Energy Policy 123 (2018) 700–710

Contents lists available at ScienceDirect

Energy Policy

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

Evaluating the causes of cost reduction in photovoltaic modules

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ARTICLE INFO

Keywords:
Photovoltaics (PV)
Solar energy
PV modules
Cost model
Technological change

ABSTRACT

Photovoltaic (PV) module costs have declined rapidly over forty years but the reasons remain elusive. Here we advance a conceptual framework and quantitative method for quantifying the causes of cost changes in a technology, and apply it to PV modules. Our method begins with a cost model that breaks down cost into variables that changed over time. Cost change equations are then derived to quantify each variable's contribution. We distinguish between changes observed in variables of the cost model – which we term low-level mechanisms of cost reduction – and research and development, learning-by-doing, and scale economies, which we refer to as high-level mechanisms. We find that increased module efficiency was the leading low-level cause of cost reduction in 1980–2012, contributing almost 25% of the decline. Government-funded and private R&D was the most important high-level mechanism over this period. After 2001, however, scale economies became a more significant cause of cost reduction, approaching R&D in importance. Policies that stimulate market growth have played a key role in enabling PV's cost reduction, through privately-funded R&D and scale economies, and to a lesser extent learning-by-doing. The method presented here can be adapted to retrospectively or prospectively study many technologies, and performance metrics besides cost.

1. Introduction

Photovoltaics have exhibited the most rapid cost decline among energy technologies (Trancik and Cross-Call, 2013) (Fig. 1). In parallel with cost declines and performance improvement, global PV deployment has grown rapidly (Trancik, 2014). Continued PV deployment could help reduce greenhouse gas emissions and other pollution from energy systems (Hertwich et al., 2015), and contribute to climate change mitigation (Trancik and Cross-Call, 2013). For PV deployment to experience sustained growth in the future, however, particularly when considering the additional costs of addressing solar intermittency (Braff et al., 2016), further cost declines are likely needed (U.S. Department of Energy, 2012). This paper aims to identify the causes of PV's rapid cost declines in the past and gain insight into maintaining the pace of improvement in the future. More fundamentally, we aim to advance a model for understanding the mechanisms of technology improvement at multiple levels, from human efforts to devices, that can be applied to many technologies and measures of performance.

Improvement trends in PV and other technologies have been studied by various research communities. Correlational analysis is a common approach in these studies, often focusing on cost (or other measures of performance) and production or research investment levels (Nagy et al., 2013). One of the most widely-used models is the experience curve, which relates a technology's cost to cumulative production as a power law. Using this relationship as an explanatory or predictive tool, studies have estimated the rates of performance improvement for a range of technologies (Grubler et al., 1999; Koh and Magee, 2008; Nagy et al., 2013; Rubin et al., 2015; Zheng and Kammen, 2014). For example, PV module costs fell by about 20% with every doubling of cumulative capacity since the 1970s (McDonald and Schrattenholzer, 2001; Nemet, 2006). Several explanations for this cost decline have been proposed, such as public research and development efforts and various consequences of market growth (Bettencourt et al., 2013), including learning-by-doing, economies of scale, and private research and development efforts (Funk, 2013; McDonald and Schrattenholzer, 2001; Sagar and van der Zwaan, 2006; van der Zwaan and Rabl, 2004; Yu et al., 2011; Pillai, 2015). These studies share an approach to examining technology cost evolution where important high-level drivers of cost reduction are assumed and their influence on cost is inferred based on correlation. Technologies are treated as black boxes and the causes of cost reduction within a technology are not modeled mechanistically.

Another group of studies uses detailed, device-level cost models, to understand how features of a technology or manufacturing process contribute to costs at one or more snapshots in time. Several such

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https://doi.org/10.1016/j.enpol.2018.08.015
Received 23 August 2017; Received in revised form 23 May 2018; Accepted 5 August 2018

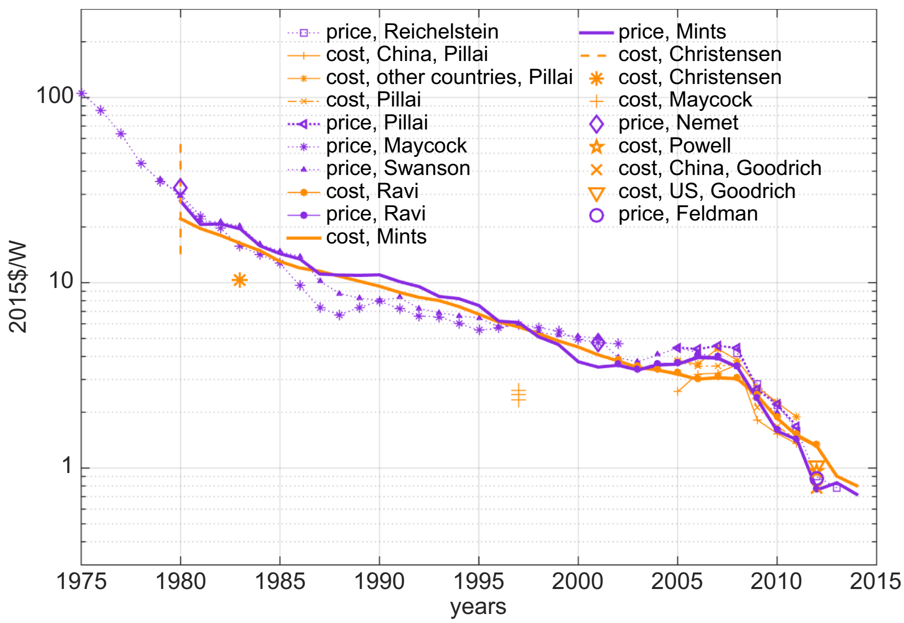

Fig. 1. Module costs and prices since 1975. Costs are shown in orange, and prices are shown in purple. References: (Reichelstein and Sahoo, 2014); (Pillai and Cruz, 2013); Maycock price data from (Nemet, 2006) and cost data from (Maycock, 1997); (Swanson, 2011); (Ravi, 2013); (Mints, 2015); (Christensen, 1985); (Nemet, 2006); (Powell et al., 2013); (Goodrich et al., 2013b); (Feldman et al., 2014). Values are averages across different crystalline silicon PV technologies except for those in (Powell et al., 2013) (multicrystalline silicon) and (Goodrich et al., 2013b) (monocrystalline silicon).

studies exist for PV, and they provide information on how individual cost components contribute to total costs, while taking into account the physics of PV technologies (Goodrich et al., 2013a; Powell et al., 2012, 2013; Woodhouse et al., 2013a, 2013b). They also propose avenues for future technical improvement at the device or manufacturing level, and estimate cost reductions that might be achieved in the future (Jones-Albertus et al., 2016). Missing from these studies, however, is a method of accurately quantifying how each change to a feature of the technology or manufacturing process contributes to cost reductions, when many changes occur simultaneously. This knowledge is needed to understand the mechanisms of cost reduction but requires further modeling advances.

Pursuing both dynamic and detailed, device-level models is critical for identifying the causes of improvement in PV and other technologies. This combined approach would address inherent limitations in using correlational analyses to identify causal effects. This approach would also address the lack of dynamics in device-level studies. A few past studies have begun to develop such a methodology by decomposing technology costs over time (McNerney et al., 2011; Nemet, 2006). A study of the drivers of PV module cost changes from the 1970s to the early 2000s (Nemet, 2006) pioneered a bridge of this kind, and found that learning-by-doing had a limited effect on cost reductions.

In this paper we propose a new conceptual framework and dynamic-yet-detailed quantitative model for analyzing PV's (or any technology's) cost evolution. We start with a cost equation that computes costs from a set of variables, such as module efficiency, wafer area, and manufacturing plant size. From this we derive cost change equations that estimate the contribution of each variable to cost changes. Multiple simultaneous changes to variables have different impacts on cost than individual changes summed together, and this must be accounted for in attributing cost changes to individual variables. Our method of estimating variable contributions is derived from adapting the total differential of cost (which decomposes infinitesimal cost changes) to finite changes.

In attributing PV's cost decline to particular causes, we draw a distinction between *low-level* causes (or mechanisms) and *high-level* causes (or mechanisms). Low-level mechanisms explain cost reduction in terms of changes to variables of a cost model, representing measurable and technology-specific determinants of cost (e.g. wafer area). High-level mechanisms explain cost reduction in terms of processes like R&D, learning-by-doing, and scale economies that subsume low-level cost reductions. Both low- and high-level mechanisms can simultaneously provide explanations for a technology's cost change. For example, suppose a technology realizes an improvement to yield from learning-by-doing on the factory floor. The resulting cost reduction can be explained in two ways. One way is to say that yield increased; the other way is to say that learning-by-doing drove down costs. Both explanations are correct, and emphasize different views of the process of improvement. The explanation based on yield improvement (a low-level mechanism) ties the cost reduction to the detailed, device-level cost model of this technology. The explanation based on learning-by-doing (a high-level mechanism) ties the cost reduction to a general improvement mechanism that is discussed widely in studies of historical technology evolution. Here we consider both levels, and thus bridge bottom-up and top-down approaches to understanding technology cost evolution.

By considering both the low-level and high-level causes of PV's improvement, we uncover lessons that are useful for a variety of decision-makers. These may include engineers who design and manufacture PV modules, or firm managers and government policy-makers who develop strategy to support technological development. For example, our findings contribute to a long-standing debate concerning the effect of public investments in R&D versus market-expansion policies (Duke and Kammen, 1999; Hoppmann et al., 2013; Zheng and Kammen, 2014).

We focus on crystalline silicon PV modules because of their long history and dominant market share among PV technologies (Fraunhofer Institute, 2017). A key goal of our analysis is to understand the mechanisms of PV technology improvement and cost reduction over time, making it essential to study costs over a long time period. Since the 1950s, this technology has improved steadily due to R&D and manufacturing efforts (Powell et al., 2012). We analyze the costs starting in 1980, when space applications of PV were overtaken by terrestrial applications, which did not require as high quality and reliability (Candelise et al., 2013; Green, 2005; Nemet, 2006). We look at typical costs globally, since PV modules are manufactured and traded globally. We focus on costs rather than prices because mechanisms of technology improvement are reflected directly in costs, while prices also include mark-ups that are influenced by other factors, such as market competition (Pillai and McLaughlin, 2013). The method we develop can be adapted to study PV systems as a whole (including non-module cost components that show significant potential for cost reduction (Fraunhofer Institute, 2015; Trancik et al., 2015)), and a wide range of other technologies and measures of performance other than cost