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Critical mid-term uncertainties in long-term decarbonisation pathways

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ABSTRACT

Over the next decade, large energy investments are required in the UK to meet growing energy service demands and legally binding emission targets under a pioneering policy agenda. These are necessary despite deep mid-term (2025–2030) uncertainties over which national policy makers have little control. We investigate the effect of two critical mid-term uncertainties on optimal near-term investment decisions using a two-stage stochastic energy system model.

The results show that where future fossil fuel prices are uncertain: (i) the near term hedging strategy to 2030 differs from any one deterministic fuel price scenario and is structurally dissimilar to a simple 'average' of the deterministic scenarios, and (ii) multiple recourse strategies from 2030 are perturbed by path dependencies caused by hedging investments. Evaluating the uncertainty under a decarbonisation agenda shows that fossil fuel price uncertainty is very expensive at around £20 billion. The addition of novel mitigation options reduces the value of fossil fuel price uncertainty to £11 billion. Uncertain biomass import availability shows a much lower value of uncertainty at £300 million.

This paper reveals the complex relationship between the flexibility of the energy system and mitigating the costs of uncertainty due to the path-dependencies caused by the long-life times of both infrastructures and generation technologies.

1. Introduction

1.1. Context

As the international scientific and governance communities reach a consensus that climate change presents a severe barrier to future human well-being and livelihoods, the UK continues to legislate for ambitious decarbonisation targets (Climate Change Act, 2008). The UK target is an 80% reduction in greenhouse gas emissions (GHG) below 1990 levels by 2050, excluding international aviation and shipping. This can be equated to a 90% reduction in energy related CO_2 emissions given the uncertainties in mitigation potential of non-CO_2 and non-energy related emissions (Usher and Strachan, 2010). This UK action is consistent with meeting an equal per capita emissions target by 2050 (Committee on Climate Change, 2008), to reduce the probability of exceeding a 2 °C increase in average global temperature over pre-industrial periods (Allen et al., 2009).

The use of bottom-up, technologically detailed energy system models, such as UK MARKAL, continues to play an important supporting role in UK policymaking following an iterative process of development (Strachan et al., 2008). The results of these studies showed that meeting an 80% reduction in GHGs in the UK is both technologically feasible and affordable. UK MARKAL was first developed for, and contributed to, the 2003 Energy White Paper (DTI, 2003) and, with funding from the UK Energy Research Centre, was extended for further projects to incorporate a macro-economic function (Strachan and Kannan, 2007) or compute a partial-equilibrium in MARKAL Elastic Demand (Strachan, 2010).

A typical analysis using an energy system model involves the development of multiple, internally consistent and plausible scenarios. While a powerful method for obtaining insights, the sheer number of scenarios may give conflicting and confusing messages to policy makers because near-term decisions can be mutually exclusive. Furthermore, uncertainties are examined through sensitivity analyses, which add to the number of scenarios. Sensitivity analysis is rarely performed in a parametric fashion, and so interaction between uncertain variables is not captured.

1.2. Literature review

Previous studies have failed to address the significant uncertainties surrounding many aspects of the transition to a low-carbon future in an integrated and systematic manner. This is (i) a problem of applying a deterministic methodology to a complex and multi-faceted problem that is inherently uncertain, and (ii) an issue with the focus on pathways and technologies rather than the uncertainties. There is recognition that the implementation of uncertainty in optimisation

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models, especially for those that rely on scenario analysis, is currently limited (Wallace and Ziemba, 2005).

The majority of modelling studies concentrate on input data uncertainty only (see for example Edenhofer et al., 2010; Clarke et al., 2009; Grubb et al., 2006). In contrast, Edenhofer et al. (2006) make a partial categorisation of uncertainty into parameter (input data) uncertainty and model (structural) uncertainty. Beven (2009) describes uncertainty in a more complete manner, as epistemic—that which can be reduced through learning and aleatory—truly random.

Responses to uncertainty range from Knopf et al. (2010) who recommend that choice and a broad technology portfolio provide hedges against uncertainty and 'limit…known risks' whereas Stern (2006) argues for more demanding long-term policy under uncertainty given asymmetrical costs versus benefits.

Within energy system models based on an optimisation paradigm, a few studies have specifically focussed on uncertainties in the energy system. These used early versions of stochastic MARKAL (Kanudia and Loulou, 1999; Condevaux-Lanloy and Fragniere, 2000; Hu and Hobbs, 2010; Loulou et al., 2009; Labriet et al., 2008, 2010; Loulou and Kanudia, 1999; Kanudia, 1998) and a stochastic version of MESSAGE (Messner, 1996). Hu and Hobbs (2010) give an overview of stochastic MARKAL developments. Early uncertainty work using MARKAL used both an expected-cost criterion (Kanudia, 1998) and Minimax Regret criterion (Loulou and Kanudia, 1999). Studies conducted since have used an expected-cost criterion and have focussed on carbon taxation, demand side management, economic growth, nuclear plant availability and carbon mitigation policies or measures. Hu and Hobbs (2010) examine uncertain CO_2 mitigation, natural gas prices and electricity demand growth under multi-pollutant policies, focussing on the electricity sector. Recently, studies using a multi-region, global incarnation of TIMES, the successor to MARKAL, have emerged. Using stochastic TIMES, Labriet et al. (2010, 2008) and Loulou et al. (2009) present preliminary insights from treating the climate sensitivity parameter as a random variable using a two-stage stochastic framework.

1.3. Research aims

In response to the above concerns, we develop a stochastic version of UK MARKAL to explore the effect of key uncertainties on the UK energy system. We present the research that evolved from work which underpinned a major new policy study (Committee on Climate Change, 2010), with particular reference to the examination of critical mid-term uncertainties for the UK including fossil fuel prices and biomass availability. Indeed, the focus on uncertainties sets this work apart from previous studies on energy system transitions. It builds on insights that are recognisable from previous work, such as electrification of transport and decarbonisation of the electricity system, to consider the interactions between uncertainty and flexibility of a system under transition. This extends the discussion of how best to meet climate reduction targets, by recognising the value of near-term decisions that are robust under uncertainty. This work is timely, notably as the UK Government has implemented an option to review the level of mitigation effort in 2014 if policy at EU and global level does not match UK ambition (HM Government, 2011). The insights from this work are also of interest to the international community: the UK is the first country to legislate mid-term emissions targets, an approach that other developed countries will need to follow to meet long-term targets.

1.4. Layout of paper

Section 2 describes the methodological details of stochastic MARKAL. We describe a useful metric, EVPI, which allows valuation and comparison of uncertainties. We then present a brief rationale for selection of key uncertainties. The results of the subsequent modelling are presented in Section 3. The paper concludes with a discussion in Section 4.

2. Methodology

2.1. Uncertainty in energy system models

Typically, users of deterministic models will assess uncertainty through a sensitivity analysis. These analyses give an indication of the sensitivity of a model's outputs (e.g. system costs) to a variation in data input values (e.g. fossil fuel price). A parametric sensitivity analysis furthers this by exploring interaction between ranges of multiple data inputs. However, a sensitivity analysis does not give any indication of the likelihood that an input or subsequent model output will take a particular value.

Furthermore, in energy system modelling, changing a model input value might result in a different pattern of investment, internally consistent, but contradictory when compared to an alternative input value, the so called 'knife edge' switching especially prevalent in optimisation models (Messner, 1996).

There is a need to move beyond sensitivity analysis when considering epistemic uncertainties. This is because (i) the process of sensitivity analysis does not allow for the probability of an input value to be quantified, (ii) the generation of many contradictory sensitivity scenarios does not result in clear near-term policy-relevant insights, and (iii) the cost of uncertainty remains unknown—there are therefore no means by which uncertainties can be ranked in importance.

Moving beyond sensitivity analysis necessitates considering alternative model formulations to deterministic modelling approaches. There is also a conflict between the complexity of the current generation of data and time intensive energy system models and the computational tractability of running these models in a fully stochastic manner.

A compromise is to use a two-stage stochastic version of the UK MARKAL model. UK MARKAL is an established, peer-reviewed energy system model of the United Kingdom. Although simple in form, the two-stage stochastic approach limits the computational burden while giving a reasonable degree of insight into the effect of uncertainty on the investment decisions for the UK energy system. It also resolves some of the issues outlined above (i) one near-term strategy is given in the results despite characterising the future as uncertain and (ii) a value can be placed on different uncertainties. However, probabilities must be specified exogenously.

Deterministic models, such as the standard variant of MARKAL, give a single solution for each combination of inputs. Stochastic energy system models relax the assumption of perfect foresight, with the two-stage stochastic MARKAL variant splitting the time horizon into a single near-term hedging strategy and multiple recourse periods, dependent upon the pre-defined number of future possibilities, known as states-of-the-world (SOW).

Stochastic MARKAL minimises the expected cost of a set of probability weighted future SOWs (Loulou et al., 2004). A stochastic model is defined by specifying one or more random variables (while the remainder remain constant) for each of up to nine future SOWs that correspond to the length of the recourse stage. A probability weighting is assigned to each SOW to determine its prior likelihood. The model then computes the best average hedging strategy given then sum of the expected costs in the recourse stage and the hedging stage (see Eq. 1)

$$\text{Minimise } Z = \sum_{w \in W(t)} \sum_{t \in T} C_{t,w}.X_{t,w}.p_{t,w}$$

$$\text{Subject to}: A_{t,w}.X_{t,w} \geq b_{t,w}, \quad \forall t \in T, \forall w \in W(t) \tag{1}$$