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Modeling intermittent renewable electricity technologies in general equilibrium models

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ABSTRACT

Economy-wide top-down (TD) equilibrium models have traditionally proved to be valuable tools for assessing energy and climate policies. New modeling challenges brought about by intermittent renewable energy sources, however, require a careful review of existing tools. This paper presents an overview of TD modeling approaches for incorporating renewable energy and describes in detail one approach, using the MIT USREP model, to identify critical parameters and assumptions underlying the general equilibrium formulation. We then quantitatively assess its performance regarding the ability to correctly estimate the participation of intermittent renewables in the electricity sector as predicted by a bottom-up electricity sector model, which is designed to analyze the expansion and operation of a system with a large penetration of wind and which is integrated within an economy-wide general equilibrium framework. We find that a properly specified TD approach to modeling intermittent renewable energy is capable of roughly replicating the results from the benchmark model. We argue, however, that the general equilibrium approach is highly sensitive to key parameters which are a priori typically unknown or at least highly uncertain. Our analysis suggests that traditional TD simulation tools have to be enhanced to avoid potentially misrepresenting the implications of future climate policies where presumably renewable energy could participate at large scale. Detailed power system models that capture system reliability and adequacy constraints are needed to properly assess the potential of renewable energy.

1. Introduction

Macro-economic "top-down" (TD) equilibrium models are widely used analytical tools to investigate the impacts of energy and climate policy in terms of technological pathways, environmental impacts (i.e., greenhouse gas emission reduction potentials) and their social costs and benefits.[1] While these models are used to derive policy recommendations, the "current generation" of TD approaches seems to lack the required detail and model features to adequately represent intermittent renewable energy sources.[2] Intermittent wind and solar energy resources require detailed temporal and spatial analyses, as well as, the study of operational implications such as the need for additional reserve requirements, storage and transmission capacity. General

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[1] See, for example, the TD equilibrium models used in inter-model comparison activities such as the Stanford Energy Modeling Forum (e.g., Fawcett et al., 2014 and the work to expand the GTAP dataset for energy and climate policy analysis Nijkamp et al., 2005).

[2] Traditional modeling approaches, both in the domains of economy-wide TD equilibrium as well as engineering-type "bottom-up" (BU) models, have proven to generate adequate and reliable model-based approximations of real-world energy (and electricity) production for systems characterized predominantly by fossil-based energy sources and technologies. TD models typically represent energy production technologies through highly aggregated (often smooth) production functions. While the strength of these models is to include energy supply and demand decisions within an internally consistent macro-economic framework, they typically lack the technological, spatial and temporal resolution. BU models, on the other hand, typically feature a highly resolved and technology-rich representation of energy (supply and demand) technologies but fail to include interactions with the broader economic system due to their partial equilibrium nature. Importantly, BU models are hence not capable of incorporating macro-economic determinants of energy demand and supply and they cannot assess policies in terms of their social cost (e.g., GDP or consumption impacts). See, for example, Hourcade et al. (2006) for a more in-depth overview and discussion of both modeling paradigms.

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equilibrium models do not have this level of detail in their formulation. The substantial and rapid increase of renewable intermittent energy sources over the past two decades, and their expected significant role in future energy systems, represent a major challenge for the further advancement of simulation models that inform climate policy design.

The objective of this paper is two-fold. First, it presents an overview of TD modeling approaches for incorporating renewable energy and describes in detail one approach to identify critical parameters and assumptions underlying the general equilibrium formulation.

Second, by quantitatively comparing a TD approach against a benchmark model that adopts an explicitly structural engineering-type "bottom-up" (BU) methodology, our analysis offers insights into how important the pitfalls of the TD approach can be. To perform our computational experiments, we use a TD general equilibrium model, both as a stand-alone model and as the component of a proposed integrated modeling framework, to look at the evolution of the energy mix with increasing penetration of wind.

To this end, we first develop a detailed BU model of the electricity sector that has been specifically designed to analyze the capacity expansion and operation of a system with large penetration of wind (Tapia-Ahumada and Pérez-Arriaga, under preparation). We put emphasis on a sufficient temporal resolution — i.e., an hourly characterization — of both wind resources and electricity demand to better capture the impacts of intermittency on the system's generation mix and operation in the long term.[3] In a second step, we then fully integrate this BU model with an economy-wide general equilibrium framework to obtain a benchmark model against which we can evaluate the performance of a TD approach to modeling intermittent renewable energy.[4] The TD component of our integrated model is based on the MIT U.S. Regional Energy Policy (USREP) model, a recursive-dynamic, multi-sector, multi-region, numerical general equilibrium model designed to analyze climate and energy policy in the United States (Rausch et al. 2010, 2011).

Our analysis is germane to the literature on integrating TD and BU models for carbon policy assessment (see Hourcade et al. (2006) for an overview). Following the seminal methodological contribution of Boehringer and Rutherford (2009) on "hard-linking" TD and BU models, an important feature of our modeling approach is that the optimization of the electric sector — with modeling details to represent intermittent generation from wind — is fully consistent with the equilibrium response of the economy, including endogenously determined electricity demand and prices for fuels, goods and intermediate inputs to production. There are only a few studies that have fully integrated a TD general equilibrium model with a BU electricity sector model in an applied large-scale setting. Sugandha et al. (2009) employ a hybrid TD–BU approach, but their framework has considerably less detail with respect to modeling important features of renewable electricity generation. Rausch and Mowers (2014) link an economy-wide general equilibrium model to NREL's ReEDS (Regional Energy Deployment System) model (Short et al., 2011), a linear programming model that simulates the least-cost expansion of electricity generation capacity and transmission, with detailed treatment of renewable electric options. They do not, however, investigate the suitability and performance of alternative modeling approaches to intermittent renewables.[5]

[3] It is becoming widely accepted that the presence of large volumes of intermittent renewable generation (wind and solar PV, typically) profoundly modifies the operation and the optimal generation mix of power systems, in ways that cannot be predicted in the absence of suitable detailed models (Pérez-Arriaga and Batlle, 2012).

[4] Note that we do not claim that the integrated modeling approach which serves as a benchmark for the evaluation of the TD model truthfully portrays reality.

[5] Hybrid modeling work in analyzing other sectors of the economy has also been attempted, see for example Karplus et al., 2013.

On a more general level, the goal of the analysis is to examine the implications of different structural modeling choices within general equilibrium models with respect to representing intermittent renewables. Thus, it also relates to the literature on role of functional forms in CGE models, and the limitations of representing some production processes with CES functions (McKitrick, 1998). Given the widespread use and increasing importance of numerical general equilibrium models to assess the impact of and derive recommendations for energy and climate policies, we believe that it is important to shed light on the conceptual foundations that underlie the representation of intermittent renewables. While it should be clear that the results presented here are based on comparing a BU approach with one particular TD approach, we nevertheless believe that the present analysis contributes to understanding the usefulness and limitations of employing numerical simulation models for economic policy analysis of economy-energy systems with significant levels of energy production from highly intermittent renewable resources.

The paper is organized as follows. Section 2 provides a brief overview of modeling approaches to represent intermittent renewables in TD general equilibrium models, and describes the USREP model renewable formulation as an example. Section 3 provides a description of the BU model for the electricity sector and details the methodology adopted to integrate the TD and BU modeling approaches. Section 4 presents the results, both from the TD-only model and the integrated model, and compares the performance of the TD-only approach through a sensitivity analysis. Section 5 concludes.

2. Intermittent renewable energy in TD general equilibrium approaches

2.1. Overview of alternative TD approaches

It is acknowledged in the literature (see, for example, Labandeira et al. (2009)) — and seems to be common knowledge in the TD modeling community — that the electricity sector is difficult to represent using TD models, in particular when disruptive renewable energy technologies are concerned. Recognizing the need to incorporate new low-carbon technologies, different techniques have been used in TD computable general equilibrium (CGE) models to portray technological change in the power sector, in particular with respect to low-carbon technologies. There are, however, several issues that arise in TD CGE models that constitute challenges or even limitations for appropriately representing energy production from intermittent renewable energy sources.

First, TD approaches typically do not explicitly model the electricity dispatch but rather use historical data to benchmark the initial conditions of the economy and stylized production functions to assess changes in generation driven by price variations in fuels and other production inputs.

Second, TD CGE models rely on constant elasticity of substitution (CES) production functions to depict production activities. Key modeling assumptions are specifying whether or not electricity is a homogeneous good (i.e., electricity supplies generated from different technologies are perfect or imperfect substitutes) and how different generation technologies trade off against each other. This typically entails choosing a specific nesting structure for CES functions among conventional fossil fuel-based generation, nuclear, hydro and new advanced technologies. Also, modelers specify the substitution structure between inputs to production within each of the different technologies. The unique attributes of the non-extant low-carbon technologies need to be captured through the parameters of the CES function.

Third, as substitution and complementarity patterns of non-dispatchable technologies are not known a priori, multiple ad-hoc assumptions are needed in TD models to approximate the costs of maintaining system reliability in power systems. This includes, for example, approximating in a reduced manner back-up generation and other