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Formalizing best practice for energy system optimization modelling

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HIGHLIGHTS

- Energy system optimization models (ESOMs) are a critical tool for policy analysis.
- Significant modeler judgment is required, yet little formal guidance exists.
- This paper formalizes best practice for energy system optimization modelling.
- We outline a set of principles and modelling steps to guide ESOM-based analysis.
- Formalized guidance comes at a critical time as ESOMs inform climate policy.

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ABSTRACT

Energy system optimization models (ESOMs) are widely used to generate insight that informs energy and environmental policy. Using ESOMs to produce policy-relevant insight requires significant modeler judgement, yet little formal guidance exists on how to conduct analysis with ESOMs. To address this shortcoming, we draw on our collective modelling experience and conduct an extensive literature review to formalize best practice for energy system optimization modelling. We begin by articulating a set of overarching principles that can be used to guide ESOM-based analysis. To help operationalize the guiding principles, we outline and explain critical steps in the modelling process, including how to formulate research questions, set spatio-temporal boundaries, consider appropriate model features, conduct and refine the analysis, quantify uncertainty, and communicate insights. We highlight the need to develop and refine formal guidance on ESOM application, which comes at a critical time as ESOMs are being used to inform national climate targets.

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1. Introduction

Sustainable energy development worldwide requires us to anticipate and shape possible future outcomes under a variety of different scenarios that consider resource availability and pricing, technology innovation, demand growth, and new energy and environmental policy. Computer models represent a critical tool that can be used to examine the future decision space under a variety of different assumptions. Energy infrastructure is long-lived, so model scenarios that aim to show significant turnover in capital stock in response to new policy must span multiple decades. However, given large future uncertainties that grow with time, using models to produce narrowly focused quantitative predictions is a perilous approach that often produces misleading conclusions. For example, retrospective analysis of energy demand projections generally shows a poor match to reality [1–4]. Even with more modelling experience, higher quality input data, and improved computational resources, model results covering multiple decades cannot be validated, making it hard to create a feedback loop that links model improvements to more accurate projections [1,5,6]. Thus the goal of energy modelling should be insights that challenge our working assumptions and mental models rather than a limited set of quantitative predictions [7–9].

Given the complexity of the modeled system and the inability to validate model results, energy modelling requires a significant amount of modeler judgment that – depending on one's perspective – makes energy modelling a blend of art and science [6] or a craft that is neither art nor science [10]. A variety of methodological approaches and models exist, each with their own strengths and weaknesses that are adapted to answer specific types of questions. Several past efforts have characterized the distinctions between different energy model types (e.g., [11,12]).

Within the field of energy modelling, energy system optimization models (ESOMs) are widely used to model the system-wide impacts of energy development using a self-consistent framework for evaluation. ESOMs include detailed, bottom-up technology specifications and utilize linear programming techniques to minimize the system-wide present cost of energy provision by optimizing the installation of energy technology capacity and its utilization. The models are subject to a number of constraints that enforce system performance criteria as well as user-defined limits. Outputs include future estimates of technology capacity and utilization, marginal commodity prices, and emissions across the energy system. Example ESOMs include ESME [13], the MARKAL/TIMES model generators [14,15], MESSAGE [16], OSeMOSYS [17], and Temoa [18]. In their basic form, ESOMs assume perfect foresight and optimize the energy system from a social planning perspective, thus producing ideal, normative results that can lead to policy-relevant insights. ESOMs have several analytical strengths. First, they provide a consistent accounting framework for specifying the techno-economic performance characteristics of all modeled processes. Second, the model formulation allows for quick and efficient normative goal seeking within highly complex systems. Third, the results can suggest a wide range of energy futures that reflect energy and environmental policy objectives. Fourth, ESOMs can capture sectoral interactions that can lead to cross-cutting insights, which are hard to capture in sector-specific models.

However, given the broad scope of ESOMs, they have become a magnet for increasing complexity as different approaches and features are developed to improve the realism associated with internal model dynamics. Examples include price-responsive demands, hurdle rates, macroeconomic feedbacks, and endogenous technological learning. Various model features and their theoretical underpinnings have been documented elsewhere (e.g., [14,15,19]), and in some cases, critical reviews of specific model elements, such as the discount rates [20] and energy efficiency [21] have been performed. Other studies review and provide high-level guidance on a broader range of energy models that can be used to inform policy [22]. However, a crucial gap remains: there is no published best practice guidance focused on the application of ESOMs, including how and when particular model features should be applied. Such decisions are model- and analysis-specific, and depend on reasoned judgment rather than objective rules. More generally, each modeler must make their own decisions about how to develop and apply ESOMs. Over time, this has led to a crowded landscape of model-based analyses that can overwhelm decision makers with their complexity.

Reflecting on our own experience with ESOMs over the last decade, we see a critical need to compile and synthesize the undocumented knowledge and reasoning behind effective model-based analysis. This review paper represents the first effort to formalize best practice associated with the application of energy system optimization models (ESOMs), which play a critical role in policy analysis. We draw on our collective experience with ESOMs as well as an extensive body of literature and synthesize it into a practical guide for energy modelling. We begin by articulating a set of overarching principles that can be used to guide ESOM-based analysis. To help operationalize the guiding principles, we outline and explain critical steps in the modelling process, including how to formulate research questions, set spatio-temporal boundaries, consider appropriate model features, conduct and refine the analysis, quantify uncertainty, and communicate insights. While the energy community has rightly focused on specific model applications to inform energy decision making, there is also a need to document the approach to ESOM applications in a way that maximizes transparency and engenders trust among those who rely on model-based results. This paper fulfills three currently unmet objectives: it provides guidance to new modelers, initiates a community-wide effort to establish and refine modelling guidelines, and fosters