Energy Policy 86 (2015) 198–218

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Review article

A review of learning rates for electricity supply technologies

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HIGHLIGHTS

- We review models explaining the cost of 11 electricity supply technologies.
- The most prevalent model is a log-linear equation characterized by a learning rate.
- Reported learning rates for each technology vary considerably across studies.
- More detailed models are limited by data requirements and verification.
- Policy-relevant influences of learning curve uncertainties require systematic study.

ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form
29 April 2015
Accepted 4 June 2015

Keywords:
Learning curves
Experience curves
Learning by doing
Learning rates
Electricity generating technologies

ABSTRACT

A variety of mathematical models have been proposed to characterize and quantify the dependency of electricity supply technology costs on various drivers of technological change. The most prevalent model form, called a learning curve, or experience curve, is a log-linear equation relating the unit cost of a technology to its cumulative installed capacity or electricity generated. This one-factor model is also the most common method used to represent endogenous technical change in large-scale energy-economic models that inform energy planning and policy analysis. A characteristic parameter is the "learning rate," defined as the fractional reduction in cost for each doubling of cumulative production or capacity. In this paper, a literature review of the learning rates reported for 11 power generation technologies employing an array of fossil fuels, nuclear, and renewable energy sources is presented. The review also includes multi-factor models proposed for some energy technologies, especially two-factor models relating cost to cumulative expenditures for research and development (R&D) as well as the cumulative installed capacity or electricity production of a technology. For all technologies studied, we found substantial variability (as much as an order of magnitude) in reported learning rates across different studies. Such variability is not readily explained by systematic differences in the time intervals, geographic regions, choice of independent variable, or other parameters of each study. This uncertainty in learning rates, together with other limitations of current learning curve formulations, suggests the need for much more careful and systematic examination of the influence of how different factors and assumptions affect policy-relevant outcomes related to the future choice and cost of electricity supply and other energy technologies.

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http://dx.doi.org/10.1016/j.enpol.2015.06.011
0301-4215/

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1. Introduction

Understanding how the costs of energy and energy supply technologies change over time is of key importance for analysts and decision-makers concerned with technology development, the evolution of national and global energy systems, and the implications of policy measures proposed to address global climate change or other energy-related issues. Over the past several decades, the concept of a learning curve (or experience curve) has been employed in the literature to relate historically observed decreases in the cost of a technology to key factors affecting its adoption and diffusion, such as its cumulative installed capacity or units of output produced. Technology "learning rates" derived from such models are now widely employed by researchers and policy analysts to project future trends in the energy and environmental domains.

In this paper, we focus specifically on technologies for electric power generation, as this sector accounts for a major portion of primary energy consumption and greenhouse gas (GHG) emissions globally (IEA, 2013a). We present the results of a literature review of models that characterize technology learning across a broad range of electric power generation options, including, pulverized coal (PC) plants with and without carbon capture and sequestration (CCS); integrated gasification combined cycle (IGCC) plants with and without CCS; natural gas combined cycle (NGCC) plants with and without CCS; natural gas-fired combustion turbines; dedicated biomass plants; nuclear plants; hydroelectric plants; geothermal plants; onshore and offshore wind farms; and solar photovoltaic (PV) power plants.

This paper builds upon and updates prior reviews of the learning curve literature in peer-reviewed journal articles (e.g., McDonald and Schrattenholzer, 2001; Yeh and Rubin, 2012) and an edited monograph focused on the energy sector with an extensive treatment of electric power technologies and energy models (Junginger et al., 2010). In extending this prior body of work, we pull together into a single journal-length article the findings of research about learning models for a broad set of energy technologies currently reported in a variety of sources. Thus, our main objectives are to (1) review the current state of models used to understand past cost trends for a broad range of electric power generation technologies, (2) summarize and compare the quantitative learning rates for different technologies, and their associated uncertainty, as reported in the recent literature, (3) draw implications of these findings for the use of learning curves in technology studies and large-scale energy-economic models, (4) critically assess the implications of using various types of learning models for energy policy analysis and (5) suggest a number of areas where additional research could be productive in addressing some of the limitations identified in this review.

To begin, Section 2 briefly reviews the theory of technological change and the principal model forms used to relate technology costs to relevant factors. Section 3 then presents the results of our literature review of learning rates applicable to the 11 electricity supply technologies studied including estimates of their uncertainties. This review focused on peer-reviewed journal articles to help assure that the results we cite have been subject to a prior degree of expert scrutiny and approval. Section 4 discusses the policy implications of using learning curves or other specifications of future technology costs in large-scale energy-economic models used to inform policy planning and analysis. Finally, Section 5 summarizes the above discussions and identifies key research needs to address major shortcomings identified in our literature review.

2. Theoretical framework

A large literature on the theory of technological change and its applications to energy system modeling underlies the discussion of learning rates in this paper. Here we briefly review highlights of that literature, including relevant aspects of our own past work, before focusing more narrowly on the models most widely used to estimate future technology costs.

Technology growth models originally treated technical change exogenously, independent of other factors or variables (Solow, 1956). This effectively meant that technological change is largely unresponsive to policy measures such as R&D spending, contrary to other evidence (Cohen, 1995; Sinclair et al., 2000; Clarke et al., 2008). An alternative formulation proposed by Romer (1986) modeled technological change endogenously as a function of selected variables—a formulation now adopted in much of the technological change literature. Endogenous change models also seek to understand the importance of cost reductions for technologies used in one industry, sector, or geographic region for the same or similar technology used in other sectors or regions, that is, understanding "spillover" effects. In all cases, however, there is still considerable uncertainty in the ability of different model formulations to represent induced technological change (Junginger et al., 2010; Yeh and Rubin, 2012).

Despite this complexity, by far the most common model used in the energy literature to forecast changes in technology cost is the "one-factor learning curve" (or "experience curve"). This widely-used formulation is derived from empirical observations across a variety of energy technologies that frequently indicate a log-linear relationship between the unit cost of the technology and its cumulative output (production) or installed capacity