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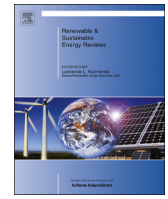

Energy systems modeling for twenty-first century energy challenges

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ABSTRACT

Energy systems models are important methods used to generate a range of insight and analysis on the supply and demand of energy. Developed over the second half of the twentieth century, they are now seeing increased relevance in the face of stringent climate policy, energy security and economic development concerns, and increasing challenges due to the changing nature of the twenty-first century energy system. In this paper, we look particularly at models relevant to national and international energy policy, grouping them into four categories: energy systems optimization models, energy systems simulation models, power systems and electricity market models, and qualitative and mixed-methods scenarios. We examine four challenges they face and the efforts being taken to address them: (1) resolving time and space, (2) balancing uncertainty and transparency, (3) addressing the growing complexity of the energy system, and (4) integrating human behavior and social risks and opportunities. In discussing these challenges, we present possible avenues for future research and make recommendations to ensure the continued relevance for energy systems models as important sources of information for policy-making.

Contents

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1. Introduction

Hamming [1] argued that the purpose of computing is insight, not numbers. The development of energy systems models is clearly linked to this need for insight, and the discussion on using them not just for numbers is as old as the models themselves (e.g., [2]). Energy policy as a distinct field began in earnest in the wake of the oil crisis in the seventies, when both industry and policymakers realized the importance of long-term strategic energy planning [3]. In order to formally represent the complexity of interactions and multiple layers of energy across a modern economy, the methods of linear programming in use for large-scale planning since the second world war were used to develop the first energy systems models [4]. The International Energy Agency (IEA) was founded in 1974, and its Energy Technology Systems Analysis Program (ETSAP), intended to develop an energy systems model, was launched in 1976. The International Institute for Applied Systems Analysis (IIASA), founded in 1972 as a center for scientific collaboration between east and west, also began efforts to develop an energy systems model soon after its founding. Both of these models remain important today. Although initially developed for use primarily in the EIA member countries and other large developed economies, these and later models have since been used for analysis in a wide range of contexts ranging from small off-grid systems in developing countries (e.g., [5–7]) to large-scale continent-wide analyses in developed economies (e.g., [8,9]).

The development of energy systems models can also be linked to the rising importance of scenario planning throughout the twentieth century. According to Chermack et al. [10], after being pioneered at the RAND Corporation in the 1940s as "future-now thinking", an increasing focus on scenario planning was again one of the lessons learned from the oil crisis in the seventies. Energy systems models helped analysts understand a sector that had grown increasingly complex, and to develop scenarios about its possible future evolution. But energy systems models did not just allow for the development of scenarios, they also made possible the formalization of scattered knowledge about the complex interactions in the energy sector, and a structured way of thinking about the implications of changes to parts of the system. Most importantly, they allowed policy-makers to explicitly state their views on the direction the energy sector should be steered towards in order to fulfill given policy goals.

Energy is closely linked to a confluence of key problems and opportunities, and in the twenty-first century this is driving a renewed effort to improve the model-based analysis of energy systems. The challenges include security, affordability and resilience of energy supply, as well as environmental concerns, ranging from local air and water pollution to, most importantly, climate change and global sustainability. But there are also opportunities: bringing new technologies to market, building competitive new industries, and providing vast new sustainable energy production to those parts of the world experiencing rapid economic growth.

While energy systems models were initially focused more on energy security and costs, climate change policy has since emerged as a powerful factor driving many studies, with a focus on pathways to achieve the significant reductions in greenhouse gas emissions called for by climate science [11]. Such mitigation scenarios are presented at a global scale for instance in the Global Energy Assessment [8], at a European scale in Schellekens et al. [12], and at a United Kingdom scale in Mackay [13] or Committee On Climate Change [14]. Because some end-use sectors (such as air transport) are difficult to decarbonize using available technology, a common theme in these studies is the need to achieve deep emissions reductions in the electricity sector, and an increase in electricity production to electrify ground transportation as well as heating and cooling. Renewable energy sources, particularly wind and solar power, play a critical role in these low-carbon electricity systems.

In this context, the established methods to model energy systems at a national and international scale are being challenged by several emerging issues: (1) the rise of flexible demand driven by new technologies such as smart meters and distributed generation, (2) the importance of electrification and intermittent supply, with the resulting need for more temporal detail, and (3) the new paradigm of distributed energy and varying renewable resource potential with the resulting need for more spatial detail. None of these issues were of concern for twentieth-century energy systems based primarily on large-scale centralized electricity production and fossil fuels.

For example, questions about the viability of renewable energy are widely debated. While one study may suggest high costs due to intermittency without adequate storage [15], others show that close to 100% of power supply can be met by renewables at feasible costs [16]. A traditional energy systems model is unable to assess such competing claims, yet now that a transition to a renewable energy system is under serious consideration, such questions become important. Scenarios produced by the large energy systems models can produce aggregate cost figures and decarbonization targets, and can thus reiterate and refine the argument for decarbonization, but they cannot answer questions about feasible configurations of a real renewables-based energy system or the possible roadblocks that stand in its way [17]. Thus, recent modeling efforts are attempting to deliver the necessary spatial and temporal resolution that can help answer these questions [18–20].

In this paper we examine how energy systems modeling is changing to address these challenges, and describe both how existing and well-established models are adapting and the types of new models that are emerging. To do so, we identify and discuss four key groups of energy systems models with an important role in underpinning national and international energy policy in Section 3. This highlights four important challenges which are discussed in Section 4, and we examine the efforts taken to address them. Finally, in Section 5, we examine the implications of our review for energy systems modeling and energy policy.

2. Method

We define an "energy system" as the process chain (or a subset of it) from the extraction of primary energy to the use of final energy to supply services and goods (i.e., the definition given in [8]). In other words, an energy system encompasses the

Table 1
Relevant recent reviews of energy systems models and related work.

Publication	Focus	Coverage
Jebaraj and Iniyan [22]	Overview of energy models	252 publications
Bazmi and Zahedi [23]	Overview of power sector optimization models	277 publications
Ventosa et al. [24]	Electricity market modeling	36 models
Foley et al. [56]	Electricity systems models	7 models
Hiremath et al. [25]	Decentralized energy planning	74 models
Sensfuß et al. [27]	Agent-based electricity market models	14 groups of models
Möst and Keles [28]	Stochastic electricity market models	20 models
Connolly et al. [26]	Renewables integration	37 models
Keirstead et al. [29]	Urban energy systems models	219 publications
DeCarolis et al. [30]	Openness of code and data	12 models