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Assessing qualitative and quantitative dimensions of uncertainty in energy modelling for policy support in the United Kingdom

Steve Pye[a,e,*], Francis G.N. Li[a], Arthur Petersen[b], Oliver Broad[c], Will McDowall[c], James Price[a], Will Usher[d]

[a] UCL Energy Institute, Central House, 14 Upper Woburn Place, London, WC1H 0NN, United Kingdom
[b] UCL Department of Science, Technology, Engineering and Public Policy (STEaPP), Boston House, 36-37 Fitzroy Square, London, W1T 6EY, United Kingdom
[c] UCL Institute for Sustainable Resources, Central House, 14 Upper Woburn Place, London, WC1H 0NN, United Kingdom
[d] Environmental Change Institute (ECI), University of Oxford, United Kingdom
[e] MaREI Centre, Environmental Research Institute, University College Cork, Cork, Ireland

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ABSTRACT

Strategic planning for the low carbon energy transition is characterised by a high degree of uncertainty across many knowledge domains and by the high stakes involved in making decisions. Energy models can be used to assist decision makers in making robust choices that reflect the concerns of many interested stakeholders. Quantitative model insights alone, however, are insufficient as some dimensions of uncertainty can only be assessed via qualitative approaches. This includes the strength of the knowledge base underlying the models, and the biases and value-ladenness brought into the process based on the modelling choices made by users. To address this deficit in current modelling approaches in the UK context, we use the NUSAP (Numeral Unit Spread Assessment Pedigree) approach to qualify uncertainty in the energy system model, ESME. We find that a range of critical model assumptions that are highly influential on quantitative model results have weaknesses, or low pedigree scores, in aspects of the knowledge base that underpins them, and are subject to potential value-ladenness. In the case of the UK, this includes assumptions around CCS deployment and bioenergy resources, both of which are highly influential in driving model outcomes. These insights are not only crucial for improving the use of models in policy-making and providing a more comprehensive understanding of uncertainty in models, but also help to contextualise quantitative results, and identify priority future research areas for improving the knowledge base used in modelling. The NUSAP approach also promotes engagement across a broader set of stakeholders in the analytical process, and opens model assumptions up to closer scrutiny, thereby contributing to transparency.

1. Introduction

1.1. Energy and climate strategy under uncertainty

Strategic planning for the low carbon energy transition is characterised by a high degree of uncertainty across many knowledge domains and by the high stakes involved in making decisions. The future availability and costs of transition technologies, the political environment under which they may be deployed, and the role of changing societal preferences and individual behaviours are key uncertainties for decision makers to contend with, and which will impact numerous stakeholders [1]. The UK has long identified the need for decarbonisation of the energy system, with legally binding national targets on emissions reduction that remain among the most ambitious globally [2]. A well-developed science policy architecture has developed over the last decade to explore and implement the transition [3,4], and some progress has been made in recent years, particularly in the power generation sector [5]. However, strategic decisions in a number of critical sectors have yet to be taken, for example in areas such as switching away from natural gas for heating in buildings, the decarbonisation of freight transportation, and how to address the growing emissions from aviation. The long-lived nature of critical infrastructures for supplying energy makes path dependencies and lock-in to legacy assets a real risk [6].

This type of challenge, where urgent near-term choices must be made in an environment where perfect information and universal

* Corresponding author at: UCL Energy Institute, Central House, 14 Upper Woburn Place, London, WC1H 0NN, United Kingdom.
E-mail address: s.pye@ucl.ac.uk (S. Pye).

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agreement amongst key stakeholders is impossible to achieve, is characterised in the scientific literature as the domain of *post-normal science* [7,8]. This is in direct contrast to the definition of *normal science* by Kuhn [9], where observations are used to iteratively resolve testable hypotheses through experimentation. The assessment of strategic options in a *post-normal science* context, such as long term energy policy, must contend with multiple epistemic uncertainties that arise from our imperfect knowledge, including those that can be quantified in modelling tools, but also those that are not easily quantifiable.

Van der Sluijs [10] argues that most quantitative-only approaches do not adequately deal with those dimensions of uncertainty that are non-quantifiable. These include the strength of the underlying knowledge base, the level of theoretical understanding of the processes modelled, and the value-ladenness coproduced by modellers themselves because of the requirement to make choices across key model assumptions. As an illustration, a quantitative analysis performed for a particular policy problem might produce modelling results which suggest that a given input parameter is highly influential on the distribution of costs of meeting a given objective. But what is typically missing from such an exercise is an assessment of the uncertainty arising from the strength of the knowledge base underpinning that quantified model outcome. Such non-quantifiable uncertainty, were it exposed to decision-makers, might reduce the perceived robustness of the model-derived quantitative insight, and lead to different conclusions for policy.

Approaches that recognise this multi-dimensional nature of uncertainty, as described in the next section, can provide decision makers with a more comprehensive understanding of uncertainty and improve the robustness of the resulting choices made. They help avoid quantitative-only approaches which only consider a "*restricted agenda of defined uncertainties – ones that are tractable*" [11]. When faced with policy challenges in the *post-normal* domain, a broad approach to uncertainty assessment is vital. It is entirely possible that *"unquantifiable uncertainties dominate the quantifiable ones"* [10] and excluding them from the analysis will risk giving decision makers a highly restricted perspective on the range of possible outcomes. The challenge is that uncertainties are numerous and appear, as per Walker's typology [12], at different stages across the modelling process, from the problem framing itself, the selection of model input parameters, the structural design and process of defining relationships, and from the subjectivity of model users.

1.2. Existing approaches and knowledge gaps

Energy models are likely to continue to play a key role in ongoing energy transitions by providing the evidence base for planning policies on climate mitigation [13], which in turn serve as key drivers behind many transitions towards sustainability [14]. The Paris Agreement [15] recommends mid-century low emission strategies and states that individual signatories must provide regular updates on their strategic plans for low carbon development (Nationally Determined Contributions, NDCs), forcing a requirement for policymakers to assess low carbon energy transitions at the country-scale [16]. Energy models provide a clear framework for systematic experiments that explore the possible consequences of the multiple different options in systems that are otherwise difficult to grapple with [17]. In the UK, for the last 15 years, energy models have been critical in providing guidance on system decarbonisation, notably in relation to the affordability and feasibility of achieving targets, on issues of path dependency, and on identifying critical feedbacks and linkages between sectors [3,4]. However, the treatment of uncertainties in strategic analysis has had a number of limitations, and practitioners in the modelling community have repeated calls for increased use and improvement of methods for uncertainty analysis [18–20]. This is mirrored by calls from strategy analysts, industry experts and government decision makers, who are cognisant of a broad spectrum of future uncertainties facing the energy transition and also the limitations of current modelling and scenario analysis practices to capture them [1,21].

Energy systems analysis in the UK (and in many other national and regional contexts) has typically focused on the use of scenarios for exploring different futures [22–25]. Historically it has been common for analysts to employ a handful of scenarios with deterministic inputs, using a coupled storyline-and-simulation approach [26]. This approach has been shown to have limitations – ex post analysis of modelled energy futures based on scenario analyses often finds that real world developments occur that are completely outside of the anticipated range [27,28]. Modelling practitioners are increasingly drawing from a range of more advanced quantitative techniques to assess parametric uncertainties as a means of capturing more of the problem space in their work. Techniques found in the UK context include probabilistic analysis [19,20], stochastic programming [18], modelling-to-generate-alternatives (MGA) [29,30] and approaches to expert elicitation [1,31,32].

While valuable for opening up dialogue and highlighting the uncertain nature of the knowledge claims made in this field, none of the above techniques alone are able to adequately identify and assess those non-quantifiable dimensions of uncertainty discussed earlier. An innovative approach to assessing uncertainties in model-based analysis is the NUSAP system [10]. NUSAP, or Numerical Unit Spread Assessment Pedigree, was first proposed by Funtowicz and Ravetz [7], before undergoing substantial development and implementation in the Dutch Government's applied policy research institutes [33]. NUSAP retains the strengths of quantitative uncertainty assessment but brings a focus on the qualitative assessment of the quality or 'pedigree' of the underlying model assumptions. This framework, which includes both standard uncertainty analysis techniques but also assessment of non-quantifiable uncertainties, increases the robustness of emerging conclusions from models, providing decision makers with an enhanced understanding of the strengths and weaknesses of model insights.

1.3. Aims and objectives of the paper

In this paper, we demonstrate how practitioners can broaden the scope of strategic advice given to energy system decision makers by holistically considering both qualitative and quantitative dimensions of uncertainty using the NUSAP approach. For this research, we have used a prominent UK energy systems model, the Energy Systems Modelling Environment (ESME) [34], which is under active development and has been used for academic [35,36], industry [37] and government [38] applications. We describe the application of the NUSAP protocol for assessing the qualitative dimension of uncertainty and show how this can be combined with insights from a quantitative mathematical sensitivity analysis (using the Morris Method).

The NUSAP system has been used before in diverse scientific fields such as the assessment of acid rain and transboundary air-pollution impacts, the global integrated assessment of climate policies, and the effects on human health of waste disposal practices [10,39–41]. The life cycle assessment community have also effectively used pedigree scoring of underlying data assumptions, which is a key element of the NUSAP approach, to better recognise its impact on uncertainty [42,43]. This is the first time such an approach has been applied to a national energy model used to inform thinking on energy transitions towards deep decarbonisation. Additionally, we incorporate novel elements into the NUSAP approach, such as the assessment of model pedigree in multiple time horizons.

The key research questions for this study were as follows:

i What are the key non-quantifiable uncertainties arising from limitations in the knowledge base underlying the ESME model?
ii How do they inform and complement our understanding of uncertainty from quantitative uncertainty approaches, and what are the implications for strategic energy transition planning, in terms of policymaking and future research needs?