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A review of approaches to uncertainty assessment in energy system optimization models

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ABSTRACT

Energy system optimization models (ESOMs) have been used extensively in providing insights to decision makers on issues related to climate and energy policy. However, there is a concern that the uncertainties inherent in the model structures and input parameters are at best underplayed and at worst ignored. Compared to other types of energy models, ESOMs tend to use scenarios to handle uncertainties or treat them as a marginal issue. Without adequately addressing uncertainties, the model insights may be limited, lack robustness, and may mislead decision makers. This paper provides an in-depth review of systematic techniques that address uncertainties for ESOMs. We have identified four prevailing uncertainty approaches that have been applied to ESOM type models: Monte Carlo analysis, stochastic programming, robust optimization, and modelling to generate alternatives. For each method, we review the principles, techniques, and how they are utilized to improve the robustness of the model results to provide extra policy insights. In the end, we provide a critical appraisal on the use of these methods.

1. Introduction

Energy models can be categorized in various ways [1]. A comprehensive review by Jebaraj and Iniyan [2] on existing energy models in 2006 classifies energy models into energy planning models, energy supply–demand models, forecasting models, renewable energy models, emission reduction models, and optimization models. Gargiulo and Ó Gallachóir [3] classify long term energy models based on underlying methodology (simulation, optimisation, economic equilibrium), analytical approach (top-down, bottom-up, hybrid [4]), and sectoral coverage (energy system [5], power system [6]).

As an important branch of energy models, energy system optimization models (ESOMs) can be characterised as technology-rich, optimization models covering an entire energy system. ESOMs have been widely used to offer critical climate and energy policy insights at national, global, and regional scales [7]. These models provide an integrated, technology-rich representation of the whole energy system for analysing energy dynamics over a long-term, multi-period time horizon. Optimal solutions are computed using linear programming techniques. The results are used to explore the least cost energy system pathways for an energy secure and low carbon future, offering insights on energy transition, economic implications and environmental impacts. One of the widely used ESOM model is the MARKAL/TIMES family of models [8] developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP) under the aegis of the International Energy Agency (IEA) since the 1970s. Other ESOM models include MESSAGE [9], ESME [10], OSeMOSYS [11] and TEMOA [12]. The schematic of a typical ESOM model is shown in Fig. 1. The model inputs including energy supply, energy demand and associated economic parameters are shown on the sides, and the model outputs are shown on the top and bottom.

While models are becoming increasingly more complex and sophisticated, projecting 50 or 100 years into the future is inherently uncertain [13]. Edenhofer et al. [14] categorizes uncertainties into parametric and structural. *Parametric* uncertainties arise due to lack of knowledge about empirical values associated with model parameters, and *structural* uncertainties refer to uncertainties in the model equations that collectively define the model structure - examples of the latter include the default ESOM formulation that ignores the heterogeneity among decision makers in the energy system, the manner in which non-

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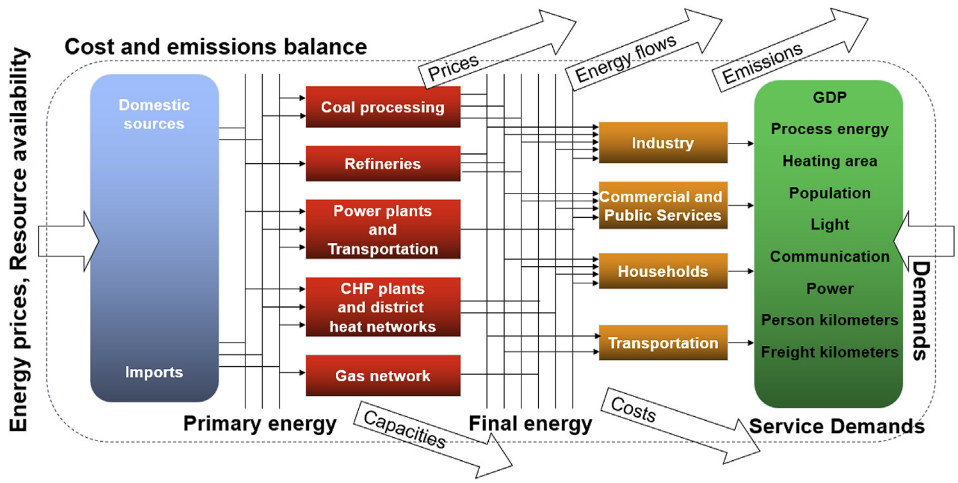

Fig. 1. Schematic of TIMES model [27].

economic considerations factor into energy purchasing decisions, and the role that politics, social norms, and culture play in shaping public policy. Due to model complexity, computational intensity, and the time pressure to produce relevant policy, many ESOMs have been used in a deterministic fashion with limited attention paid to uncertainty. A review of energy system models by Pfenninger points out that assessing uncertainties has become one of the major challenges of ESOMs [15]. When formalizing best practices for using ESOMs, DeCarolis et al. [16] highlight the importance of quantifying uncertainties. Ignoring uncertainty is problematic as many of the issues that ESOM analyses consider are deeply uncertain. They can be described as belonging to the area of "post-normal science" [17], where both the uncertainties and the decision stakes inherent in these issues are high. As Lempert [18] points out, the long-term policy analysis conducted with ESOMs requires decision making under *deep uncertainty*, where analysts and decision makers do not know or agree on (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes (i.e. as they correspond to different policy objectives). This underlines the importance of modelers carrying out uncertainty analysis in a more systematic way to improve the robustness of model outputs and their use for providing policy insights. By systematic, we mean analysis that applies a formal approach to a broad range of uncertainties, and which explicitly addresses the three aspects of *deep uncertainty* in order to provide additional policy insights beyond simple scenario analysis.

It is informative to survey the types of methods available for undertaking uncertainty assessments in different types of energy, economy, environment, and engineering (E4) models, for which a number of reviews have been undertaken. Energy models are designed with different end uses and research problems in mind. Due to the differences in model paradigm and analytical approach across various models, the uncertainty techniques available for each type of model vary. Several existing reviews focus on certain types of models, such as integrated assessment models [19–21], optimization models [22], power systems models [23], environmental models [24], or energy related issues such as climate change [25] and sustainable energy planning [26].

Given an expectation of increased global efforts to limit global warming to well below 2° after the adoption of the Paris Agreement, ESOM models are likely to become critical tools that can supply an evidence base for governments, research institutions and international organizations exploring future pathways to deep decarbonization of energy systems. Therefore, it is necessary to target specifically on ESOMs and undertake a comprehensive review of the literature to identify the application of uncertainty methods. The review was done systematically, using a pre-defined search strategy. We identified four main techniques that have been applied, including Monte Carlo analysis (MCA), Stochastic Programming (SP), Robust Optimization (RO), and modelling to generate alternatives (MGA). Besides introducing the principles and formulations of each technique, the paper focuses on discussing how the different techniques are applied to provide additional policy insights that cannot easily be obtained from deterministic scenario runs. We also provide an appraisal and recommendations on the choice of uncertainty techniques according to the policy issue and the types of uncertainty in question. This paper is organized as follows. In Section 2, we present the literature search methodology carried out. Section 3 thoroughly reviews the four uncertainty techniques. Section 4 provides a brief discussion and concluding remarks.

2. Literature search

To capture the relevant literature on uncertainty analysis in ESOMs we carried out a systematic literature search using a three-phase search strategy based on the techniques described in [28].

The first phase was a broad literature search for all primary studies possibly relevant to the research question using the electronic database engines Scopus and ScienceDirect. The search terms used were grouped into two lists as shown in Table 1. The first list includes keywords associated with ESOMs, and the second list includes those related to uncertainty. The actual search strings applied were obtained by connecting two keywords from both lists with the Boolean "AND". The search terms contained both generic search terms and specific terms. Generic terms such as "uncertainty", "stochastic" and "energy modelling" ensured a wide set of result coverage without missing key studies. More specific search terms were identified from previous search results and included model names such as "MARKAL" and "ESME", as well as uncertainty techniques like "Monte Carlo analysis" and "stochastic

Table 1
Search term lists for literature search.

Energy Model Related	Uncertainty Related
Energy system model	Uncertainty
Energy systems	Stochastic
Energy modelling	Sensitivity analysis
Energy modeling	Monte Carlo analysis
MARKAL	MGA
TIAM	Stochastic programming
ESME	Robust optimization

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