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A retrospective analysis of compact fluorescent lamp experience curves and their correlations to deployment programs

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HIGHLIGHTS

- We develop a segmented regression technique to estimate historical CFL learning curves.
- CFL experience curves do not have a constant learning rate.
- CFLs exhibited a learning rate of approximately 21% from 1990 to 1997.
- The CFL learning rate significantly increased after 1998.
- Increased CFL learning rate is correlated to technology deployment programs.

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ABSTRACT

Experience curves are useful for understanding technology development and can aid in the design and analysis of market transformation programs. Here, we employ a novel approach to create experience curves, to examine both global and North American compact fluorescent lamp (CFL) data for the years 1990–2007. We move away from the prevailing method of fitting a single, constant, exponential curve to data and instead search for break points where changes in the learning rate may have occurred. Our analysis suggests a learning rate of approximately 21% for the period of 1990–1997, and 51% and 79% in global and North American datasets, respectively, after 1998. We use price data for this analysis; therefore our learning rates encompass developments beyond typical "learning by doing", including supply chain impacts such as market competition. We examine correlations between North American learning rates and the initiation of new programs, abrupt technological advances, and economic and political events, and find an increased learning rate associated with design advancements and federal standards programs. Our findings support the use of segmented experience curves for retrospective and prospective technology analysis, and may imply that investments in technology programs have contributed to an increase of the CFL learning rate.

1. Introduction

1.1. Compact fluorescent lamps background

Compact fluorescent lamps (CFLs), first invented in the 1970s, are valued for their energy efficiency and compatibility with existing fixture designs. Early adoption of CFLs was hindered by high product prices, low electricity prices, consumer resistance to change, and poor product performance in areas such as color quality, flickering, and start-up time (PNNL, 2006). But even as product performance improved and life-cycle costs were reduced throughout the 1990s, consumer awareness and high initial cost limited wider scale adoption.

In this work, we examine empirical market data and program activities in an experience curve framework in order to review historical development and determine to what extent deployment and other activities affected the CFL market. An underlying motivation for reviewing the market development of CFLs is to improve our understanding of the role of technological advancements, economic incentives, and external events (such as trade sanctions and electricity prices) for a unique technology that experienced several technical changes and underwent several market changes. Section 4 discusses some of the changes and influences on the CFL market that make it a technology of interest.

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1.2. Technology learning

Learning curves and experience curves are a common framework for assessing how a technology's cost reduces with increasing production volume (Taylor and Fujita, 2013). Learning curves specifically examine the relationship between cumulative production and labor costs and are parameterized by a "learning rate" which describes the improvement in worker efficiency that comes with experience. More broadly, experience curves relate cumulative production with total unit cost or market price and are also parametrized by a learning rate as described below Empirically observed price reduction may be due to a wide range of factors such as economies of scale, improved manufacturing process control, technological improvements such as enhanced design or greater parts-integration, increased competition, material or component cost reductions, etc. Therefore, the learning rate parameter on a price-based experience curve encompasses many improvements throughout the supply chain beyond worker efficiency. These curves are empirically found to follow a power law, as shown in Eq. (1), with the rate of cost reduction a power law function of cumulative production volume.

$$C(t_2)/C(t_1) = \left(V(t_2)/V(t_1)\right)^{-b} \quad (1)$$

where:

$C(t_2)$=cost or price at time t_2

$V(t_2)$=cumulative production volume at time t_2.

$C(t_1)$=cost or price at time t_1.

$V(t_1)$=cumulative production volume at time t_1.

b=empirically observed parameter.

The percent by which cost decreases for every doubling of production volume is referred to as the learning rate ($LR=1-2^{-b}$).

1.3. Prior CFL learning and experience curve literature

Existing CFL learning rate literature contains many issues with transparency, methodology, and comparability. Iwafune (2000) estimated CFL learning rates from 1992 to 1998 to be approximately 22% for price per thousand lumens of delivered lighting output. Disaggregating into specific product types, the study reported learning rates of 41–16%. These curves were constructed using four years of data with a three-year gap before the final year ('92, '93, '94, '98), a small number of years relative to the history of CFLs in the marketplace. The missing years force data interpolation, particularly when assuming a constant learning rate. For example, excluding the last year of data as shown in Fig. 1 of this report gives a learning rate of 37% as opposed to the reported value of 21%, with a much higher correlation coefficient. In addition, the mixed units on the learning curve plot (price per thousand lumens versus price per cumulative unit production), are not consistent with other works' methods of using consistent units on both axes. Ellis (2007) created an experience curve with an often-cited learning rate of 10%, using data obtained from the Australian Greenhouse Office (AGO, 2006) and an unreferenced source cited as "Du Pont, 2005". Unfortunately we found the creation and reporting of this learning rate unsatisfactory, due to issues such as data misinterpretation (annual sales used as cumulative sales) and possible calculation errors (a recreated curve using their data yields a drastically different rate than what is reported). Weiss et al. (2008) developed a global CFL experience curve for 1988–2006 and found a learning rate of 16–21% for price per watt-equivalent, while Gerke et al. (2014) found a learning rate of 14% for 1992–1994, using US-only production and *cost* data.

From this study of historically reported data, we therefore see the need for new development of the CFL experience curve. In addition, we desire a curve that is not constrained to a constant

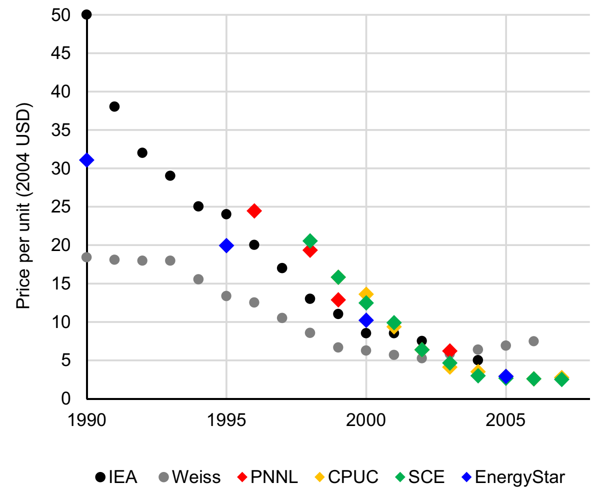

Fig. 1. Aggregated price data from six sources. Two international sources: IEA (Waide, 2010), Weiss et al. (2008); four US sources: PNNL (2006), CPUC (The Cadmus Group, Inc., 2010), Southern California Edison (Itron, Inc., 2008), and ENERGY STAR (Bickel at al., 2010).

learning rate, as informed by past works relating changes in product learning rates to public programs (Grübler et al., 1998; Van Buskirk et al., 2014; Wei et al., in press). In this work, we hope to reconcile the many differences in the reported CFL learning rates and present defensible and more easily interpretable learning rates.

2. Challenges with experience curve development

2.1. Data discrepancies

Experience curves require two datasets for a given timeframe: cost or price and cumulative production. Often, information must be collected from multiple sources and processed, distilled, and combined into useful sets. Details such as product types, purchasing scale, distribution channel, and geographical region, are often unreported with the data and can vary widely for a given technology. Cost data is further challenged by price versus cost confusion, prices normalized to varying performance metrics (e.g., $/thousand lumens) and whether the currency-year units are reported (e.g., 2010 US dollars). Often-available *annual* production data cannot be converted to the needed *cumulative* production without an initial point, i.e., the cumulative production prior to the first year of data. There is therefore enormous difficulty in determining a definitive or canonical experience curve for a technology, since many learning rates may be derived depending on one's interpretation of the data.

All of these difficulties are in force when deriving an experience curve for CFLs, as many gaps and inconsistencies are present in existing data. Moreover, several reported learning rates do not explicitly reference the source of data, units, or details about specific product and sales conditions. We manage these challenges by collecting readily available price and production data that is not meant to be representative of any specific product or bulb type, but the market as a whole. By analyzing the market on a per-unit basis, where a "unit" represents a single bulb (often referred to as a "lamp"), we are able to capitalize on a larger database of price and production data. Other metrics such as lumens or wattage of the units are not readily available to normalize the units of data. This distinction is important when comparing results to other studies of CFLs or other lighting products that may be normalized by service level (lumen) or energy use (watt). Details about the