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Modeling technical change in energy system analysis: analyzing the introduction of learning-by-doing in bottom-up energy models ☆

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Abstract

The main objective of this paper is to provide an overview and a critical analysis of the recent literature on incorporating induced technical change in energy systems models. Special emphasis is put on surveying recent studies aimed at integrating learning-by-doing into bottom-up energy systems models through so-called learning curves, and on analyzing the relevance of learning curve analysis for understanding the process of innovation and technology diffusion in the energy sector. The survey indicates that this model work represents a major advance in energy research, and embeds important policy implications, not the least concerning the cost and the timing of environmental policies (including carbon emission constraints). However, bottom-up energy models with endogenous learning are also limited in their characterization of technology diffusion and innovation. While they provide a detailed account of technical options—which is absent in many top-down models—they also lack important aspects of diffusion behavior that are captured in top-down representations. For instance, they often fail in capturing strategic technology diffusion behavior in the energy sector as well as the energy sector's endogenous responses to policy, and they neglect important general equilibrium impacts (such as the opportunity cost of redirecting R&D support to the energy sector). Some suggestions on how innovation and diffusion modeling in bottom-up analysis can be improved are put forward.

Keywords: Learning curve; Bottom-up energy models; Technology diffusion

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1. Introduction

Throughout history technological development has fundamentally changed the structure of the energy sector by making possible the diffusion of new and cheaper technologies. However, the new production processes have also given rise to negative impacts on the environment, perhaps best illustrated by the current concerns about climate change, which is caused (primarily) by the burning of fossil fuels. Somewhat paradoxically, policy makers worldwide now hope that future technological development will solve the problems it has given rise to in the past. In addition, the long-term effects of global warming require policy efforts to be heavily focused on innovation and technological change in the energy sector. For the above reasons there exists a need to understand more closely the process of technical change and how different policy instruments can be used to influence this process.

It is generally agreed that energy modelers and analysts do not yet possess enough knowledge about the sources of innovation and diffusion to properly inform policymaking in technology dependent domains such as energy and climate change. Even though the literature on technical change stresses the fact that

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technological change is not exogenous in the sense that it simply appears as manna from heaven, most energy models still rely on exogenous characterizations of innovation. Specifically, in exogenous representations technical change is reflected through autonomous assumptions about, for instance, cost developments over time or annual efficiency improvements. However, in real life new technologies require considerable development efforts, much of it by private firms. In recent years energy researchers have therefore shown an increased interest in introducing endogenous (induced) technical change into energy system models, often with the purpose of analyzing explicitly the impact of technical change on energy systems. Thus, in such representations technical change is influenced over time by energy market conditions, policies and expectations.[1]

The overall purpose of this paper is to provide an overview of the literature on introducing endogenous technical change in energy systems models. Special emphasis will be put on surveying recent attempts at integrating learning-by-doing impacts into 'bottom-up' (technology-specific) energy systems models with the use of so-called learning curves, and on analyzing the relevance of learning curve analysis for understanding innovation and technology diffusion in the energy sector. In contrast to previous surveys on induced technical change in energy system modeling—see in particular Grubb et al. (2002) and Löschel (2002)—this paper focuses in more detail on the usefulness and the limitations of learning curve applications and the incorporation of learning-by-doing in bottom-up energy models. This focus is motivated by the fact that there now exist a relatively large number of empirical applications, which make a more detailed evaluation of the method possible. In addition, the learning-by-doing hypothesis has gained plenty of empirical support, and the studies surveyed here have been pointed out as some of the most satisfactory approaches towards the characterization of induced technical change (e.g., Grubb et al., 2002).

In essence, learning curve analysis in its simplest form highlights and aims at measuring the empirical relationship between the cumulative experience of a given technology and cost reductions. In other words, it is not only the case that a new technology is used because it becomes cheap; it also becomes cheap through increased deployment and learning-by-doing. Empirical studies of learning curves result in so-called "'learning-by-doing' rates", which indicate the cost reduction (in percent) for a given technology resulting from each doubling of capacity (or production). Recently researchers have extended this simple representation by also incorporating R&D expenses as additional drivers of innovation in the energy field. These specifications are typically referred to as two-factor learning curves, and result in so-called 'learning-by-searching' rates (see Section 3 for details). The estimated learning rates for different technologies can be implemented in larger-scale 'bottom-up' models, which explicitly specify technological options using both technical and economic parameters. In this paper we survey these recent studies and discuss their most important policy implications and limitations.

The paper proceeds as follows. In Section 2 we outline two different broad types of energy system models (top-down and bottom-up models) and discuss briefly in what way endogenous technical change can be introduced in these model approaches. The remainder of the paper focuses in detail on bottom-up models, and Section 3 provides an analysis of learning curves and explains in what way such representations of technological change can be integrated into bottom-up models. Section 4 surveys some selected recent studies that have employed bottom-up energy models with endogenous learning. In Section 5 we critically analyze the most significant policy implications as well as important limitations of these research efforts, while Section 6 outlines some concluding remarks and provides some suggestions for future research efforts in the field.

2. Energy modeling approaches and technical change

In practice there are two basic methodological approaches used to model the interactions between energy, economy and environment (i.e., E3 models): the top-down approach and the bottom-up approach. What is common for the above two approaches is their focus on analyzing the impact of different policies such as the costs of carbon dioxide constraints or the impact on technology choice as a result of, for instance, changed energy taxation. Even though the paper has a decisive focus on bottom-up energy models, it is useful to briefly review also the top-down models, not the least since some of the important limitations of bottom-up models are highlighted in selected top-down modeling approaches. The main differences between top-down and bottom-up approaches are explained in more detail in Sections 2.1–2.2, but in essence they "differ mainly with respect to emphasis placed on a detailed, technologically based treatment of the energy system [bottom-up], and a theoretically consistent description of the general economy [top-down]," (Löschel, 2002, p. 107).

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[1] In their survey of previous studies on energy models and induced innovation Grubb et al. (2002) identify four types of evidence supporting the important role of induced technical change. These include: (a) case studies of emerging energy technologies (e.g., wind power); (b) learning curve analysis based on engineering cost data (see also Section 3); (c) the established empirical relationship between energy prices and efficiency; and (d) international comparisons (e.g., inter-country differences in energy efficiency as a result of varying policy settings).