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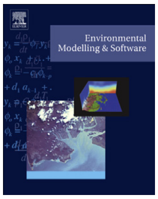

Modelling to generate alternatives with an energy system optimization model

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ABSTRACT

Energy system optimization models (ESOMs) should be used in an interactive way to uncover knife-edge solutions, explore alternative system configurations, and suggest different ways to achieve policy objectives under conditions of deep uncertainty. In this paper, we do so by employing an existing optimization technique called modeling to generate alternatives (MGA), which involves a change in the model structure in order to systematically explore the near-optimal decision space. The MGA capability is incorporated into Tools for Energy Model Optimization and Analysis (Temoa), an open source framework that also includes a technology rich, bottom up ESOM. In this analysis, Temoa is used to explore alternative energy futures in a simplified single region energy system that represents the U.S. electric sector and a portion of the light duty transport sector. Given the dataset limitations, we place greater emphasis on the methodological approach rather than specific results.

Software availability

Name of software: Tools for Energy Model Optimization and Analysis (Temoa)
Developers: Joseph DeCarolis, Sarat Sreepathi, Kevin Hunter, Binghui Li, Suyash Kanungo
Contact: jdecarolis@ncsu.edu
Year First Available: 2012
Hardware required: A personal computer
Software Required: Microsoft Windows, Mac OSX, or Linux operating system. Python, Pyomo, GLPK, Graphviz, Matplotlib
Software Availability: Temoa source code can be accessed through the project website: http://temoaproject.org or directly through Github: https://github.com/TemoaProject/temoa
Cost: All software elements are open source and freely available. Temoa is offered under the GNU General Public License, version 2

1. Introduction

Effective mitigation efforts that avoid or limit dangerous anthropogenic influence with the climate require fundamental changes in the way energy is supplied and demanded globally over the next half century. Because energy infrastructure is expensive and long-lived, a critical challenge is to develop robust planning and investment strategies that account for future uncertainty. Energy system optimization models (ESOMs) represent a key tool that can be used to probe the future decision space under different future scenarios (DeCarolis, 2011; DeCarolis et al., 2012). Such models calculate an intertemporal partial equilibrium on energy markets by optimizing the energy system over time in order to minimize cost or maximize surplus. ESOMs generally have a national to global scope and are optimized over several future decades in order to see the system response to exogenous conditions such as new policy implementation, fuel price shifts, or technology innovation.

Given the expansive physical and temporal system boundaries involved, ESOM-based analyses are faced with conditions of deep uncertainty. Deep uncertainty reflects circumstances in which stakeholders do not know or cannot agree on (1) the choice of models to accurately capture key system interactions, (2) the probability distributions associated with key uncertain parameters, and (3) how to value the desirability of outcomes (Walker et al., 2013). Disagreement over the choice of models reflects structural uncertainty, whereby the relationship among key modeled and unmodeled factors is not fully known (Lempert et al., 2003). All ESOMs are radical simplifications of complex real world

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phenomena and no single model structure can completely capture it (DeCarolis, 2011). In addition to imperfect models, the future values or even distributions of key uncertain parameters used to populate the models are often highly uncertain. Furthermore, it is not clear how best to value future outcomes; for example, through the choice of intertemporal discount rate. The difficulty in applying subjective, valued-based judgement to find socially desirable – or even acceptable – solutions led Rittel and Webber (1973) and Liebman (1976) to characterize ill-defined public planning problems as "wicked."

Given such deep uncertainty about the future, singular model projections have little or no value and can often be misleading. The focus should be on producing model-based insights rather than "precise-looking" projections; the latter can distract and unduly influence the planning process with false precision (Huntington et al., 1982; Peace and Weyant, 2008). A common approach to model-based analysis that avoids the pitfalls associated with forecasting is scenario analysis, where each scenario corresponds to a storyline about how the future may unfold along with a set of exogenous assumptions consistent with the storyline that are used to drive the model. However, as Morgan and Keith (2008) point out, scenarios with detailed storylines can play into cognitive biases by appearing more plausible and probable than they are in reality. Another limitation of scenario analysis is that mutually exclusive and exhaustive subjective probabilities are often not assigned to scenarios, leaving decision makers with a disparate set of energy futures to ponder (Morgan and Keith, 2008; Kann and Weyant, 2000). Finally, traditional scenario analysis can be effective with small groups of clients whose concerns are well known to the scenario developers, but can fail to generate consensus in broad public debates that include divergent interests and values (Bryant and Lempert, 2010).

Kann and Weyant (2000) assert that "ideal results" from uncertainty analysis with ESOMs would include probability-weighted model outputs, optimal decisions that account for imperfect information, a measure of risk or dispersion in the outcome, and the value of information associated with key variables. Such output metrics help inoculate model-based analysis from both false precision and cognitive heuristics. However, an overarching framework is required that enables users to iterate models, produce results, and formulate high-level insights that can be applied within the decision making process. For example, Computer-Assisted Reasoning (CAR) is an approach to decision making under deep uncertainty that enables efficient model iteration and enhanced user ability to interrogate model results through computer visualization and search (Lempert, 2002).

By contrast, most ESOM-based analyses are published with insights summarized by the authors, and do not demonstrate how the models can be used in an iterative approach to generate insights and inform decisions. This paper is a step towards addressing this deficiency. The purpose of this paper is to illustrate how an ESOM can be used to explore alternative energy system designs under conditions of deep uncertainty using an optimization technique known as modeling to generate alternatives (MGA). By generating a sequence of near optimal solutions that are very different in decision space, MGA can produce alternatives for further evaluation by the analyst. While DeCarolis (2011) discussed the utility of MGA in an energy systems context, this paper represents the first published application of MGA to an ESOM.

To conduct the analysis, we use Tools for Energy Model Optimization and Analysis (Temoa), an open source, bottom-up energy system model (Hunter et al., 2013) along with a simplified input dataset constructed for this analysis. The dataset is focused on the U.S. electric and light duty transportation sectors, and can capture sector interactions through the deployment of plugin electric vehicles (PEVs) that require electricity for charging. Given the limited dataset used for this analysis, we place greater emphasis on the methodological approach rather than specific results. Our intention is to illustrate how an iterative approach to modeling using MGA can lead to insights that might not be realized through conventional scenario analysis.

2. An electric and transportation sector case study

Together, the U.S electric and light duty transportation systems account for approximately 60% of national CO_2 emissions (U.S. EIA, 2015). Following the OPEC oil embargo, which led to the retirement of nearly all U.S. oil-fired power plants, the electric and transportation sectors have evolved more or less independently, with petroleum representing 0.7% of U.S. electricity supply, and 91% of light duty transportation (U.S. EIA, 2015). However, PEVs – including both plugin hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) – have been rapidly deployed over the last 5 years and may lead to a significant coupling of the electric and transport sectors in the future.

Given the threat of climate change, both sectors represent key targets for CO_2 emissions reductions. While there have been several Congressional bills that mandate a federal cap-and-trade program for greenhouses gases, none have been implemented (U.S. EPA, 2015). This analysis is focused on using MGA to explore different technology pathways to achieve a low carbon energy future. Prior to applying MGA, we ran three scenarios for comparative purposes: a base case scenario with no policy as well as moderate and aggressive climate policy scenarios. The moderate climate scenario includes a cap on CO_2 emissions that begins in 2025 and decreases linearly to 40% below 2015 values by 2050. The aggressive climate scenario also begins in 2025, but requires an 80% decrease below 2015 levels by 2050. These scenarios serve as a useful benchmark for the MGA runs. We then apply MGA to the moderate climate policy scenario in order to search for alternative cost- and emissions-constrained solutions. Applying MGA in this way allows us to efficiently and systemically explore the model decision space. The resultant solutions can be used to characterize the tradeoff between system cost and emissions, and to identify alternative technology deployments that may be preferable to the original ones. While some MGA solutions may have higher cost, they may have appealing attributes to the planner if they capture unmodeled issues.

2.1. Model description

We have developed Tools for Energy Model Optimization and Analysis (Temoa), a bottom-up, technology rich ESOM embedded within a larger framework for analysis. Temoa includes two key features that make it unique within the energy modeling community: (1) all source code and data are publicly archived online using a modern revision control system (TemoaProject, 2015), and (2) the model was designed to operate in a high performance computing environment in order to facilitate rigorous uncertainty analysis (Hunter et al., 2013). Temoa utilizes linear programming techniques to minimize the system-wide cost of energy supply by optimizing the deployment and utilization of energy technologies over a user-specified time horizon to meet end-use demands. The model is subject to a number of constraints that ensure proper system performance, including conservation of energy at the process and system-wide levels. In addition, users can impose additional constraints such as emissions bounds, minimum or maximum capacity and activity constraints, and growth rate limits. Model outputs by future time period include the optimal installed technology capacity and utilization, marginal energy prices, and

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