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Model uncertainty and energy technology policy: The example of induced technical change ☆

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ABSTRACT

Numerical modeling based on economic principles has become the dominant analytical tool in U.S. energy policy. Energy models are now used extensively by public agencies, private entities, and academic researchers, and in recent years have also formed the core of "integrated assessment" models used to analyze the relationships among the energy system, the economy, and the global climate. However, fundamental uncertainties are intrinsic in what has become the typical circumstance of multiple models embodying different representations of the energy-economy, and producing different policy-relevant outputs that model users are compelled to interpret as equally plausible and/or valid. Because the policy implications of these outputs can diverge substantially, policy-makers are confronted with a significant degree of model-based uncertainty and little or no guidance as to how it should be addressed.

This problem of "model uncertainty" has recently been the focus of work in macroeconomics, where scholars have studied the problem of how a decision-maker should proceed in the face of uncertainty regarding the correct model of an economic system that is the object of policy. A unifying theme in this work is the identification of decision-rules that are *robust* to such uncertainty. This paper describes an application to energy modeling of the macroeconomists' insights and methods related to model uncertainty and robust analysis, focusing on the important example of model representations of technical change. Using a well-known model by Goulder and Mathai, we treat contrasting assumptions on technical change – and their implications for CO_2 emissions abatement policy – as a phenomenon of model uncertainty. We apply a non-Bayesian decision rule – so-called "min–max regret" – to this problem and computationally solve the model under the min–max regret criterion, yielding a policy – an emissions abatement path – that reflects a form of robustness to the model uncertainty.

1. Introduction

Over the past four decades, numerical modeling based upon economic principles has become the dominant analytical tool in U. S. energy policy. Models of the energy system or sub-systems, of the national economy with emphasis on energy sectors, and combinations of these two types have both proliferated in number and increased in complexity and detail. They are now used by regulatory agencies, university researchers, private companies and non-profit organizations. Moreover, in recent years numerical energy-economic models have formed the core of "integrated assessment" models that represent the relationships among the economy, the energy system, and the global climate.[1]

Their usefulness notwithstanding, however, the widespread application of numerical energy-economic models in policy analysis poses certain challenges for decision-makers. Among these is the situation of multiple, "co-existing" models embodying what amount to competing representations of the energy-economy, and producing different policy-relevant outputs. While structured multi-model scenario analyses are a well-established methodology in the energy modeling community, this community does not provide formal or quantitative model rankings. As a consequence, results from a now

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[1] We will use the term "energy model" to refer to each of these types, i.e., numerical economic equilibrium (partial or general) or optimization models, with or without linked environmental components.

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sizable group of models must often be interpreted by users as equally plausible and/or valid. Given that the policy implications of these results can diverge substantially even in structured comparisons, this circumstance confronts policy-makers with a significant degree of uncertainty and little or no guidance as to how it should be addressed.

The aim of this paper is to demonstrate how this type of fundamental model uncertainty can be represented and analyzed in the context of one of this era's most important energy policy problems: determining optimal strategies for reducing carbon dioxide (CO_2) emissions from the energy sector that contribute to global climate change. We focus on a particularly significant dimension of model uncertainty: the representation of technological change, in this case of the type that lowers the cost of CO_2 emissions abatement. Our approach is to apply a non-Bayesian decision rule and solution concept to a model that incorporates the key mechanism while being sufficiently simple to clearly exemplify the analytical approach and provide insight into the results.

The importance of fundamental energy and integrated assessment model uncertainty, and the practical implications of not addressing it, were noted by Fischer and Morgenstern [1] in their study of the divergence of model-based estimates of the potential costs to the U.S. economy of the Kyoto carbon emissions reduction agreement. These estimates varied by a factor of five. As these authors pointed out, "…this variability in cost estimates undermines support for mandatory policies to curb emissions, as policy makers are generally reluctant to adopt a major program without an understanding of its true costs."

Not all multi-model, policy-relevant outputs in energy analysis display this level of variation. Nonetheless, inter-model differences large enough to be policy relevant are the norm rather than the exception. Decision-makers may reasonably infer that such "ensemble uncertainty" accurately reflects the present-day limits of our ability to predict the consequences of large-scale energy or environmental policy. If so, then the problem of rationally using multi-model policy outputs should be addressed in its own right.

In macroeconomics, this problem of model uncertainty has been the focus of work by Hansen and Sargent [2–4] and Brock et al. [5–7]. These scholars have studied the problem of how a decision-maker should proceed in the face of uncertainty regarding the correct model of an economic system that is the object of policy. A unifying theme in this work is identification of decision-rules that are "robust" to such uncertainty. While there are different technical definitions of this concept, colloquially it refers to decisions, or policies, that will yield acceptable although not necessarily optimal outcomes regardless of which model within a certain set is "true."

This paper is based on the observation that, for the reasons described above, this form of uncertainty characterizes the present state of energy modeling, and that the macroeconomists' insights and methods are applicable and can yield important insights. Our focus on technical change is motivated by the long-standing recognition by both experts and non-specialists that assumptions regarding the determinants and dynamics of technical change are a primary driver of model-based projections of the feasibility, costs, and outcomes of long-run energy policies – especially those aimed at reducing CO_2 emissions from the energy sector. Among current energy models, quite different sets of such assumptions are maintained – i.e., in different models – and they have divergent policy implications. Broadly speaking, there are two paradigms for representing technical change. In the "autonomous" representation, which can be traced back to Solow's work on aggregate productivity in the 1950s, technical change dynamics are determined exogenously to the market economy [8]. Moreover, while these dynamics may be influenced by government policy, the mechanisms of this influence are left unspecified. By contrast, "endogenous" or "induced" technical change refers to theories, and their numerical implementations, in which technical change is explicitly treated, albeit in simplified form, as an outcome of choices by economic agents acting within markets; in certain examples, this paradigm also allows for the representation of government influences such as R&D funding.

As might be expected, these two approaches have quite different theoretical and quantitative implications for energy policy. Yet – even after decades of basic and applied research – there is an absence of consensus within the energy modeling community regarding the appropriate paradigm for representing technical change, reflected in a continuing divergence among different numerical models. The departure point for this paper is the observation that this state-of-affairs is best characterized as one of fundamental model uncertainty, and as such can in principle be addressed by bringing to bear the appropriate concepts and tools developed in macroeconomics.

As noted above, the modeling community does not quantitatively rank or assign weightings to sets of models. This state-of-affairs can be thus be viewed as one of "Knightian uncertainty," which refers to uncertainty that cannot be readily described by probabilities. This perspective also underlies the pioneering contribution of McInerney et al. (e.g., [9]) to the analysis of robust decision-making in integrated assessment modeling, which is one of our inspirations.

In this paper, we follow the modeling paradigm reflected in Brock et al. [5–7] and in Hansen and Sargent [2–4], which is to employ models that are sufficiently simple that they can be thoroughly analyzed and can facilitate understanding of the basic concepts. This perspective also reflects the view that, in the words of a prominent energy modeler, "the purpose of energy modeling is insight, not numbers" [10], which became a widely-accepted precept in the modeling community (e.g., [11]).

The paper is organized as follows. In the next section, we sketch the history and key concepts of model uncertainty and validity in the energy analysis and policy field. We then further discuss the representation of technological change in energy models and its policy implications. Against this background, we present a model of Goulder and Mathai [12] that, while relatively simple, nevertheless allows for analysis of several fundamental issues associated with differing technical change assumptions and how they affect model-derived policy conclusions. We briefly discuss technical aspects of the model and the key conclusions reached by Goulder and Mathai. Next, we consider the Goulder–Mathai framework from the perspective of model uncertainty, and, following Brock et al. [6], introduce two decision rules – min–max and min–max regret – that are applicable in the context of this form of uncertainty. We briefly review previous and recent applications of min–max regret in energy and integrated assessment modeling. We then describe a computational version of the model and discuss its solution under the min–max regret criterion, comparing this to solutions based on expected cost minimization. The paper ends with a summary and concluding remarks.

2. Validity and uncertainty in energy modeling

As noted in the introduction, the concept of model uncertainty entails multiple models of a given system being assigned equal weight, credibility, or validity, whether explicitly or – as in the case of energy modeling – implicitly. The prevalence of this form of uncertainty raises the question of why some form of validation procedure cannot be applied to compare and ideally rank models in terms of their likelihood. The answer to this question involves the history and development path of this area of modeling.