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FROM MY PERSPECTIVE

Representing spatial technology diffusion in an energy system optimization model

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ABSTRACT

In this study, we develop a series of technology diffusion formulations that endogenously represent empirically observed spatial diffusion patterns. We implement these formulations in the energy system optimization model MESSAGE to assess their implications for the market penetration of low-carbon electricity generation technologies. In our formulations, capacity growth is constrained by a technology's knowledge stock, which is an accumulating and depreciating account of prior capacity additions. Diffusion from an innovative core to less technologically adept regions occurs through knowledge spillover effects (international spillover effect). Within a cluster of closely related technologies, knowledge gained through deployment of one technology spills over to other technologies in the cluster (technology spillover effect). Parameters are estimated using historical data on the expansion of extant electricity technologies. Based on our results, if diffusion in developing regions relies heavily on earlier deployment in advanced regions, projections for certain technologies (e.g., bioenergy with carbon capture and storage) should be tempered. Our model illustrates that it can be globally optimal when innovative economies deploy some low-carbon technologies more than is locally optimal as it helps to accelerate diffusion (and learning effects) elsewhere. More generally, we demonstrate that by implementing a more empirically consistent diffusion formulation in an energy system optimization model, the traditionally crude—or nonexistent—representation of technology diffusion in energy-climate policy models can be significantly improved. This methodological improvement has important implications for the market adoption of low-carbon technologies.

1. Introduction

1.1. Integrated assessment models

The preponderance of scientific evidence indicates that continued emission of greenhouse gases (GHGs) will cause further increases in global temperatures, likely resulting in severe and irreversible negative impacts (IPCC, 2014). Growing concern about climate change has led governing bodies at all levels to implement or at least to consider policies to reduce emissions. Example policy instruments include emissions pricing, emissions trading schemes with quantity limits, renewable portfolio standards, and feed-in tariffs. A key question is how do these policies affect the market deployment of different technology options—and hence GHG emissions—and how do policies in one jurisdiction (e.g., a country) potentially affect the market uptake of new technologies in other jurisdictions. These research questions are traditionally explored via formal models and in assessing alternative future policy and technology scenarios.

To evaluate the economic and environmental consequences of potential climate policies, researchers have developed a host

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of integrated assessment models (IAMs) that combine elements of the linked energy, economic, and environmental systems (including land-use) in a unified inter-disciplinary framework (Wilkerson et al., 2015). The primary intention of IAMs is not to provide exact forecasts, but rather to suggest plausible future scenarios based on model assumptions about population growth, economic growth, technological change, and other factors (Moss et al., 2010). These models feature a diverse set of methodologies, and several attempts have been made to classify them into distinct categories (Schneider and Lane, 2005; Schneider, 1997; Stanton et al., 2009). Although these taxonomies differ, it is fairly straightforward to identify several broad classes of IAMs that differ in terms of level of integration, detail represented, and the applied solution method, each with distinct strengths and weaknesses that make it well suited for certain applications and research questions, but not others.

Cost–benefit IAMs contain reduced-form representations of the climate system and represent feedbacks from the climate to the economy. By placing an economic value on damages caused by GHG emissions, these models weigh the benefits of reducing emissions against the costs it would entail. Cost–benefit IAMs are designed to address the question of the best climate policy, such as an optimal carbon price schedule. They are typically simple and transparent in structure, but feature little (if any) regional or technological detail. Cost–benefit IAMs include the DICE, FUND, and PAGE models employed by the Interagency Working Group on Social Cost of Carbon to inform U.S. government policy (Interagency Working Group on Social Cost of Carbon, 2010).

General equilibrium IAMs include detailed representations of the economy, often disaggregated into different regions and sectors. Firms maximize profit, consumers maximize utility, and the model solves for the equilibrium prices that equilibrate supply and demand across all markets. Most general equilibrium models rely on a recursive-dynamic solution approach rather than an inter-temporal optimization scheme. General equilibrium IAMs are well suited for evaluating the economic impact of a policy, particularly when feedbacks between economic sectors could be significant. Partial equilibrium IAMs follow a similar modeling paradigm but solve for equilibrium prices only within certain markets of interest such as energy commodities or electricity generation. The EPPA model (Paltsev et al., 2005) is a prototypical general equilibrium IAM, while GCAM (Kim et al., 2006) is representative of partial equilibrium models.

IAMs based on energy system optimization models take the perspective of an energy system planner whose problem is to select the set of energy technology investments that minimizes total cost subject to a variety of constraints. These constraints reflect the need to meet energy end-use demands, the finite availability of energy resources, limits on technology diffusion rates, and possibly caps on GHG emission quantities. Energy system optimization IAMs often feature many technologies represented in great parametric detail, including fixed and variable costs, conversion efficiencies, capacity factors, and lifetimes. As a result, these models are frequently applied to assess the prospects for, or value of, individual energy technologies under a range of assumptions. Examples of this model class include TIAM (Loulou and Labriet, 2007; Loulou, 2007), based on the MARKAL/TIMES energy system model (Loulou et al., 2004), and MESSAGE (Riahi et al., 2007), the modeling framework utilized in this study.

1.2. Energy technology assessments

Technology-detailed IAMs have been used to conduct a wide range of energy technology assessments. The goals of such assessments vary, but common objectives are to develop scenarios for the adoption of a technology, determine its economic value, evaluate its environmental impact, and investigate how these results change under different assumptions about end-use demands, technological change, climate policy, and other parameters. In this subsection, we briefly review some recent, multi-model energy technology assessments to demonstrate how IAMs are applied in this context and highlight the challenges that arise.

The Stanford Energy Modeling Forum Study 27 (EMF 27) examined the role of technology for achieving climate policy objectives by comparing results from 18 IAMs (Weyant and Kriegler, 2014). Scenarios varied in their assumptions about technology availability, placing different constraints on technologies like nuclear, bioenergy, solar, wind, and carbon capture and storage (CCS). For each technology scenario, the models produce a range of global mitigation costs required to meet 450 ppm and 550 ppm atmospheric carbon dioxide equivalent (CO_2e) concentration targets. Comparing the cost ranges across technology scenarios establishes the value of individual technologies, or groups of technologies, for meeting the climate policy objective. The study results suggest that bioenergy and CCS are particularly valuable mitigation technologies due to their potential applications beyond the electricity generation sector and their combined ability to produce negative emissions (Kriegler et al., 2014).

Similar to EMF 27, the European Union's Adaptation and Mitigation Strategies—Supporting European Climate Policy (ADAM) project employed a collection of IAMs to assess the value and competitive potential of certain energy technologies for achieving low atmospheric GHG concentration targets (Edenhofer et al., 2015). Across the participating models, the ranking of individual technology options by importance was fairly robust (Edenhofer et al., 2010). Renewables and CCS are the most valuable technologies, and biomass is also important if its availability is high and the climate target is ambitious. Nuclear was found to be of lesser importance. Many energy transition pathways are possible to achieve modest climate policy goals, but stringent targets imply heavy reliance on particular technologies and a loss of flexibility to substitute technologies within the energy mix. The project results suggest that understanding limits to the availability of technologies with potentially adverse side effects, such as bioenergy and CCS, should be a high priority of future research.

The Report on Energy and Climate Policy in Europe (RECIPE) project analyzed the economic and technical dimensions of decarbonization using three IAMs and a variety of policy and technology scenarios (Edenhofer et al., 2012). Echoing the results of the ADAM studies, the RECIPE project findings indicate that CCS and renewables are the most valuable low-carbon technology options due to their flexibility and broad applicability (Tavoni et al., 2011). Nuclear is again found to have comparatively lesser importance. Prospects for renewables are highly sensitive to assumptions about technological

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