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Impact of technology uncertainty on future low-carbon pathways in the UK

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ABSTRACT

Energy and climate policy-making requires strong quantitative scientific evidence to devise robust and consistent long-term decarbonisation strategies. Energy system modelling can provide crucial insights into the inherent uncertainty in such strategies, which needs to be understood when designing appropriate policy measures.

This study contributes to the growing research area of uncertainty analysis in energy system models. We combine consistent and realistic narratives on several technology dimensions with a global sensitivity analysis in a national, bottom-up, optimizing energy system model. This produces structured insights into the impact of low-carbon technology and resource availability on the long-term development of the UK energy system under ambitious decarbonisation pathways. We explore a variety of result metrics to present policy-relevant results in a useful and concise manner. The results provide valuable information on the variability of fuel and technology use across the uncertainty space (e.g. a strong variation in natural gas demand). We demonstrate the complementarities and substitutability of technologies (e.g. the dependency of hydrogen technologies on the availability of CCS). We highlight critical low-carbon options and hedging strategies (e.g. the early decarbonisation of the electricity sector or the stronger use of renewable sources as a hedging against failure in other technologies) and demonstrate timing and path dependencies (e.g. the importance of early decarbonisation action in the presence of multiple technology uncertainty). The results also show how the availability of a given technology can have wider impacts elsewhere in the energy system, thus complicating the management of a long-term energy transition.

1. Introduction

Quantitative energy modelling currently plays a fundamental role in informing decision-making in energy and climate policies on efficient long-term decarbonisation strategies, both on a global [48] and national level [31]. Given the uncertainty and complexity of future low-carbon pathways, these energy-economic studies usually present their results as a small set of qualitatively different scenarios which can be described as “plausible, challenging and relevant stories about how the future might unfold” [76].

In brief, the modelling/policy process works as follows. Decision makers rely upon policy reports for objective and balanced information. The development of a policy report is supported by the results of a modelling exercise. And these reports are used to help set long-term target levels for emission reduction, energy efficiency or use of renewable energies and outline the major technology strategies to fulfil these objectives. But particularly when analysing national policy reports, it becomes obvious that they usually rely on a small set of scenarios (e.g. Refs. [19,34] derived from deterministic energy system models. While acknowledging the need to deliver clear and concise messages to policy makers, it is apparent that such analyses are limited in terms of their description of uncertainty in the projected decarbonisation pathways they report. This may lead to an overreliance on certain technologies or mitigation strategies which feature strongly in the presented scenarios (availability bias).

While climate analysis has already progressed considerably in terms of uncertainty analysis (cf. for example [50], it still seems to be an emerging technique in energy systems studies. Different approaches to represent uncertainty in energy-economic models

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can be observed in literature. The most common methods are *Sensitivity Analyses* evaluating the variability of the model output as a function of changing input parameters in deterministic models [79]. In order to further include interactions between input parameters, *Global Sensitivity Techniques*, which vary several uncertain input parameters at a time to explore the interaction effects, in some cases through probabilistic and Monte Carlo methods, have been developed [95]. Recent studies with global sensitivity approaches in energy systems research are [1,2,6,73,89,92]. Other methods include *Stochastic Modelling* [53,54,56,60,80,84,90], *Modelling to Generate Alternatives (MGA)* [18,86,93] and *Multi-model comparisons* [55,58,85,98].

Some background on these modelling techniques is provided in Table A-1 in the Annex. Most of these advanced uncertainty methods lead to a rising number of scenarios. This surely leads to a better exploration of the uncertainty space, but at the same time it has to be made sure that such studies produce relevant and transparent policy insights [87].)

This study contributes to the growing research area of uncertainty analysis in energy system models. Using the approach of a global sensitivity analysis in a national, bottom-up, optimizing energy system model, the aim is to identify which low-carbon technologies and resources have the most influence on the long-term development of the UK energy system under ambitious decarbonisation pathways. Our motivation stems from the fact that most forward looking scenarios rely on the rapid scaling up of technologies, that currently either occupy a fairly small niche, but have not yet demonstrated the capability of such growth or entered commercial markets. While it seems likely that at least one of the technologies will be able to scale up, it seems equally likely that at least one of the technologies will suffer an unforeseen setback. Our analysis aims to see how sensitive the outcomes are to the failure of one or more key technologies, what are the interactions between the technologies and at what point reaching targets may become difficult. We emphasise the relevance to policy by (1) basing the quantitative scenario analysis on consistent and, in the UK context, realistic narratives for each technology dimension; (2) limiting the analysis to a manageable number of scenarios such as to have sufficient variability to assess the effect of technology uncertainty, while still being able to analyse each scenario in detail and (3) exploring various metrics to present the results across the scenario matrix in an insightful and concise manner. The limited number of dimensions of uncertainty allows us to conduct a global sensitivity analysis by computing scenarios for the all the combinations of the combinations of parameters.

The paper is structured as follows. Chapter 2 provides an overview of the methodology, including a description of the modelling framework, the qualitative technology narratives and the approach for the sensitivity analysis. The result metrics for the quantitative scenario analysis are presented in Chapter 3 focusing on the reference case, variability in fuel use, emissions and cost indicators as well as insights on technology complementarity and substitutability. The paper concludes with a discussion of findings and policy implications in Chapter 4.

2. Methodological approach

2.1. The national energy system model UKTM

We use the new national UK TIMES energy system model (UKTM) [17,36] to conduct a quantitative scenario analysis. UKTM has been developed at the UCL Energy Institute over the past two years as the successor to the UK MARKAL model [52]. It is based on the model generator TIMES (The Integrated MARKAL-EFOM System), which is developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) [62].

UKTM is a technology-oriented, dynamic, linear programming optimisation model representing the entire UK energy system from imports and domestic production of fuel resources, through fuel processing and supply, explicit representation of infrastructures, conversion to secondary energy carriers (including electricity, heat and hydrogen), end-use technologies and energy service demands. Generally, it minimizes the total welfare costs (under perfect foresight) to meet exogenously defined sector energy demands under a range of input assumptions and additional constraints. The model delivers a cost optimal, system-wide solution for the energy transition over the coming decades.

The model is divided into three supply side sectors (resources & trade, processing & infrastructure and electricity generation) and five demand sectors (residential, services, industry, transport and agriculture). All sectors are calibrated to the base year 2010, for which the existing stock of energy technologies and their characteristics are known and taken into account. A large variety of future supply and demand technologies are represented by techno-economic parameters such as capacity factor, energy efficiency, economic lifetime, capital costs, O&M costs etc. The investment cost assumptions for the most important electricity generation technologies are presented in Table A-2 in the Annex. The model also includes assumptions for attributes not directly connected to individual technologies, such as energy prices, resource availability and the potentials of renewable energy sources. UKTM has a temporal resolution of 16 time-slices (four seasons and four intra-day timesslices). In addition to all energy flows, UKTM tracks CO_2, CH_4, N_2O and HFC emissions. For more information on UKTM see Ref. [37].

In addition to its academic use, UKTM is the central long-term energy system pathway model used for policy analysis at the Department of Energy and Climate Change (DECC) and the Committee on Climate Change (CCC).

2.2. Technology uncertainty dimensions

To arrive at a comprehensive picture of the potential impacts of technology (and resource) uncertainty on the decarbonisation pathways in the UK, 5 key low-carbon technology dimensions have been chosen for the sensitivity analysis: nuclear energy, carbon capture and storage, bioenergy, renewable electricity and demand-side change. For each dimension, a consistent narrative for, both, the central case and the sensitivity variant, has been developed and then further translated into quantitative model input assumptions (Table 1).

2.2.1. Nuclear energy (N)

According to the most recent government cost estimates, nuclear energy is currently the low-carbon technology with the lowest generation costs in the UK [23] and is therefore at the centre of the government's decarbonisation strategy with a contribution of up to 75 GW by 2050 (compared to the current 11 GW) according to the UK's Carbon Plan (scenario “Higher nuclear; less energy efficiency”; [19].

But even though nuclear power constitutes a proven technology and has contributed to electricity generation in the UK for more than five decades, a number of uncertainties surround its future development, most importantly with respect to costs and public acceptance. Nuclear power costs have recently risen considerably, leading to long delays in starting construction as well as difficulties in finding investors. The future competitiveness of nuclear power with other low-carbon technologies is far from certain [5,88]. Public acceptance of nuclear energy is generally relatively high in the UK compared to other countries [72], but it remains to be seen whether the possible delays and significant cost increases for the