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General equilibrium, electricity generation technologies and the cost of carbon abatement: A structural sensitivity analysis

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ABSTRACT

Electricity generation is a major contributor to carbon dioxide emissions, and abatement in this sector is a key determinant of economy-wide regulation costs. The complexity of an integrated representation of economic and electricity systems makes simplifying assumptions appealing, but there is no evidence in the literature on how important the pitfalls may be. The aim of this paper is to provide such evidence, drawing on numerical simulations from a suite of partial and general equilibrium models that share common technological features and are calibrated to the same benchmark data. We report two basic findings. First, general equilibrium inter-sectoral effects of an economy-wide carbon policy are large. It follows that assessing abatement potentials and price changes in the electricity sector with a partial equilibrium Marshallian demand can only provide a crude approximation of the complex demand-side interactions. Second, we provide evidence that widely used top-down representations of electricity technologies produce fuel substitution patterns that are inconsistent with bottom-up cost data. This supports the view that the parametrization of substitution possibilities with highly aggregated production functions is difficult to validate empirically. The overall picture that emerges is one of large quantitative and even qualitative differences, highlighting the role of key structural assumptions in the interpretation of climate policy projections.

1. Introduction

Electricity generation is a significant contributor to carbon dioxide (CO_2) emissions, and potentially has an important role in abatement efforts. The current research paradigm for ex-ante carbon policy assessment mainly involves two classes of models (Hourcade et al., 2006). On the one hand, technology-rich 'bottom-up' models provide a detailed representation of generation technologies and the overall electricity system. By construction, these models are partial equilibrium, and typically include no or very limited interactions with the macroeconomic system. On the other hand, economy-wide 'top-down' models represent sectoral economic activities and electricity generation technologies through aggregate production functions. While these models are designed to incorporate general equilibrium effects, the use of smooth functions is not well suited to capture the temporal and discrete nature of technology choice.[1]

The integration of bottom-up technology representation and economy-wide interactions into 'hybrid' models is the subject of a large literature. For example, reference is often made to 'soft-linked' models, where the combination of the two models either fail to achieve overall consistency (Drouet et al., 2005; Hofman and Jorgenson, 1976; Hogan and Weyant, 1982; Jacoby and Schäfer, 2006), or complement one type of model with a 'reduced-form' representation of the other, thereby lacking structural explicitness (Bosetti et al., 2006; Manne et al., 2006; Messner and Schrattenholzer, 2000; Strachan and Kannan, 2008). An alternative and more recent approach, referenced to as 'hard-linked', is to directly embed a set of discrete generation technologies into a top-down model (Böhringer,

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[1] In principle, production technologies can accommodate any microconsistent elasticity structure (Perroni and Rutherford, 1995), including time or regional differentiation. In practice however, data limitations make empirical validation of the parameters driving substitution possibilities difficult. In addition, we note that top-down representations of the electricity sector violate basic energy conservation principles away from the benchmark calibration point (see Sue Wing, 2008).

1998; Böhringer and Rutherford, 2008; Sue Wing, 2006). Under this approach, however, the representation of technological detail significantly increases the dimensionality of the model, thus severely constraining large-scale applications. Finally, a decomposition algorithm by Böhringer and Rutherford (2009) employs an iterative solution procedure to solve top-down and bottom-up model components consistently. This approach is essentially a soft-linked approach, but overcomes issues of dimensionality and consistency, and has been employed in the context of U.S. climate policy in Tuladhar et al. (2009).

Despite the large literature documenting efforts to reconcile top-down and bottom-up modeling paradigms, and a tendency towards ever more detailed models, there is no quantitative evidence on the pitfalls of different simplifying assumptions. The objective of this paper is to explore the implications of different structural assumptions concerning electricity supply and demand for the assessment of economy-wide carbon policies, thereby going beyond the usual parametric sensitivity analysis. As it is impossible to derive general qualitative propositions for such an issue, we employ a suite of numerical partial equilibrium (PE) and general equilibrium (GE) models that share common technological features and are calibrated to the same benchmark equilibrium. Our benchmark model consistently integrates a bottom-up technology representation of the electricity sector within a general equilibrium setting based on the decomposition method by Böhringer and Rutherford (2009). The economy-wide component is based on a static version of the MIT U.S. Regional Energy Policy (USREP) model, a multi-sector multi-region numerical general equilibrium model designed to analyze climate and energy policy in the U.S. (Rausch et al., 2010a, b). The electricity sector is represented by a multi-region model based on a comprehensive database of electric generators from the Energy Information Administration (EIA, 2007a), and features detailed plant-level information on the generation costs and capacity, fuel switching capabilities, and season-specific load profiles.[2] We assume imperfect factor mobility in the economy and fixed capacity of electricity generation technologies, so that the response to a policy shock is of short- to mid-term horizon.[3]

Our results are as follows. First, we find that general equilibrium income and substitution effects induced by an economy-wide carbon policy are of first-order importance to evaluate the response of the electricity sector. Changes in electricity prices and abatement potentials are largely driven by both the slope and the location of the demand schedule. Following the suggestion in an early and influential article by Hogan and Manne (1977), we explore whether price elasticities of electricity demand simulated from a GE model can approximate general equilibrium effects in a partial equilibrium setting. We report evidence that such a modeling strategy is not sufficient to capture the underlying economy-wide changes, as represented in an integrated model. For example, we calculate that general equilibrium effects mitigate electricity price increases by up to 20% in the case of even moderate carbon prices of around $25 per metric ton of CO_2.

Our second set of results relates to the representation of electricity generation technologies in general equilibrium top-down models by means of aggregate substitution elasticities. We implement two top-down technology specifications based on nested constant elasticity of substitution (CES) functions (Bovenberg and Goulder, 1996; Paltsev et al., 2009) which are widely adopted for ex-ante climate policy assessment. Our analysis suggests that these representations produce fuel substitution patterns that are inconsistent with bottom-up cost data, mainly because top-down representation of electricity markets implies that the price of electricity reflects the total carbon content of generation. This contrasts with real markets (and the bottom-up approach), where the carbon price is reflected in the electricity price through the carbon content of the marginal producer at a given point in time (Stavins, 2008). In our setup, structural assumptions about the technology representation translate into country-wide welfare costs that differ by as much as 60% for an emissions reduction target of 20%. We further observe large heterogeneity in regional discrepancies, mostly driven by the benchmark shares of carbon-intensive technologies.

On a more general level, our findings demonstrate the significance of structural assumptions embedded in top-down and bottom-up modeling approaches for the assessment of carbon and energy policies. While both approaches rely on the assumption of fully rational behavior, the structural setting makes empirical validation of the behavioral response in each modeling approach is difficult. Any analysis inevitably involves simplifications from a more complex reality, but we usually do not know how misleading assumptions might be when drawing policy conclusions from quantitative analysis. By providing evidence on the magnitude of structural assumptions, albeit in the context of models also using a set of restrictive assumptions, we believe that our investigation contributes to an improved understanding of the theoretical and methodological basis for carbon policy assessment with large-scale simulation models.

The remainder of this paper proceeds as follows. Section 2 provides an overview of the economy-wide model, describes the top-down and bottom-up representations of the electric power sector, and presents the integrated model. Section 3 investigates the importance of general equilibrium factors and the implications of top-down versus bottom-up technology representation for carbon policy assessment. Section 4 concludes.

2. Analytical framework

This section presents the different components of our numerical modeling framework. We first provide an overview of the economy-wide model, and then describe the top-down and bottom-up models of electricity generation. The final subsection describes the integrated framework.[4]

2.1. The MIT U.S. Regional Energy Policy model

The economy-wide model is based on a static version of the MIT U.S. Regional Energy Policy (USREP) model (Rausch et al. 2010a, b), a multi-region and multi-sector general equilibrium model for the U.S. economy. USREP is designed to assess the impacts of energy and climate policies on regions, sectors and industries, and different household income classes. It is built on state-level data for the year 2006 that combines economic Social Accounting Matrix (SAM) data from the IMPLAN data set (Minnesota IMPLAN Group, 2008) with physical energy and price data from the State Energy Data System (EIA, 2009b). As a detailed description of the model is provided in Rausch et al. (2010a), including a full algebraic characterization of equilibrium conditions, we here only give a brief overview of key model features.

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[2] Our database has a high resolution at the operator level, which allows us to incorporate realistic assumptions about the market structure in the electricity sector. To facilitate the comparison of top-down and bottom-up approaches, the present analysis maintains the usual assumption of marginal cost-pricing and perfect competition in the electricity sector. In a companion paper, we incorporate cost-of-service regulation at the operator level and non-competitive (Cournot) pricing behavior by large operators to investigate the role of non-competitive behavior for the design of climate policies.

[3] We refrain from using ad-hoc vintaging assumptions to restrict capital mobility in the economy-wide model, or specifying some capacity expansion elasticities in the electricity sector model, for example allowing expansion of renewable technologies under a carbon price. Our qualitative conclusions are not affected by these assumptions. Issues related to the structural representation of electricity demand and supply still apply in a dynamic setting, but forward-looking responses to carbon policy shocks is beyond the scope of our comparison exercise.

[4] All models are written in the GAMS software system and solved with the PATH solver (Dirkse and Ferris, 1995) for mixed complementarity problems (MCP).