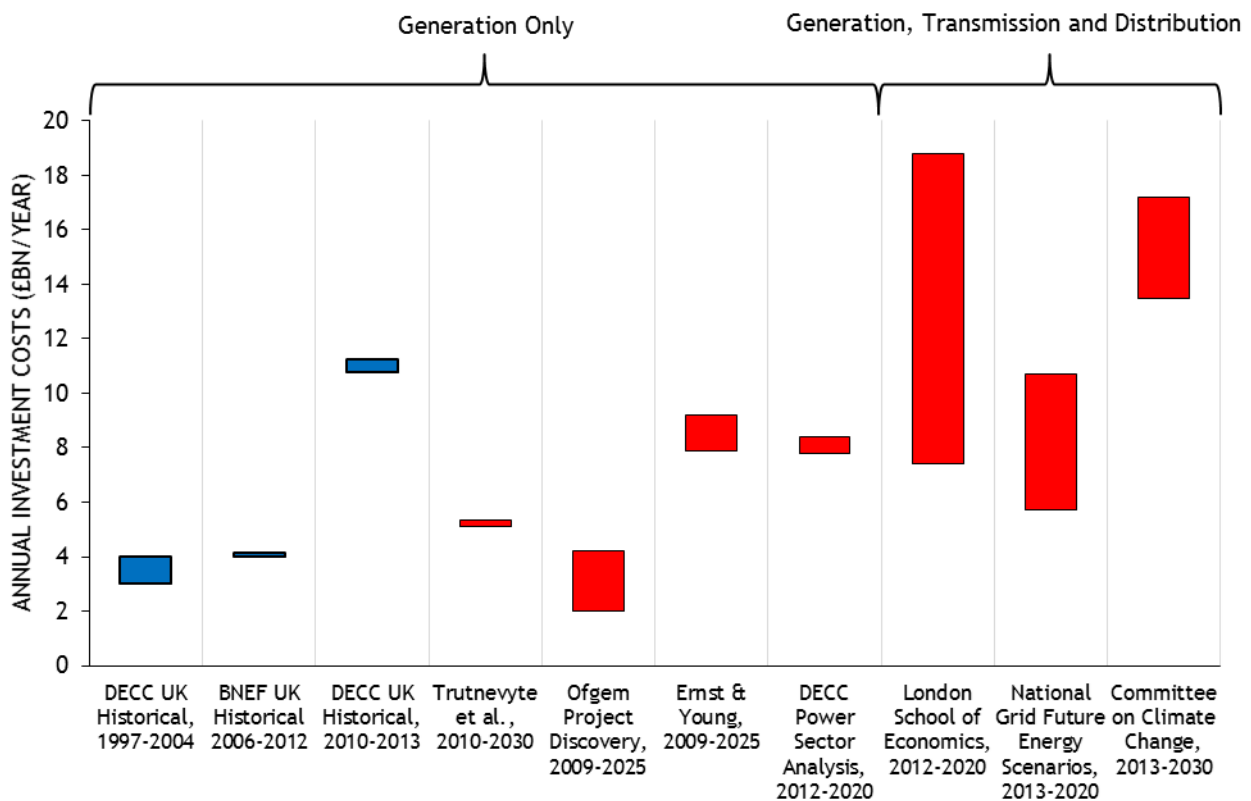
Historically, after the UK energy market liberalisation of the 1990s, investment into the power sector averaged around £3-4bn [20], with this rising to an average of £11bn from 2010 to 2013 [50]. Figure 1 shows that there is significant variation in the estimates of future investment requirements. This variation not only arises from the different time horizons considered, but also from differing assumptions with respect to technology-specific investment costs, electricity demand, and the future electricity generation mix. Despite the relatively large number of published estimates (Figure 1), understanding the scale of the investment challenge remains difficult. The spread of estimates is wide and it is not immediately clear where the differences come from. A cross-comparison of existing estimates is a useful starting point for discussion but does not begin to unpick the complex web of uncertainties affecting the future investment requirements. To assess these uncertainties, some of the core assumptions are compared in Table 1.

Table 1 – Uncertainties explored in existing studies of the future UK electricity sector investment requirements

Study	Uncertainties Explored					
	Restricted commercial availability of specific technologies	Technology costs and project finance	Fuel costs	Energy demand growth	Climate target stringency / level of policy support	Time horizon
Trutnevyte et al. [20]	✓	✓	✓	✓	✗	2050
Ofgem Project Discovery [43,44]	✓	✓	✓	✓	✓	2025
DECC Projections [46] interpreted by Blyth et al. [41]	✗	✗	✓	✓	✓	2030
London School of Economics [47]	✓	✗	✗	✗	✓	2030
National Grid Future Energy Scenarios [21]	✓	✗	✗	✓	✓	2035
Ernst and Young [48]	✓	✗	✗	✓	✗	2025
Committee on Climate Change [49] interpreted by Blyth et al. [41] using costs by Pöyry [51]	✓	✓	✓	✗	✓	2030

From a methodological perspective, the studies reported in Table 1 used scenarios accompanied by a narrative, following a "storyline and simulation" approach [52] for exploring future uncertainties. Past UK Department of Energy and Climate Change (DECC) projections [46] incorporated Monte Carlo sampling of some key inputs. Trutnevyte et al. [20] and the Ofgem Project Discovery studies [43,44] included a simple sensitivity analysis. Nearly all studies incorporated pathways with restricted availability of different low-carbon generation options, such as nuclear and CCS. Only a single study explored electricity sector pathways under conditions where bioenergy was restricted [21], although the UK Committee for Climate Change (CCC) has explored UK bioenergy availability in depth in other work [53].

Many pathways relied on static technology-specific costs for low-carbon generation technologies and did not explore uncertainties surrounding their future variation through time. Just over half of the reviewed studies explored variation in fuel costs and underlying growth in energy service demands, although only a few studies considered these elements simultaneously. Finally, most studies explored the impact of varying levels of policy support, with some explicitly considering cases involving the failure of UK climate policy (London School of Economics [47], and National Grid [21]). These studies showed wider ranges when compared with those that evaluated

costs under pathways designed to achieve climate targets (such as Trutnevyte et al. [20]).

This review of the existing investment estimates shows that no past work has simultaneously considered the key uncertainty dimensions identified. These studies have investment estimates that diverge from both the historical experience and from each other through very different sensitivities and end points. This gives the intended policy audience a restricted view on the landscape of possible future investment requirements. Depending on which study is reviewed, the intended audience might conclude that investment requirements either need to be massively increased when compared with the past, or not to increase at all. There is therefore a need for a more systematic approach to be taken towards UK electricity sector investment appraisal in the period to 2050.

4.0   The state of the art in energy systems models and uncertainty analysis

Energy economy models have seen long and extensive use for exploring technology pathways and the associated costs of achieving climate targets in the UK [54,55] and internationally [56]. Bottom-up energy system optimisation models (ESOMs), such as TIMES [57], OSEMoSYS [58], or MESSAGE [59], are among the most popular models used for national-scale energy policy analysis and decarbonisation pathway planning. The main strength of such models is their ability to explore trade-offs between different technologies and to simultaneously evaluate pathways that consider all energy using sectors of the economy from a whole systems perspective. Typically, these models are employed in a deterministic fashion, producing a single pathway of the future evolution of the energy system for each set of input assumptions. This single pathway relies on a linear programing approach that optimises the total costs of the whole modelled system. Such an approach delivers solutions that are assumed to arise from the action of a benevolent social planning agent maximising the total welfare in the system [60].

The global optimum solution is sometimes found at a very sharp peak or a deep trough in the multidimensional problem space and can be fragile when subjected to even small variations in input conditions [61]. It is sometimes argued that in the real world, under conditions of deep uncertainty, truly optimal solutions often do not exist [62]. A recent retrospective review of the UK electricity sector transition between 1990 and 2014 also found that a cost optimisation approach did not approximate real-world developments [63]. Estimates of the total system costs deviated by 9-23% and actual plant deployments were qualitatively very different between the modelled cost-optimal pathway and the real-world transition. These shortcomings point to the need for an expanded consideration of uncertainty in energy systems models [64].

Our approach, as demonstrated in this paper, is to combine the strengths of a whole system cost optimisation model with an advanced model for exploring patterns in uncertain futures. This approach analyses both strictly cost-optimised pathways as well as pathways that are "near-optimal". We employ a scenario-based approach to explore policy uncertainties that lead to changes in energy demand and GHG emissions [65]. To explore parameter uncertainty, we employ Monte Carlo simulation, where the input parameters are randomly sampled from user defined distributions of input variables [66]. Finally, to explore structural uncertainty we use

the Modelling to Generate Alternatives (MGA) technique. MGA explores the space around a global optimum by allowing deviations from cost optimality, helping to address structural uncertainties that arise when the real-world transition deviates from the cost drivers [67–70].

This novel combined approach retains the strengths of a whole system energy economy model while offering new insights into the deep uncertainties surrounding the future evolution of the UK power sector, the decarbonisation of which is a key element in the energy and industrial strategy for the country [17–19]. While the UK context remains the focus of the paper, the insights are both novel and relevant for researchers and policymakers in other countries seeking to decarbonise their economies under the Paris Agreement.

5.0   Method

5.1   Model background and key features

In order to systematically explore a range of UK electricity sector transition pathways between 2010 and 2050, and appraise the associated investment costs in line with the study objectives outlined in Section 2.0, we employ a pair of energy system models, UKTM and D-EXPANSE. In this section, we first describe the background and key features of each of these models in turn, before illustrating their combined application.

5.1.1   UKTM

The UK TIMES Model (UKTM) [11], is a technology-rich partial equilibrium energy system optimisation model with perfect foresight, based on the International Energy Agency's Energy Technology Systems Analysis Programme (IEA-ETSAP) model generator [71,72]. UKTM was developed at the UCL Energy Institute as the successor to the UK-MARKAL model [73], which was used to underpin key decisions on UK energy policy from 2003-2013 [54]. The MARKAL and TIMES models have been used in the UK for much of the last decade to provide a whole systems perspective on decarbonisation pathways across the energy supply, industry, buildings, industry and transport sectors. As well as being used extensively for academic research [11,14,74–79], the models have played an important role in providing the evidence base for key energy strategy publications by the UK's Committee on Climate Change (CCC) and the UK Department of Energy and Climate Change (DECC) [13,18,19,80,81] as well as supporting UK efforts under the United Nations Deep Decarbonization Pathways Project [82]. UKTM use continues in government under the recently formed UK Department for Business, Energy and Industrial Strategy (BEIS) following DECC's closure. Full documentation for UKTM can be found online [83].

According to the taxonomy of energy economic models by Hourcade et al. [84], UKTM is a bottom-up model that majors on technological detail rather than macro-economic completeness. UKTM employs linear programming to make technology and fuel choices under greenhouse gas (GHG) emission and resource constraints. The model also includes other constraints, such as limits on technology build rates, and demand and supply matching in different diurnal and seasonal time periods to impart

a degree of operational realism. A strength of UKTM for exploring energy transitions is that it captures the whole energy system and can account for cross-sector interactions, such as the allocation of scarce biomass resources between electricity generation, industry, transport, and heating [76]. In this study, UKTM is used to explore the energy economy wide picture and generate logically consistent whole system policy scenarios that provide boundary conditions for D-EXPANSE (discussed in more detail below in Section 5.2). These include pathway trajectories for future electricity demand and GHG emissions levels that are consistent with the UK energy system transforming to achieve different climate policy targets.

5.1.2   D-EXPANSE

Like UKTM, D-EXPANSE (Dynamic version of EXploration of PAtterns in Near-optimal energy ScEnarios) is a technology-rich bottom-up optimisation model with perfect foresight. D-EXPANSE builds on past work using the EXPANSE methodology, described in [70]. As the model involves a set of highly computationally intensive techniques, D-EXPANSE focuses on representing the electricity sector only, rather than the whole energy system. D-EXPANSE can be distinguished from other optimisation tools through two key features that are not simultaneously combined in any other UK energy system models:

i.   D-EXPANSE employs Monte Carlo simulation to take into account parametric uncertainty, e.g. exploring various assumptions for future technology costs, technology performance, or other key inputs.

ii.   D-EXPANSE not only assesses cost-optimal pathways, but also uses a Modelling-to-Generate Alternatives approach [67–70] to explore the pathways that lie in the near-optimal region around the mathematically least-cost solution. As the diversity of such near-optimal solutions is vast, an algorithm to select a small number of maximally-different pathways is then used [63,70]. Such an approach allows D-EXPANSE to consider some structural uncertainties due to energy transition deviations from a pure cost rationale. In this study, a deviation of up to 15% in total system costs from the cost-optimal pathway is assumed; this is consistent with the past evidence [63].

D-EXPANSE significantly expands the consideration of uncertainty in energy system modelling due to the combination of Monte Carlo and Modelling-to-Generate Alternatives techniques. The model simultaneously generates and analyses a large ensemble of energy pathways (in this study, we explore 400 pathways for each D-EXPANSE run: this is made up of 20 Monte Carlo runs with 20 cost-optimal and near-optimal pathways for each). This allows for a systematic appraisal of investment costs associated with these multiple pathways. Full documentation for EXPANSE is provided in [63]. The model has also been tested in a multi-model comparison with other UK energy models [85].

5.2   Combined UKTM and D-EXPANSE analysis approach

Future energy system transitions are likely to involve a broad range of technologies and involve complex interactions between vectors such as electricity, heating, and transport. Analysis must therefore go beyond considering a single sector or a small range of technologies [86–88]. While the focus of the analysis in this paper, as outlined in the study objectives (Section 2.0), is resolving the myriad uncertainties facing future power sector investment, there is an obvious requirement to carry out this work within the context of a whole-system analysis of energy system decarbonisation. To achieve this, we combine for the first time the whole energy system model UKTM with the advanced exploratory pathway generator model D-EXPANSE. The relationship between the two models is illustrated below in Figure 2.

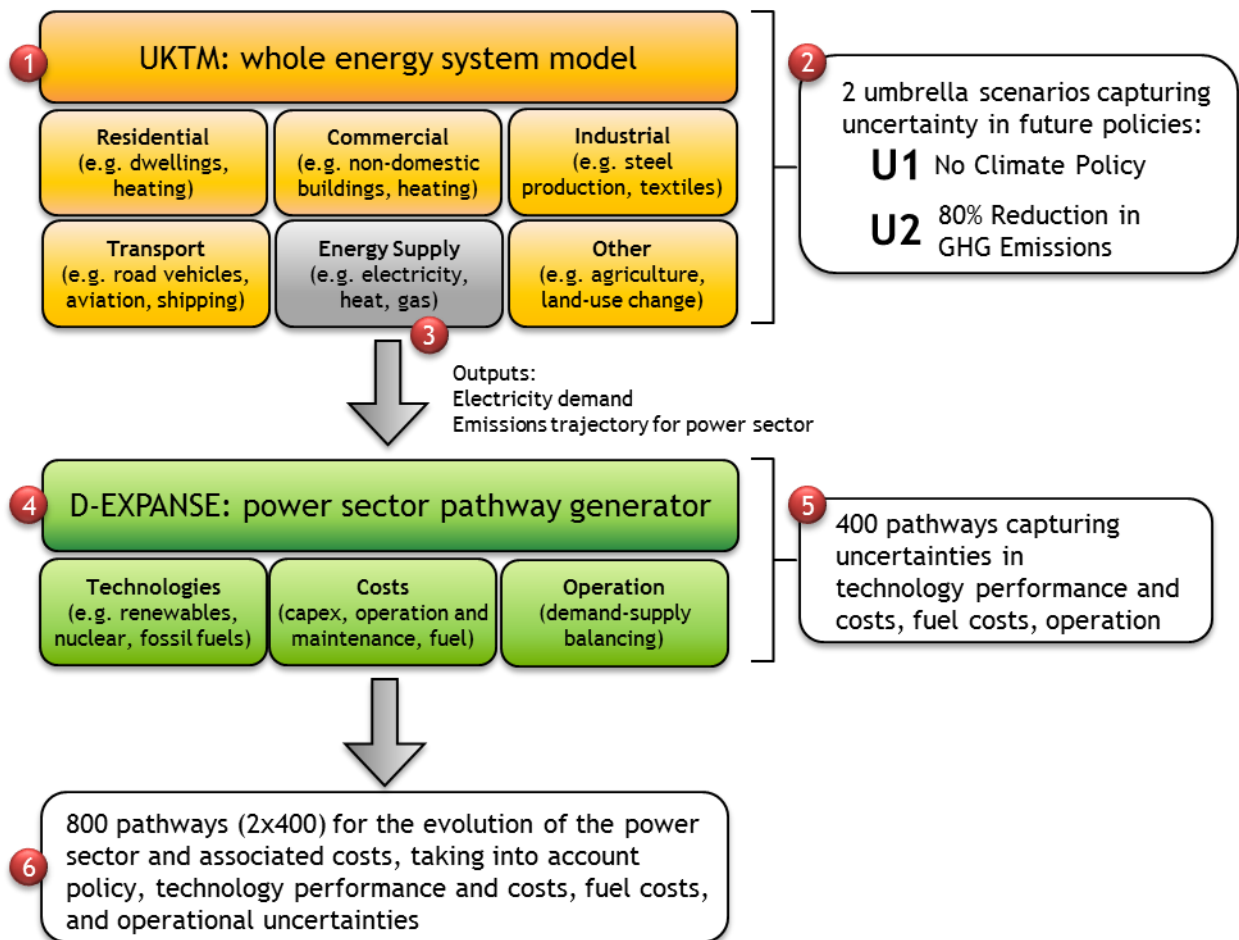Figure 2 – Analysis approach combining UKTM with D-EXPANSE

Figure 2 can be understood as a step-by-step process by following labels (1-6):

1) UKTM carries out a cost optimal evaluation of future changes to energy demand, GHG emissions, and technological diffusion in multiple sectors of the energy economy, including buildings, industry, transport, and energy supply.

2) UKTM is used to determine the energy economy-wide picture for future energy transitions over the period 2010-2050. Climate policy is a major

driver of key system attributes such as technological change, total energy demand, and what fraction of key end-use sectors such as heating and transport become electrified. In this analysis we run UKTM twice to consider two different transitions. These represent two possible extremes for future national climate policy. We investigate:

- A *No Climate Policy* case (**U1**) where the energy system transition is guided by demand growth, technology availability and costs, being totally unconstrained by any policy requirement to reduce GHG emissions.

- An *80% Reduction in GHG Emissions* case (**U2**), where transitions must simultaneously meet growth in demand but also achieve UK national climate targets for 2050. This leads to strong increases in electricity demand due to heat and transport electrification as well as a technological shift towards low-carbon sources of electricity.

3) By taking into account the changes to energy demand and new technologies being deployed in other sectors in order to achieve the GHG targets specified by the policy conditions under (2), UKTM estimates the electricity demand and the emissions trajectory for the power sector under cost-optimal conditions. Electricity demand and power sector emissions over the period 2010-2050 are passed as constraints to D-EXPANSE.

4) D-EXPANSE is then used to explore a broad range of cost-optimal and near-optimal electricity generation pathways for the power sector that satisfy the electricity demand supplied by UKTM.

5) For each set of demand assumptions from UKTM, D-EXPANSE explores 400 separate pathways for the power sector, taking into account uncertainties in technology performance, technology costs, technology lifetimes, and plant operation (how much demand is met by each technology). No previous study simultaneous combines these elements.

6) The final set of results comprises 800 separate pathways for the evolution of the power sector.

5.3   Modelling assumptions

Both UKTM and D-EXPANSE consider energy transitions through time from 2010-2050 in 5-year intervals. Key model assumptions that affect fundamental considerations such as energy demand and GHG emissions are aligned with standard UK government assumptions used in decarbonisation pathway planning. These include an annual average GDP (gross domestic product) growth of 2.4% [89], and annual average population growth of 0.5% [90], which drives end-use demands in the UKTM model for energy services (heating, appliances, lighting, mobility, etc.). Industrial demand drivers are calibrated against outputs from the UK Department of Energy and Climate Change (DECC) as described in previous work using UKTM by Fais et al. [11].

The actual final demands for energy commodities such as electricity, heat and gas are computed endogenously by UKTM under the two umbrella scenarios **U1** and **U1**, described above in Section 5.2, and are affected by considerations such as technological change and energy efficiency. This enables the model to use technological improvements to offset growth in demand if these choices are affordable and lie on the cost optimal pathway. Key results from UKTM are discussed later in Section 6.0.

In D-EXPANSE, carbon pricing under the *80% Reduction in GHG Emissions* scenario is based on guidelines for carbon valuation by DECC [91], while there is no carbon price signal applied in the *No Climate Policy* scenario. Fossil fuel prices are based on UK government projections [92], while the future costs and performance for energy generation technologies and their economic lifetimes are based on a series of reports commissioned by the UK government from major engineering consultancies [93–95]. The analysis explicitly takes into account future changes to costs and performance for different power sector technologies, such as reflecting the falling costs for renewable energy generation. Monte Carlo simulation is used in D-EXPANSE to explore how variation in these key uncertainties results in different power sector pathways.

A summary of key input parameters is given below in Table 2. Documentation for technology representation in IEA-ETSAP models can be found in work by Loulou et al. [71,72]. Detailed assumptions for the settings used in D-EXPANSE, including technological characterisation, are provided as Supplementary Material to the online version of this paper.

Table 2 – Key model input parameters for UKTM and D-EXPANSE

Parameter	Source	Implementation
Energy service demands	Based on UK Department of Energy and Climate Change (DECC) [96], Office for National Statistics [90], Office for Budget Responsibility [89]	Time series, 2010-2050, in 5-year intervals; Central drivers used for major end-use sectors (residential, commercial, industrial, transport) in order to align with standard UK government assumptions, including GDP growth of 2.4% and population growth of 0.5% to 2050.
Base year power generation technology portfolio and existing plant decommissioning profile	Based on UK Department of Energy and Climate Change (DECC) [97]	UKTM and D-EXPANSE both calibrated to base year 2010.
Fossil fuel prices and carbon pricing	Based UK Department of Energy and Climate Change (DECC) [91] and [92]	Time series, 2010-2050, in 5-year intervals; Transposition to UKTM uses Central Projections; Implementation in D-EXPANSE uses High, Central, Low ranges as basis for distributions.
Power generation capital costs, operation and maintenance costs, and economic lifetimes	Based on consultant reports for the UK Department of Energy and Climate Change (DECC) by Parsons Brinckerhoff [93,94] and Arup [95]	Time series 2010-2050, in 5-year intervals; Implementation in D-EXPANSE uses High, Central, Low ranges as basis for distributions; So-called "First of a Kind (FOAK)" costs applied for fossil thermal CCS and nuclear costs to 2024, with "Nth of a Kind (NOAK)" costs, intended to reflect more mature technology developments applied thereafter; Real costs for key renewable energy resources such as offshore wind and solar photovoltaics assumed to fall to 2030

		and plateau thereafter in line with UK government assumptions.
Power sector capacity margin	Historically, the UK's Central Electricity Generating Board would have based system planning requirements on a capacity margin of 20% during the period of public ownership of the electricity system between 1957-1990 [98].	
Power sector discount rate	UK Treasury [99]	UK government guidelines for policy assessment are to use a social discount rate of 3.5% to 2040 and 3% thereafter.
Demand and plant operation assumptions	As described in the UKTM [83] and D-EXPANSE documentations [63]	UKTM features 16 different time-slices for supply-demand balancing, and distinguishes between four diurnal time periods (night, day, evening peak, late evening) and four seasonal time periods (winter, spring, summer, autumn); D-EXPANSE model supply-demand constraints for peak load, shoulder load, and base load only.

6.0   Results

6.1   System level energy and emissions trajectories

Figure 3 shows the energy and emissions trajectories for the two umbrella scenarios used in this paper, **U1** and **U2**, and how they compare against 11 key low carbon scenarios from the UK literature on decarbonisation pathway analysis. These include 3 scenarios from the UK Energy Research Centre (UKERC) [100,101], 3 scenarios for the Committee on Climate Change (CCC) [102], 2 scenarios for the Department of Energy and Climate Change (DECC) [103], and 3 scenarios from the UK's Deep Decarbonization Pathways Project (DDPP) [82]. All scenarios (with the exception of **U1**, *No Climate Policy*) were carried out in the context of exploring UK pathways to achieving an 80% reduction in GHG emissions by 2050, compared to 1990 levels. Overall, Figure 3 shows that the **U1** and **U2** umbrella scenarios used in this study are fairly typical in energy consumption terms when compared to studies found in the literature, while the **U2** scenario also mirrors the steep decline in emissions found in past work.

Differences between the decarbonisation trajectories in the scenarios arise mainly from three sources: different treatment of non-CO_2 GHGs and international aviation and shipping, different base year conditions, and variation in the underlying demand, cost and performance data. The DDPP and **U1/U2** scenarios both use the UKTM model which considers all GHG emissions, while the DECC, CCC and UKERC scenarios use the older UK-MARKAL model, which considered CO_2 emissions only. A number of the scenarios using UK-MARKAL (i.e. some of the DECC, CCC, and UKERC scenarios in Figure 3) aimed for deeper cuts to CO_2 emissions (e.g. a 90% reduction target) to allow headroom for other non-CO_2 GHGs, and to make allowances for emissions from the UK's share of international aviation and shipping. The scenarios using UKTM (**U1**, **U2**, and the DDPP scenarios) on the other hand consider all GHGs as well as international aviation and shipping endogenously. Other differences between results in Figure 3 occur from UK-MARKAL being calibrated to operate from 2000-2050, while UKTM is set to cover the period 2010-2050, and because models are frequently updated over time to reflect the latest demand, cost and technology performance

data, as well as the latest climate science on issues such as land use change. These differences in the underlying data cause further variation between results.

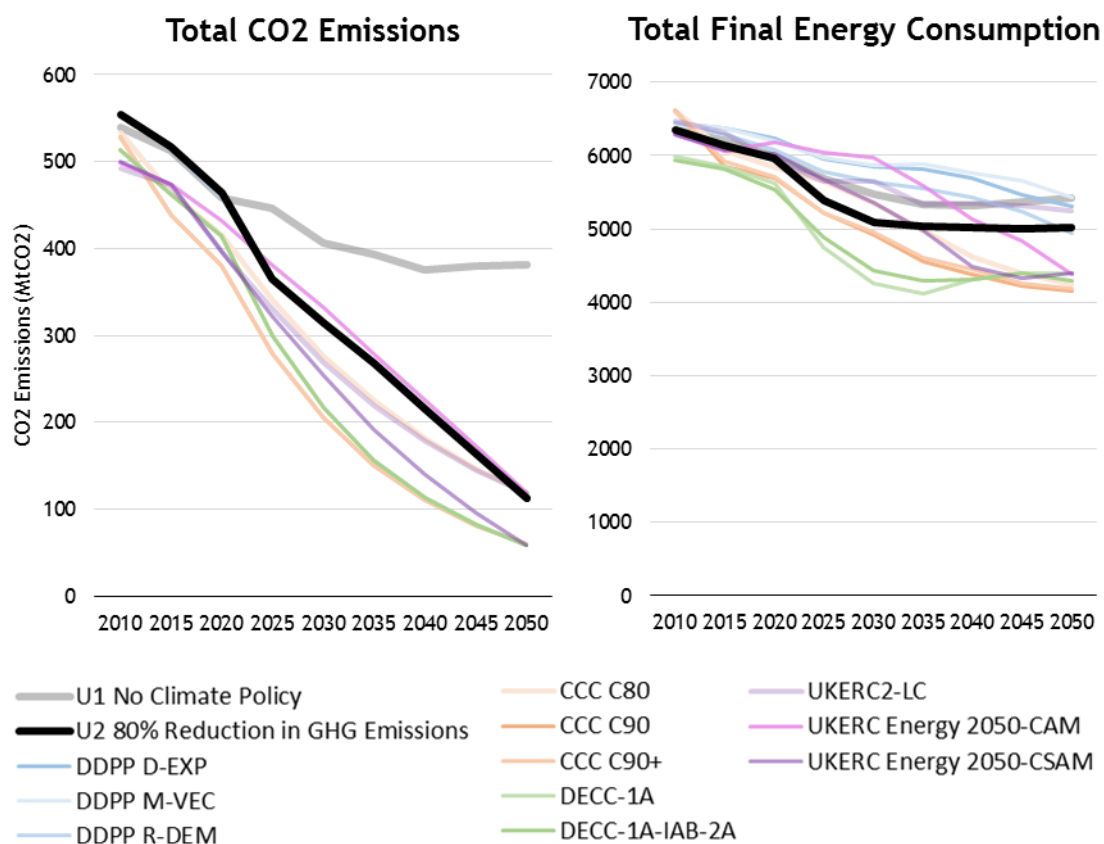Figure 3 – Comparison of total energy and emissions trajectories

Figure 4 further disaggregates final energy consumption into key end-use sectors. As expected, the **U1** and **U2** scenarios show very similar trends to the DDPP model runs because they both use the UKTM model and the UK government's latest demand, cost, and technology data. They show higher residential energy consumption than many of the past studies using UK-MARKAL, but also show much lower industrial energy consumption. This possibly reflects the more detailed characterisation of the industrial sector and its technology options found in UKTM as compared to UK-MARKAL, as well as the government's latest view on future industrial sector structure [11]. Future energy use in the commercial and transport sectors for **U1** and **U2** are within the ranges shown in past studies and are found to be most closely aligned with the DDPP and UKERC scenarios.

Figure 4 – Comparison of final energy consumption by end-use sector
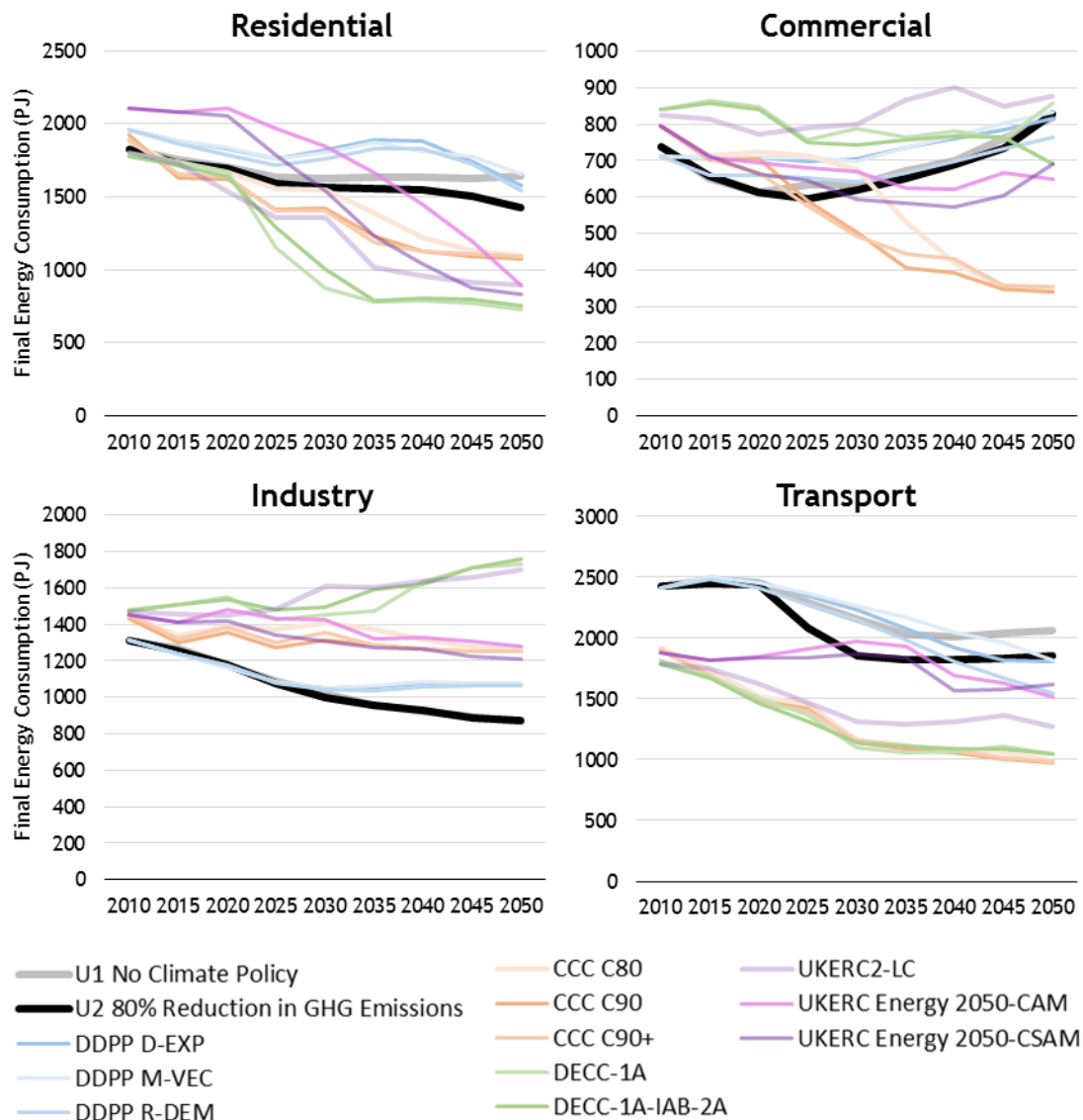

6.2   Energy consumption and GHG emissions

Figure 5 illustrates outputs from UKTM for final energy consumption (in petajoules, PJ) and GHG emissions (in megatonnes of CO_2 equivalent, $MtCO_{2eq}$) across all modelled sectors and energy vectors. Three sets of data are visualised so that starting condition for the model in the 2010 base year can be compared against the final 2050 conditions from the two scenario pathways *No Climate Policy*, and *80% Reduction in GHG Emissions*. Figure 5 shows that both 2050 scenarios see absolute reductions in energy consumption when compared with the starting year of 2010 as more efficient technologies are deployed in spite of population growth and increased industrial and service sector demand.

In terms of GHG emissions, Figure 5 shows that these were 659 $MtCO_{2eq}$ in the 2010 starting year. In the *No Climate Policy* scenario, some decarbonisation does occur in the period to 2050 as the relative costs of alternatives to fossil fuel technologies change across the time horizon. For example, low carbon energy supply costs fall and

energy efficiency technologies become more widespread. These effects cause the *No Climate Policy* scenario to reduce GHG emissions to 474 MtCO$_{2eq}$ by 2050.

In the *80% Reduction in GHG Emissions* scenario, the uptake of low carbon technologies is significantly accelerated due to the binding emissions constraint used in the model i.e. the model must optimise technology selection to achieve the UK's 2050 target. Under these conditions, not only is there rapid uptake of energy efficiency options but negative emissions sequestration technologies such as bioenergy with CCS become economically attractive. Net emissions in 2050 are 228 MtCO$_{2eq}$, with significant emission reductions in buildings, industry and transport. This chart also shows that the power sector must become completely decarbonised in order for the energy system to achieve national targets.

Figure 5 – Total final energy consumption and emissions by sector
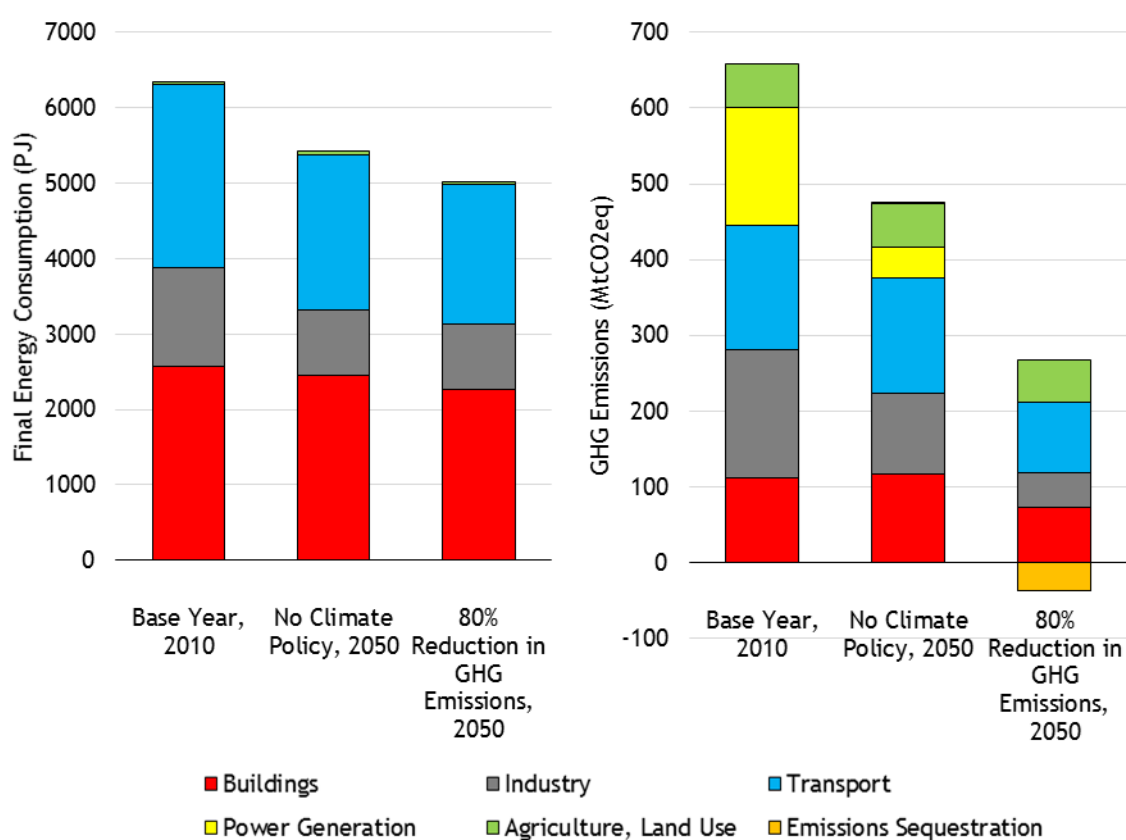
6.3 Electricity consumption and electrification of end-use sectors

Figure 6 illustrates key trends in electricity consumption that occur in the umbrella scenarios, focusing in particular on heating and transport. Total modelled consumption in 2010 is 1218 PJ (338 TWh). Under the *No Climate Policy* scenario, electricity consumption falls in the period to 2050 by 30% to 852 PJ (237 TWh), due to increased efficiency and shifts in industrial energy use. Under the *80% Reduction in GHG Emissions* scenario, electricity consumption in 2050 remains at similar overall levels to 2010, standing at 1252 PJ (348 TWh). The higher overall electricity use for the *80% Reduction in GHG Emissions* scenario arises from an increased use of decarbonised electricity for heating and transport purposes as well as for industry, where there is a shift away from fossil fuel processes to more manufactured fuels such

as hydrogen. The electrification of heating and transport is particularly pronounced in the *80% Reduction in GHG Emissions* case, where it more than doubles from 196 PJ (54 TWh) in 2010 to 470 PJ (131 TWh) in 2050.

Figure 6 – Electricity consumption by end-use
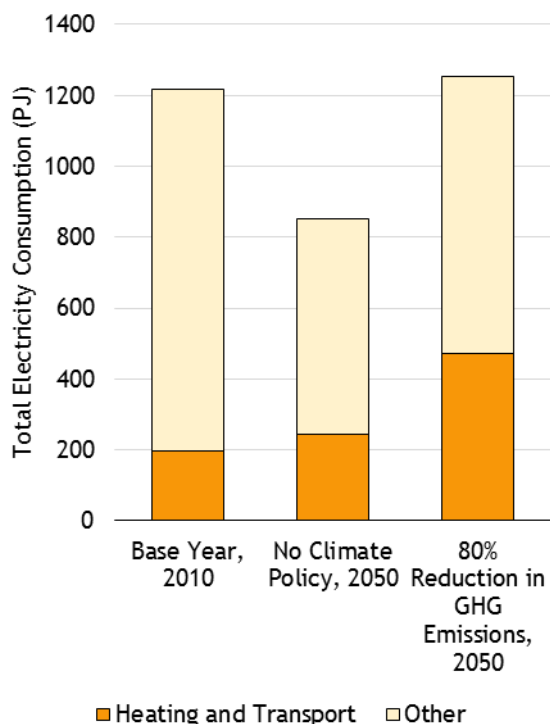
6.4 Power sector technology pathways

As described in Section 5.2, each of the two umbrella scenarios (**U1, U2)** are implemented in D-EXPANSE with aforementioned inputs from UKTM. D-EXPANSE then generates an ensemble of pathways by combining Monte Carlo sampling and the MGA approach. For each umbrella scenario, 20 Monte Carlo runs are carried out. For every Monte Carlo run, one optimal pathway and 19 near-optimal pathways are generated. This gives an ensemble of 400 individual pathways for each of the two umbrella scenarios (800 in total). In each of the 800 pathways, the deployment of different technologies can vary significantly. In this section we illustrate the variation in deployment across all 800 pathways for different power generation technologies, including electricity from fossil fuels (with and without CCS), nuclear power, and renewable energy.
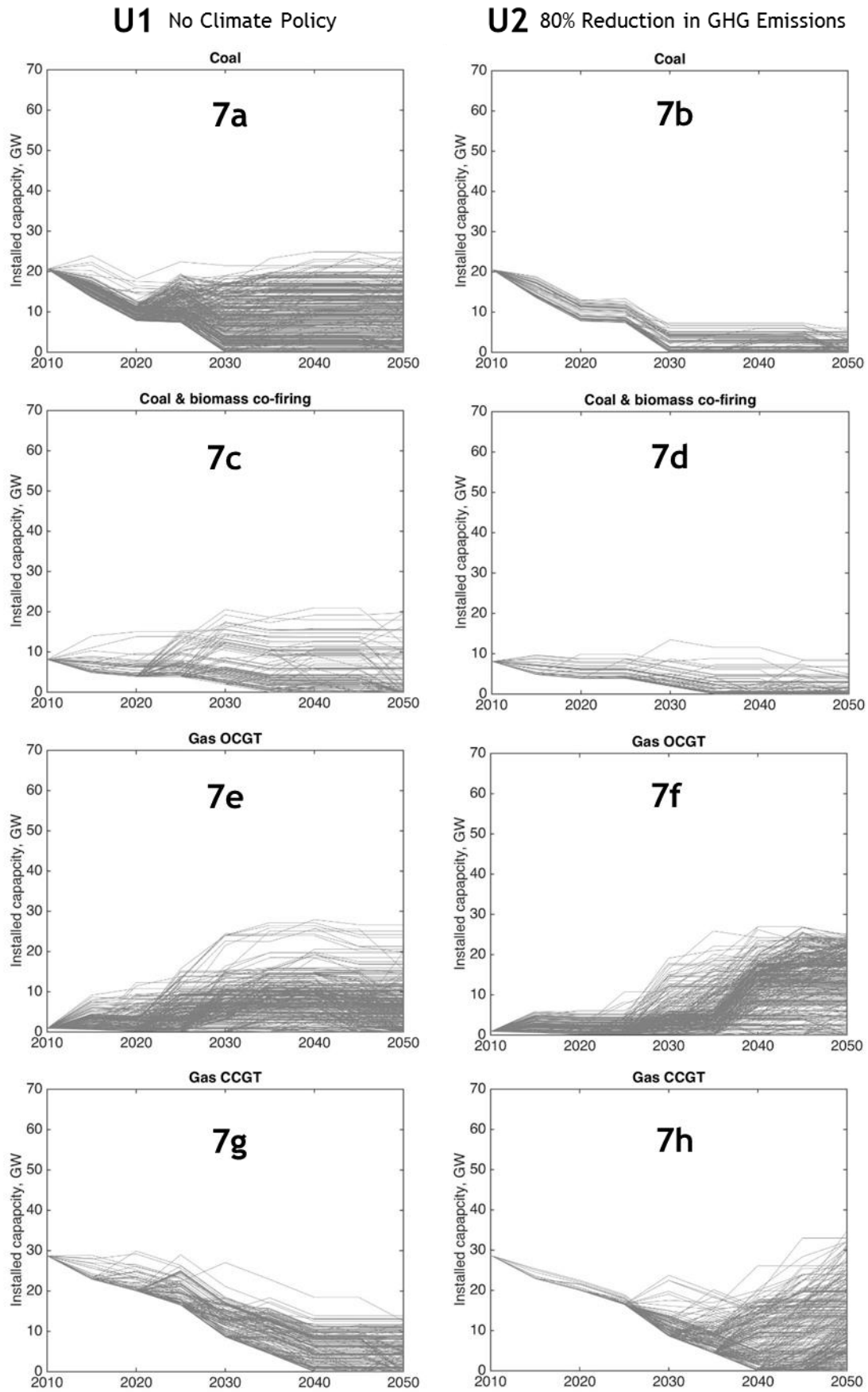
6.4.1 Fossil fuel generation

Figure 7 illustrates variation in fossil fired power plant deployment in umbrella scenarios **U1** (*No Climate Policy*) and **U2** (*80% Reduction in GHG Emissions*). Under conditions without emissions constraints (Figure 7a), it can be seen that there are many cost-optimal and near-optimal outcomes in which the deployment of coal power plants is significant. Coal power plant capacity in some pathways can be as high as 20GW. If the UK achieves deep decarbonisation on the other hand (Figure 7b), the role of coal is shown to be significantly reduced, with deployment always below 5GW of capacity. This effect is also found to occur for thermal generation that

includes a strong coal component, such as coal and biomass co-firing (Figure 7c and 7d). The loss of market share by coal-fired power plant in the low carbon scenario results in other technologies being deployed to fill the gap in supply requirements. This can be seen clearly in later sections.

The observations for natural gas fired generation are more nuanced. Low carbon policies appear to increase the deployment of open cycle gas turbines (OCGTs) while decreasing the potential for combined cycle gas turbines (CCGTs). OCGTs serve a core function in the UK power system by providing balancing services to the grid. Grid balancing is a requirement in both umbrella scenarios **U1** and **U2**. OCGTs in this analysis show a similar total range of deployment between the maximum and minimum values in both umbrella scenarios. However, most of the modelled pathways under the *No Climate Policy* case (Figure 7e) feature a low installed base of OCGTs (<10GW) when compared to the *80% Reduction in GHG Emissions* case (Figure 7f). Under the *80% Reduction in GHG Emissions scenario*, there is a more uniform range of outcomes between the minima and maxima found for OCGT installed capacity (Figure 7f) i.e. more of the pathways rely on OCGTs for balancing (up to ~20GW). This indicates that more pathways in the climate constrained world show an increased requirement for peaking plants. This is correlated with increased use of renewable power (Section 6.4.4).

Combined cycle gas turbines (CCGTs), together with coal and nuclear plants, provide the UK's current baseload electricity generation. Under the *No Climate Policy* case (Figure 7g), there is less variation in CCGT deployment and most pathways only deploy up to 10GW of CCGTs because coal power, which is cost competitive with gas, remains an important player. Under the *80% Reduction in GHG Emissions* case (Figure 7h), there is a much wider range of potential outcomes, including cases where up to 30GW of CCGTs are used. This wide variation in CCGT deployment in the near-optimal pathways for the low GHG umbrella scenario can be attributed to both the constraints placed on coal due to its high per unit emissions on the one hand, and CCGT competition with other baseload technologies such as nuclear power and fossil fuel plants with CCS (see Sections 6.4.2 and 6.4.3) on the other.

Figure 7 - Fossil fuel generation in cost-optimal and near-optimal pathways under umbrella scenarios U1 and U2

6.4.2 Fossil fuel generation with CCS

Figure 8 illustrates variation in the deployment of fossil fuelled power plants with CCS in the umbrella scenarios **U1** (*No Climate Policy*) and **U2** (*80% Reduction in GHG Emissions*). With *No Climate Policy*, the installed capacity of both coal and gas CCS plant reaches almost 20GW (Figures 8a and 8c), while under an *80% Reduction in GHG Emissions*, it can be as high as 30GW (Figures 8b and 8d). Implementing a binding national climate target therefore significantly increases the number of pathways that include fossil generation with CCS, which is intuitive as there exists a cap on GHG emissions released to atmosphere.

However, the range of installed capacity outcomes under umbrella scenario **U2**, both for coal CCS and gas CCS, is large and some pathways include little or no CCS plant. This broad range of possible outcomes reflects the fact that these technologies are broadly interchangeable with one other (in cost and performance terms) as well as with other forms of low carbon generation, such as natural gas (Section 6.4.1), nuclear power (Section 6.4.3) or renewables (Section 6.4.4). The closer that the total costs of these technologies are to one another, the greater the degree of interchangeability observed in the near-optimal space.

Figure 8 – Fossil fuelled plants with CCS in cost-optimal and near-optimal pathways under umbrella scenarios U1 and U2
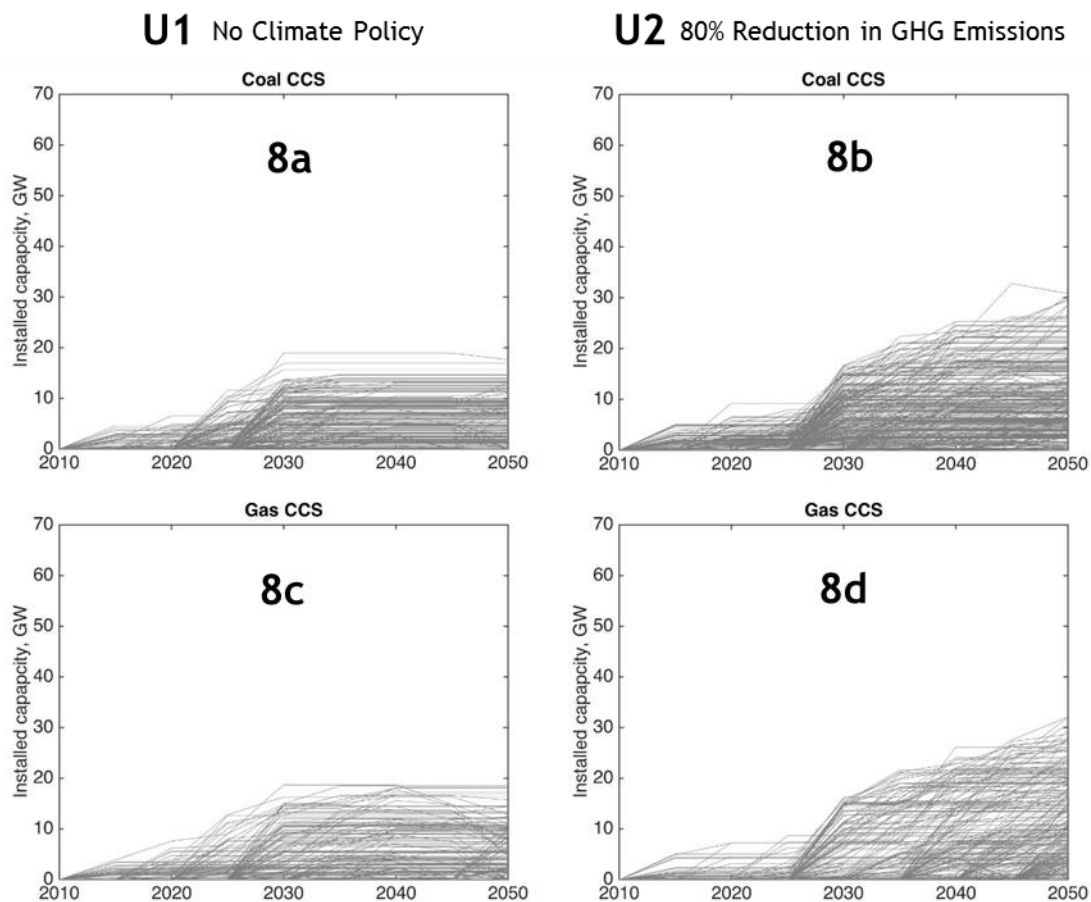
6.4.3 Nuclear power

Figure 9 illustrates variation in nuclear power deployment between scenarios **U1** and **U2**. There is a broad range of outcomes for all pathways, which reflects the competition faced by nuclear power from other centralised power generation technologies such as coal and gas CCS. The maximum potential for nuclear power found under the pathways explored with *No Climate Policy* (Figure 9a) is found to be around 20GW, while under an *80% Reduction in GHG Emissions* (Figure 9b) it is as high as 32GW. This reflects an increased demand for low carbon sources of baseload electricity generation in pathways that include for climate policy considerations and a loss of market share for unabated coal and gas generation (Sections 6.4.1 and 6.4.2).

Figure 9 - Nuclear power in in cost-optimal and near-optimal pathways under umbrella scenarios U1 and U2
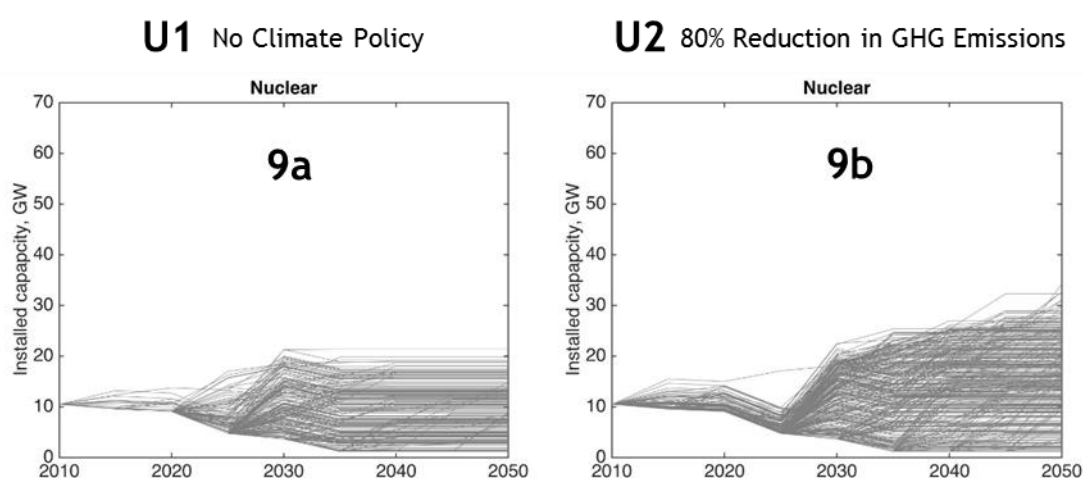
6.4.4 Renewable technologies

Figure 10 illustrates variation in the deployment of wind and solar power and Figure 11 shows the deployment of marine and biomass technologies. The D-EXPANSE model also considers hydropower, biogas, and electricity generation from waste, but they are not illustrated here due to their relatively minor role in the overall modelled UK electricity mix. It can be seen from Figure 10 that a significant deployment of renewable technologies is possible by 2050 in pathways modelled under both the *No Climate Policy* (**U1**) and *80% Reduction in GHG Emissions* (**U2**) scenarios. The results show that a greater number of pathways tend to make use of onshore and offshore wind resources when the model is run with a climate target (see Figures 10b and 10d).

Deployments of solar PV capacity of up to 20GW by 2050 are found in both the **U1** and **U2** cases (see Figures 10e and 10f). Interestingly the pathway assessment finds that the deployment of solar PV is lower after 2035 in the climate-constrained world of **U2** than in the unconstrained **U1** scenario. This result stems from the fact that under the **U2** scenario a large stock of low-carbon technologies must already installed by the year 2030 in order to replace decommissioned fossil fuel-based generation that reaches the end of its lifecycle in the 2020's. Solar PV, which has comparable costs to other low-carbon technologies by 2030, does see deployment in most pathways during this period, but begins to face increased competition from wind, nuclear and

CCS after 2030. These technologies push the total system costs up, crowding out additional deployment of solar PV, whose low capacity factor still results in relatively high overall costs despite technology learning effects bringing down its capital costs. Solar PV also contributes relatively little to capacity required for meeting peak electricity demand and is thus outperformed by other low-carbon technologies. In the **U1** case the total system costs are lower due to the significant capacity of cheaper coal and gas generation. Near-optimal **U1** pathways can thus accommodate costlier solar PV without raising the total system costs beyond the near-optimal threshold. An expanded discussion of our observations on investment costs can be found in Sections 6.6 and 6.7.

Figure 10 - Wind and solar power plants in cost-optimal and near-optimal pathways under umbrella scenarios U1 and U2
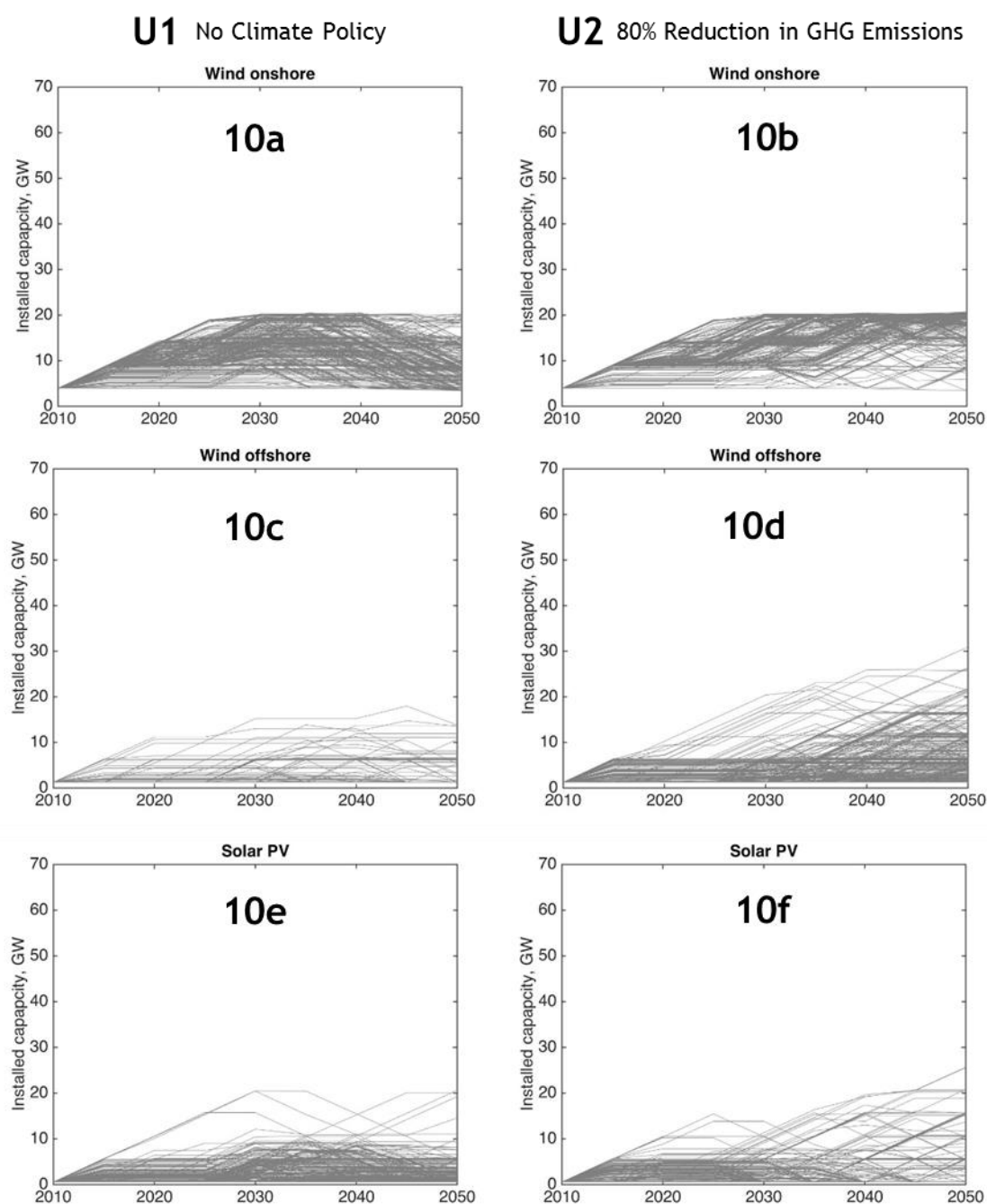
Figure 11 shows that marine and biomass power see limited deployment across all pathways, due to restricted resource availability. There is however, an increased density of pathways above the zero line for all technologies under the low GHG umbrella scenario **U2** (Figures 11b, 11d, and 11f). As with other pathways explored under the *80% Reduction in GHG Emissions* scenario, this reflects an increased demand for low-carbon power and the displacement of unabated coal and natural gas plant.

Figure 11 - Marine and biomass power plants in cost-optimal and near-optimal pathways under umbrella scenarios U1 and U2
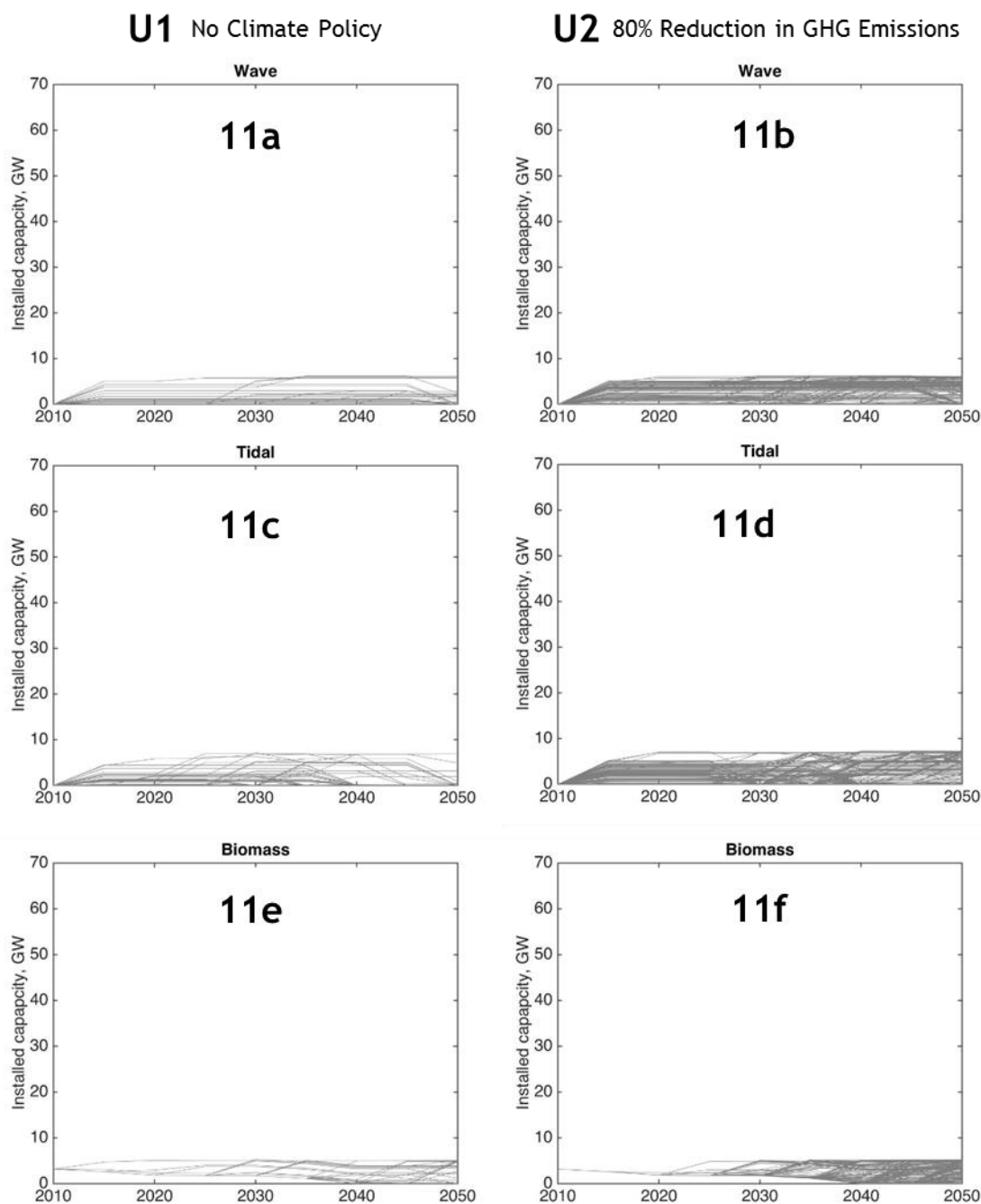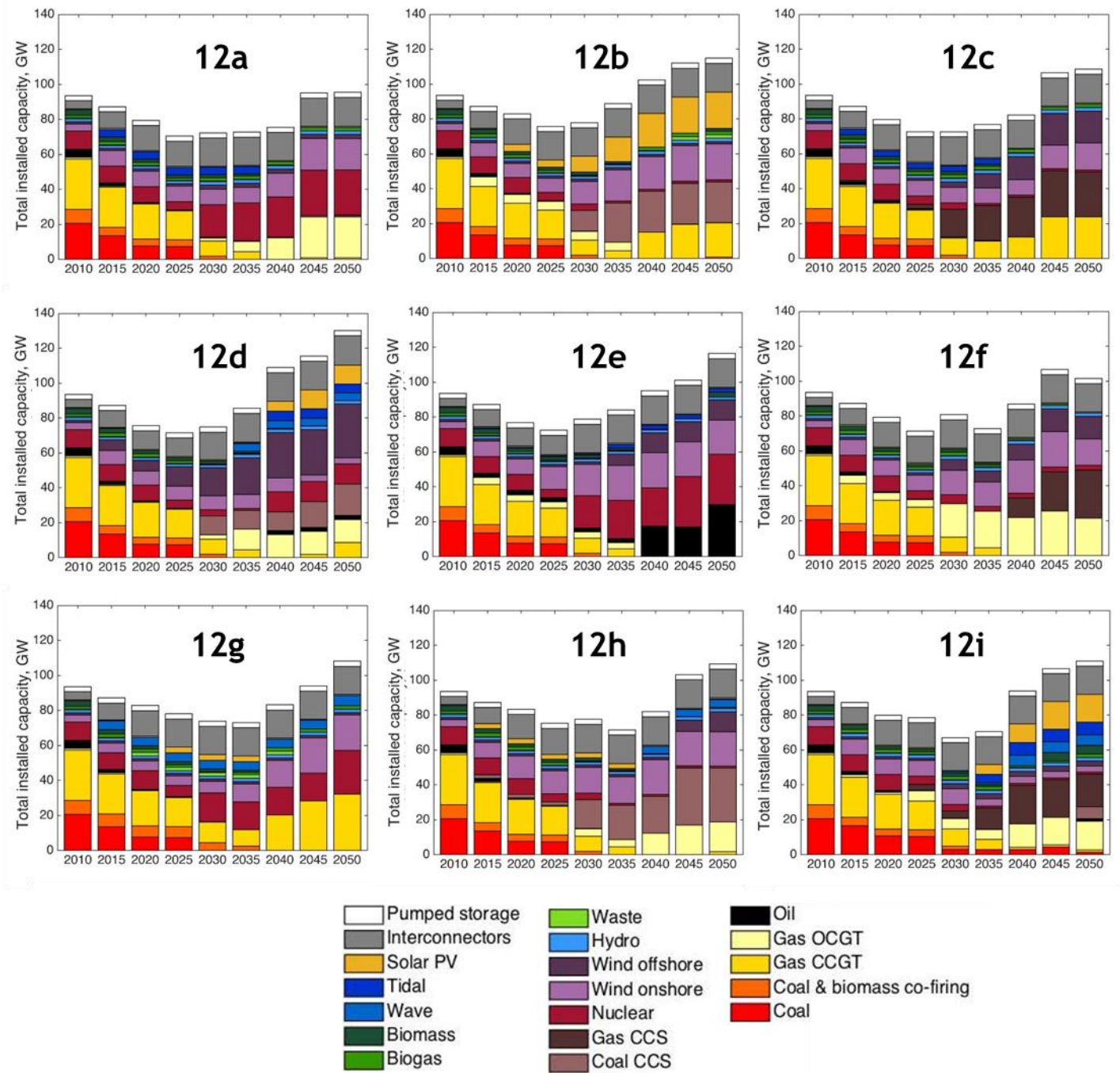
6.5   Maximally-different pathways

Section 6.4 discussed the variation in deployment levels for individual technologies under cost-optimal and near-optimal pathways, but did not illustrate how these technologies combine into complete transition pathways. A key feature of D-EXPANSE is the identification of pathways within the near-optimal space that are "maximally different" from one another. By "maximally different", we mean that these scenarios are a subset of the total ensemble of simulated pathways that differ from each other as widely as possible. This is determined using an adapted distance-to-selected algorithm using harmonic averages [104], as described in previous work using the EXPANSE methodology [70].

Figure 12 illustrates nine maximally-different pathways from the 400 pathways generated for umbrella scenario **U2**. All of the pathways start with the same power sector technology portfolio in 2010, but ultimately arrive at very different places by the year 2050. For example, some pathways show a transition towards a future characterised primarily by large centrally dispatched technologies such as CCGTs coal and gas CCS, and nuclear power (Figures 12a, 12e, 12f, 12h), while other pathways demonstrate combinations of central generation with wind and solar power (Figures 12b, 12c, 12g). Finally, there are examples of highly diverse pathways that include roles for nearly all modelled technologies (Figures 12d, 12i).

Figure 12 – Examples of nine maximally-different pathways in umbrella scenario U2

While Figure 12 shows a number of example transitions through time, Figure 13 focuses on the maximally-different power sector portfolios for the target year of 2050, comparing the results from the *No Climate Policy* (**U1**) umbrella scenario against those that achieve an *80% Reduction in GHG Emissions* (**U2**). The installed capacity for power generation in the No Climate Policy Case is generally found in the region of 60 – 77GW, while under an 80% Reduction in GHG Emissions it is much higher, being between 100GW and 130GW. The large difference arises from fundamental differences in electricity demand between the two umbrella scenarios. The whole energy system model runs carried out under UKTM show that to meet climate targets under umbrella scenario **U2** there is a significant increase in electricity consumption associated with electrification of end-use demands such as building heating and transport (Sections 6.2 and 6.3). Another factor contributing to higher installed capacities under umbrella scenario **U2**, is that many of the sources of low-carbon energy that are deployed are intermittent in nature, and require additional supporting generation plant to cover periods when they do not operate.

Many observations regarding technological variation, previously discussed in Section 6.4, can also be recognised in this diagram. For example, there are more pathways with a high deployment of CCGTs under the climate constrained scenario (**U2**), and much fewer employing unabated coal fired power plants. Overall there is a high diversity of pathways that fall within the cost-optimal and the near-optimal range, a finding that is consistent with previous MGA exercises [63,68]. This diversity reveals the multiplicity of future options for decarbonising the UK power sector that could evolve under future government policy choices, governance arrangements, and market developments.

Figure 13 – Maximally-different pathways in 2050 for umbrella scenarios U1 and U2
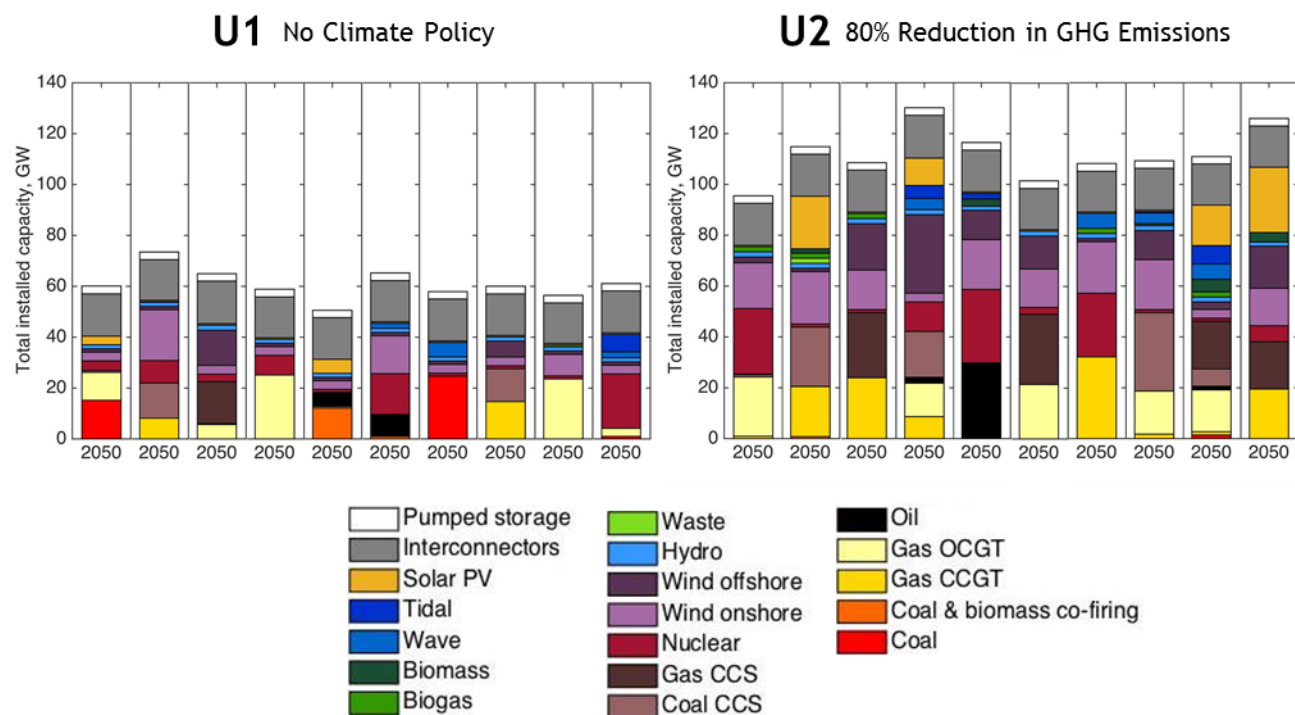
6.6 Cumulative investment costs

Rather than present an investment appraisal for each and every single one of the 400 pathways assessed for each of the two umbrella scenario (**U1** and **U2**), we instead compare distributions of results to understand the broad patterns or trends that emerge from the analysis. Figure 14 compares the temporal distribution of cumulative total investment costs into UK electricity generation as a whole. Boxplots are used to illustrate the mean, the interquartile range (between the 25th and 75th percentile), and the maximum and minimum estimates for all pathways. It can be seen immediately in Figure 14 that the tails of the investment cost distributions are very long. This is to be expected, as a broad range of uncertainties, including technology characteristics, costs, climate policy considerations and the final demand for electricity are accounted for. Figure 14 also shows that the level of uncertainty in the cost estimates for all pathways increases through time.

Considering both the maxima and minima across all cost pathways, Figure 14 shows that under the *No Climate Policy* scenario, cumulative investment costs range from £45bn to £110bn, while under an *80% Reduction in GHG Emissions*, they are between £75 and 210bn. If the more extreme outliers are not considered and we focus on the interquartile ranges, we find that cumulative investment costs for the *No Climate Policy* scenario are between £60bn and £75bn, while under an 80% Reduction in GHG Emissions they are between £110 and £140bn. In general terms therefore, it can be seen that achieving UK policy targets for 2050 approximately doubles the investment required in the power sector under most of the possible technology pathways. This finding is consistent with observations made in Section 6.3, which show that achieving climate targets may require large increases in installed capacity owing to the electrification of significant end-use sectors such as transport and heating. Not only is there an increase in capacity, but there is also a shift towards low carbon generation, which also increases costs further. This is because many low-carbon technologies are capital-intensive, and replace fossil fuel based plants that have high operational rather than investment costs. Another contributing factor is the intermittent nature of many sources of low carbon electricity, which leads to additional investment in supporting generation capacity.

Figure 14 – Comparison of cumulative investment costs for umbrella scenarios U1 and U2. The boxplots depict mean, 25th and 75th percentiles, upper and lower bound of cumulative investments costs.

U1 No Climate Policy   **U2** 80% Reduction in GHG Emissions
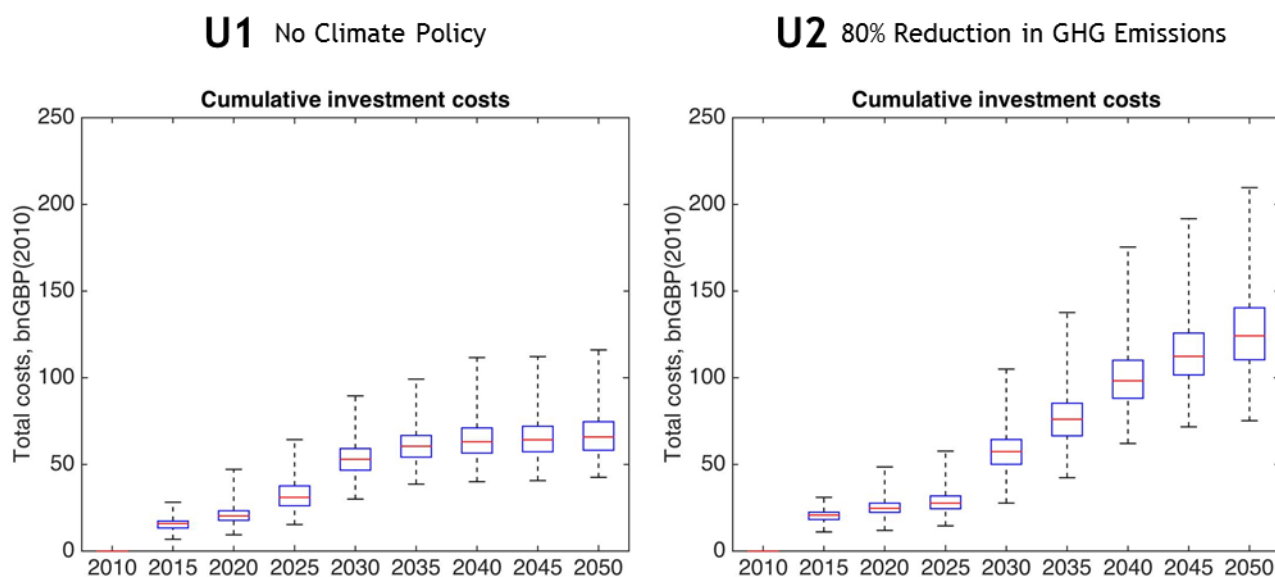

6.7   Annual investment costs

Figure 15 illustrates variation in annual investment costs for each umbrella scenario. As with Figure 14, the tails of the distributions in Figure 15 are again very long due to the vast diversity of plausible pathways found in the near-optimal space. Figure 15 shows that there is a range of investment patterns through the time horizon, and that there are instances of pathways with very low annual investment in one time segment followed by very high annual investment in the next segment, and vice versa. Looking at the interquartile ranges and comparing between the two umbrella scenarios (**U1, U2**), it can be seen that most pathways have distinct peaks in investment levels at similar time periods. The first peak in investments for most pathways occurs after 5 years of model time, in 2015, and is associated with the retirement of existing UK fossil fuelled generation capacity (much of which is due to be decommissioned before 2020). The second peak occurs 15 years into the time horizon in 2030. It can also be seen that the pattern of investment in the period 2035 – 2050 is different in both cases. We can compare these three distinctive periods as follows:

- **2015 investment peak:** under the *No Climate Policy* scenario, the interquartile range is between £2.5bn/year and £3.5bn/year, while under an *80% Reduction in GHG Emissions* it is slightly higher and between £4bn/year and £4.75bn/year.

- **2030 investment peak:** under the *No Climate Policy* scenario, the interquartile range is between £3.25bn/year and 5bn/year, while under an *80% Reduction in GHG Emissions* is it generally much higher and between £4.75bn/year and £7.5bn/year

- **2035-2050 period:** under the *No Climate Policy* scenario, investment levels fall to around £1-2bn/year and remain £1bn/year or less thereafter. Under an *80% Reduction in GHG Emissions*, annual investments do not

fall down to very low levels after peaking in 2030, but actually stay in the range £1-6bn/year.

These findings are consistent with observations made for total cumulative investment found in Section 6.6. They demonstrate that technology pathways under the low carbon scenario have higher investment requirements and that much of the additional investment actually occurs in the period 2030-2050.

Figure 15 – Comparison of annual investment costs for **U1** and **U2** umbrella scenarios. The boxplots depict mean, 25th and 75th percentiles, upper and lower bound of cumulative investments costs.
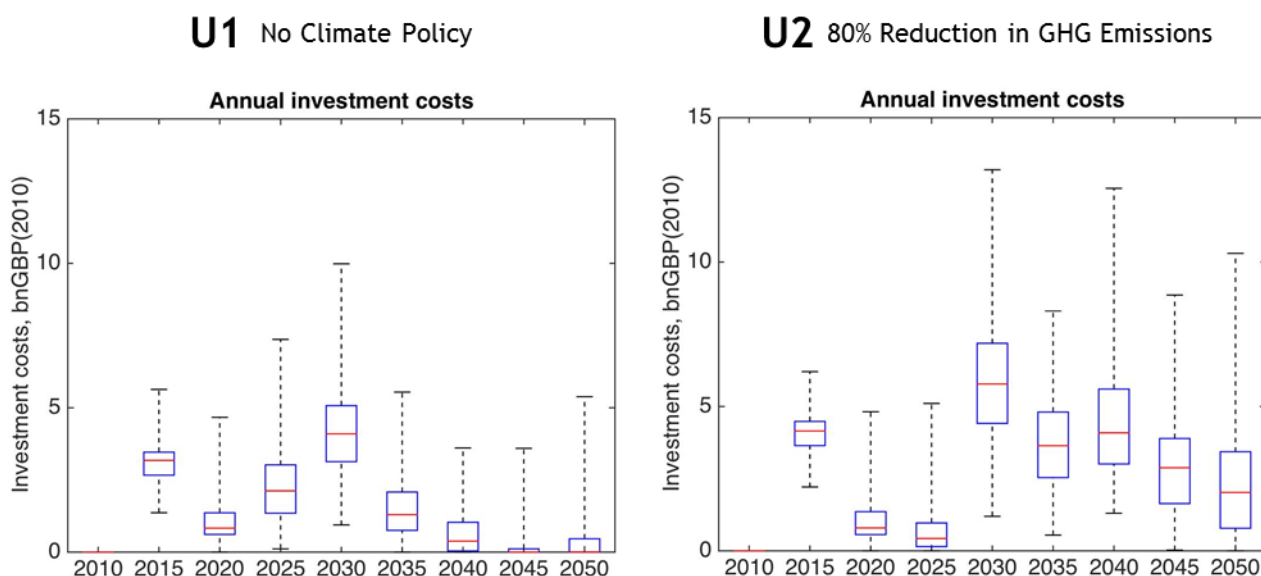
7.0 Discussion

7.1 Comparison with past studies

As highlighted in the introductory framing for this paper (Section 1.0), there is an urgent requirement for countries to develop strategies for deep decarbonisation of their energy systems in line with global agreements on climate change mitigation. In the UK, one of the major policy uncertainties is understanding how much investment needs to be mobilised for the energy transition, particularly in the power sector. Our literature review (Section 3.0) finds that while UK climate targets are for 2050, past estimates of investment requirements to transform the power system have tended to only focus on the 2030 period and to only explore a relatively narrow range of future uncertainties. An important and policy relevant application of energy models is therefore to quantify future investment requirements into the power sector in the period to 2050 and expand the consideration of uncertainty.

This study demonstrates a novel approach that compares and contrasts 800 separate pathways for the UK power sector in the period to 2050, under two different climate policy conditions and a wide range of variations in future technology and cost parameters. This arguably represents the most wide-ranging attempt to consider future uncertainties facing the UK power sector to date, and is undertaken in the context of the decarbonisation of the whole energy system. Our approach goes

significantly beyond what has been attempted previously in past studies (Section 3.0), each of which, when taken in isolation, only presents a relatively narrow and arguably subjective viewpoint on possible developments rather than revealing the actual broad scope of future possibilities.

The range of annual investment rates found in historical transitions is £3-11bn/year, while estimates from other studies for future investment requirements (when focusing on those figures that cover power generation only, rather than the whole electricity system) are for 2-9bn/year. The annual investment rates shown in Figure 15 illustrate that the outputs from our combined UKTM and D-EXPANSE model assessment spans a comparable range, and slightly beyond (some outlier pathways reach 13bn/year). The work presented in this paper is therefore consistent with other studies but demonstrates an approach that is able to explain the range of outcomes explored as a function of uncertain technology selection, cost, and policy assumptions.

7.2   Implications for policy

The work presented raises a number of important insights for energy policy in the UK. It first corroborates the findings of other analyses that demonstrate the requirement for a massive investment in new generation capacity if the UK is to meet its 2050 climate targets. The power generation pathways found within the cost-optimal and near-optimal space under stringent climate constraints (the *80% Reduction in GHG Emissions* umbrella scenario) all involved 2050 generation capacities above 100 GW, in comparison to pathways found under the *No Climate Policy* scenario, which featured capacities in the 60-75 GW range (Section 6.5).

We find that, in general terms, a power sector transition pathway to 2050 without any form of GHG emissions policy requires cumulative investments of between £60bn and £75bn. Pathways that meet UK climate policy targets for 2050 on the other hand, require a doubling of cumulative investment requirements to between £110 and £140bn (Section 6.6). The model assessment also gives some insights into the profiling of investments through time. We find that not only are peaks in power sector investment likely to be higher when meeting climate targets, but that a large portion of the difference in future costs occurs from deployment activity in the period 2030-2050 (Section 6.7).

In terms of technology selection, the analysis across the 800 different modelled pathways demonstrates that there are a very large number of different electricity generation mixes that lie within a relatively small, near-optimal space around the mathematically least cost solution (i.e. +/- 15%). Another way of looking at this is that many diverse technological solutions to the energy transition challenge have broadly similar costs. With *No Climate Policy*, potential for coal-fired power could be as high as 20GW in 2050, while under an *80% Reduction in GHG Emissions*, the maximum observed deployment was 5GW (Section 6.4.1). The shift away from unabated coal in many pathways is found to be accompanied by an increased potential for low carbon power generation. Nuclear power, coal CCS, and gas CCS all see their maximum deployment potential increase from around 20GW under *No Climate Policy*, to 30GW when an *80% Reduction in GHG Emissions* is pursued (Sections 6.4.2 and 6.4.3). Other interesting features of many low carbon pathways are an increased preference for

renewable energy resources (Section 6.4.4) and an increased deployment of power plants traditionally used for system balancing such as open-cycle gas turbines (OCGTs).

What does this diversity in model solutions in the near-optimal space mean for energy policy? Many advanced economies such as the UK have partially or wholly liberalised electricity markets. The UK energy market is dominated by a number of large energy firms, known collectively as the "Big Six" [105]. Only two of these companies are domestically owned, and the UK government itself does not directly own or operate any major parts of the electricity system. Similar market arrangements for the electricity sector can be found in countries as diverse as Germany [106], Spain [107], Chile [108], and Australia [109], while Japan is also observed to be moving in this direction [110]. The official UK Government position is to create the conditions for a market-led transition whereby the best value portfolio of electricity generation emerges from competition [19,23]. As fossil-fuelled technologies currently dominate power generation, a key role for Government is to provide mid-term policy support for low-carbon generation options in order that they can become cost-competitive with these fossil-fuelled technologies. The findings from our study imply that the UK Government's stated policy of maintaining technology neutrality and encouraging market competition in order to drive decarbonisation could be viewed in a positive light [19,23]. However, whether or not the UK's current market-led framework will actually able to incentivise investment at the levels required to drive the transition remains to be seen.

The model results illustrate that at least £45bn will need to be found to replace aging generation plant in the UK whether the Government strives to achieve its ambitious climate targets or not. It is expected that the majority of this capital will be found from the private sector and institutional investors, such as large pension funds. Therefore, it is critical that policymakers seek to create an attractive environment for investment in the period to 2030, and one that can endure thereafter as high annual investment rates need to be sustained to 2050 in the climate-constrained world. This may involve the packaging of investments so that some risks are passed to taxpayers and consumers, making the asset more "investable" for the financier while keeping the overall economic cost to society manageable [24]. Another approach is to explore how new capacity requirements might be met through non-traditional forms of ownership and financing, such as energy co-operatives [111] or energy service companies (ESCOs) [112]. Finally, while a return to complete state ownership of the electricity may seem unlikely in the context of the political preferences of successive UK governments for market-driven solutions [113], it is not impossible to imagine a role for greater state intervention (e.g. as imagined in Foxon [25,114]). Government can potentially borrow at extremely favourable rates and is in a position to take on board significant risk premiums when compared to many private firms, which raises the prospect of the government acting as a guarantor or counterparty for private sector investments [20].

7.3   Implications for research

While our specific case study is for the UK, we can draw from our analysis a number of useful insights for studies of deep decarbonisation at the international level. Our work

shows that the common approach of assessing future investment requirements for energy transitions, which is to use a handful of deterministic scenarios, based on small sets of (at times) minimally varying assumptions, can underplay the extent to which plausible future pathways can differ from one another, even when incurring similar economic costs. This relaxed approach to uncertainty consideration has the effect of disguising the full spectrum of possible futures for policymakers. We find that this effect is present even in studies that use advanced whole energy system models that take into account trade-offs and interactions between diverse parts of the energy economy such as buildings, industry and transport.

While whole system models of this type are useful for exploring "cost-optimal" paths, the fact that they are commonly used with relatively few scenarios (typically <10) means that they risk focusing policymaker attention on the optimal result, which is not necessarily more likely to occur than other near-optimal outcomes, an observation that is well understood in the decision theory community (e.g. see [61]). In complex systems with deep uncertainties it is often argued that a useful application of models is to bound the extremes of the problem space rather than to focus on producing single "optimal" pathways [63,115,116].

Computational limits often preclude the use of whole energy system models with hundreds of scenarios. We propose therefore that whole systems analysis of energy systems may benefit from combined application with detailed sectoral models, and approaches that generate large ensembles of results in order to explore parametric and structural uncertainties. We have demonstrated one such novel approach here by applying our whole system energy optimisation model UKTM in concert with the D-EXPANSE model. UKTM provides the whole system overview, while D-EXPANSE performs an advanced sensitivity analysis around the optimal pathways in a single sector, delivering robust insights for policymakers. Researchers undertaking decarbonisation analysis in other countries can benefit from using similar approaches.

Our experience in visualising and interpreting the results of the analysis here is that the use of large pathway ensembles in conjunction with a whole energy systems modelling approach creates large volumes of output data (pathways). This presents its own challenges for analysis and communication of insights [64]. For example, this study shows that the key trends from the analysis cannot be accomplished by using a few deterministic trend lines, but instead involves a "spaghetti" of multiple pathways that can overlap significantly. Many policymakers and indeed, scientists, can find this unsettling, and without guidance may be inclined to believe that the results mean that "anything can happen". Future research on methods to reveal, visualise, interpret, and communicate uncertainties is therefore needed.

There are ongoing efforts to incorporate advanced approaches for searching within high-dimensional results spaces for trends and patterns, such as data clustering techniques and machine learning [117]. For example, these approaches are starting to be used in global-scale climate policy assessments that rely on large pathway ensembles [118]. The extension of these techniques to national level energy policy insights is a logical progression, and the energy research community may well benefit from future developments in this field. As discussed above however, such approaches place an additional burden on both researchers and policymakers to appreciate and plan for uncertainty [119]. Researchers should refer to the existing literature on science-policy communication for guidance in this critical area (e.g. [120]).

8.0   Conclusions

Past investment appraisals of the UK electricity sector transition have considered a relatively narrow range of uncertainties and have focused on the mid-term time horizon to 2030 rather than the climate policy timeframe of 2050. This paper addressed this gap by exploring an interlinked set of policy, technology and cost uncertainties related to the future UK electricity sector evolution. The analysis linked outputs from a whole energy economy model UKTM (UK TIMES) with the D-EXPANSE model that generates large ensembles of cost-optimal and near-optimal UK electricity generation pathways. D-EXPANSE achieves this by combining Monte Carlo analysis with Modelling to Generate Alternatives (MGA). A large ensemble of 800 UK electricity sector pathways was produced, spanning a much broader range of uncertainties than those considered in past published investment appraisals.

The results for the 800 modelled transition pathways show that policies aimed at achieving climate targets are likely to significantly increase the installed capacity required for meeting electricity demand in 2050. With *No Climate Policy*, installed generation capacities were found in the range 60GW – 75GW, while under an *80% Reduction in GHG Emissions*, between 100GW – 130GWof plant were required. Meeting climate targets for 2050 was also found to increase the investment requirements for new electricity generation. The interquartile range for cumulative investments in new generation under the *No Climate Policy* scenario ranged from £60bn – £75bn, while under an *80% Reduction in GHG Emissions*, modelled investment requirements approximately double to £110bn - £140bn.

An investment profiling assessment shows that capital flows into new electricity generation will likely need to match or exceed historical precedents of £3bn - £11bn in the period to 2030, regardless of whether or not climate targets are pursued or not. This is driven by the need to replace aging elements of the UK generation fleet that will see their economic lives expire during the 2020's. Post 2030, the decision on whether to achieve climate targets for 2050 or not becomes crucial, because following a climate mitigation pathway implies the need to sustain elevated levels of new plant deployment and investment. With *No Climate Policy*, investment levels in new generation can fall to around £1bn annually in the period 2035-2050, while to achieve an *80% Reduction in GHG Emissions*, they need to be sustained at levels of between £1bn/year - £6bn/year over the same timeframe.

From a policy perspective, our findings align with those of other researchers that identify a pressing need for the UK government to incentivise investment in new low-carbon generation. The privatised nature of the UK electricity system and the difficulties experienced to date in attracting capital into the sector from traditional sources of financing puts the government in a potentially difficult position. Resolving this policy challenge may require new and innovative models of ownership and financing such as energy co-operatives and energy services companies, and also may require an attractive "packaging" of investments that transfers enough of the risk away from investors to enable capital to flow. Politically, this could be perceived as less than desirable, but the UK government appears to have few alternatives beyond resurrecting the state ownership of energy assets, a concept to which successive UK governments over the last 30 years have demonstrated consistent opposition.

From a research perspective, this study demonstrates a novel approach that combines a national whole energy systems model with an exploratory pathway generator for delivering policy insights under deep uncertainty. The study shows that adequately expanding the consideration of uncertainty in energy transition modelling leads to large volumes of modelled pathways. Presenting the relevant findings in such a way that the quantitative analysis assists the decision process and does not simply overwhelm policymakers, and indeed researchers, with its complexity, is identified as being crucial to the future use of such approaches. This work also shows that cost minimisation as an approach to making policy decisions on energy transitions has its limitations, and should be augmented or complemented with techniques that tackle high dimensional uncertainties. Grappling with the unknown in long term energy studies is undoubtedly a very challenging exercise, but robust policy insights are unlikely to result from approaches that attempt to minimise, abstract away, or exclude uncertainty from the analysis.

9.0   Glossary

BEIS	UK Department for Business, Energy and Industrial Strategy
CCC	The UK Committee on Climate Change
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
DECC	The UK Department of Energy and Climate Change
EFOM	Energy Flow Optimisation Model
IEA-ETSAP	The International Energy Agency's Energy Technology Systems Analysis Programme
D-EXPANSE	Dynamic version of EXploration of PAtterns in Near-optimal energy ScEnarios
GHG	Greenhouse Gas
ESOMs	Energy System Optimisation Models
MARKAL	MARKet ALlocation Model
MESSAGE	Model for Energy Supply Systems And their General Environmental impact
MGA	Modelling to Generate Alternatives
OCGT	Open Cycle Gas Turbine
Ofgem	UK Office of Gas and Electricity Markets
OSEMoSYS	Open Source Energy Modelling System
PV	Photovoltaics
TIMES	The Integrated MARKAL-EFOM System
UKTM	UK TIMES Model

10.0   Acknowledgements

11.0   References

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