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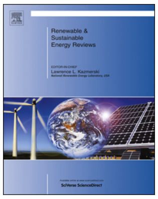

Photovoltaic learning rate estimation: Issues and implications

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ABSTRACT

This paper surveys the results of estimating learning rate (LR) equations for the photovoltaic (PV) industry at the world level, and reports new results, placing emphasis on estimation issues, and other shortcomings surveyed recently. The results are reported in detail, one relevant finding being that the learning rate parameter might reach values substantially higher than those usually reported (18–20%). This result, however, does not necessarily translate to other energies. The relevance of selecting the estimation sample, dynamic specification, and omitted variables in simple standard specifications for the estimated learning rate is highlighted. A solution for the LR in dynamic non stationary models is presented. The modeling of silicon prices is also discussed, and the concept of the total learning rate (TLR) is introduced. Probability confidence intervals for the main estimated learning rate parameters are analyzed, and the time decomposition of PV module prices is discussed, highlighting the role of fossil energy prices. It is found that the total LR might reach values above 27% with a 95% probability.

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1. Introduction

Applications of photovoltaic energy were implemented first in space research in 1955. Since that time, the cost of PV modules and cells downfall, and the associated growth in installed capacity have been phenomenal, after being introduced in commercial applications around 1977 – from 77 USDw. in 1977 to 0.55–0.65 USDw. at the end of 2014, and from 0.55 Mw global installed capacity in 1977 to nearly 180 Gw at the end of 2014; see, e.g., [1–6], for the most up to date data. The decline in cost has been generally attributed to the 'learning by doing' hypothesis [7].

This hypothesis was brought into mainstream economics by Arrow [8], and simple statistical models relating costs and deployment have been estimated in many industries since then. Early critiques and discussion of this hypothesis and its applications can be found, for instance, in Ref. [9–13].

1.1. *A review of significant allied research*

Nemet [9] conducts a detailed study of the components that possibly affect cost reductions in the PV industry, and concludes that it is scale, as measured by plant size, cost efficiency improvements, and silicon costs, what are the main drivers of cost reductions, rather than 'learning-by-doing'. The study is based on a global sample for the period 1975–2001, and implements an additive model with seven potential explanatory factors. That is a large number of variables for 27 observations in statistical terms, and in spite of that, barely 60% of the cost change is explained. Interestingly enough, the model is used to forecast the capacity required to achieve a cost of 1.0 USD per w. in 2050, the result being 1.3 Tw of capacity. The reality has been that just in 2013 and with barely 140 Gw. (=0.14 Tw), the hallmark 0.75 USD w. was reached. Ferioli [10] also considers the cost component approach, adopting an additive model for total costs – note that a multiplicative model is also a valid option; see Section A.2 in the Appendix. This model is useful to show limitations to the simple cost reduction 'law' imposed by several factors, technological, economic or otherwise – a case in point being the raw materials requirements, steel and cement, of wind turbines. Neij [11] stresses the point that economic costs are just one of several aspects that authorities should take into account when devising policy support measures – pollution mitigation, and a host of other externalities. Albrecht [12] also notes that cost is only one among several properties to be considered. In fact, and from a CAPM energy portfolio optimization point of view renewable energies, PV in particular, once the best locations for wind energy have been developed, would decrease the aggregate price volatility caused by prices of fossil energy sources without reducing profitability significantly – the analysis is conducted for the year 2025. La Tour et al. [14] include explanatory variables, other than capacity, in the learning rate equation. They find that silicon prices are relevant and build and estimate a two-factor explanatory equation from there. Although the amount of silicon required to produce PV cells has decreased impressively in the last years, and silicon dedicated factories have come into the production line starting in 2008 – see for e.g. [15] –, silicon prices are still a relevant PV module cost factor – see Section 3.2. They also find that other variables, notably scale and R&D, are very highly correlated with capacity, implying that this last driver may adequately explain the overall aggregate effect.

Efforts to collect and summarize this literature, and the research results of independent authors, have also been conducted. A survey of the early literature was conducted by Dutton et al. [16], who surveyed 100 empirical and theoretical studies of progress functions in industrial engineering, economics and management. These models were fairly simple, partly because the econometric techniques were not well developed, and also because computing facilities were not generally available. More recent surveys can be found in [14,17,18]. For the PV industry, an early survey is Neij [11]. An up to date survey for several electricity supply technologies is [19]. Although this research claims that the variability of results is too wide to be of practical use for policy guidance, with potentially costly and misleading implications, the results for the PV are not in fact so disparate, and can be traced easily to the differences in the sample period, the geographical area, or the explanatory variables employed. While those points must certainly be addressed, the overwhelming negative relationship between costs and capacity at the global level, however variable it may be, is undeniable.

Recently, Nordhaus [20], has questioned the validity of this hypothesis and its estimation counterparts. First, he considers that 'learning by practice', might be alternatively explained by exogenous technical progress. Second, he notes the over simplified statistical models implemented in practice, and emphasizes that small changes in the learning parameter estimate may yield large changes in simulations. In the same line [21] reports estimates of a panel of 15 world firms over the period 2005–2012, finding that silicon prices and efficiency explain costs, while the learning rate variable turns out insignificant statistically – but note that this period includes the years 2005–2008, when the long standing downward PV cost trend stalled, and even broke; besides, the learning process in the PV is global, and any disaggregated approach is likely to underestimate it, as discussed in Section 2.3. In a more comprehensive accounting and review of the model, its foundations, and available estimates for the PV case, a panel of experts identified the main open questions – Wiesenthal et al. [22] – which can be organized as follows: 1) the underpinnings of the concept of 'learning-by-doing', the relevance of technical progress, and omitted variables closely related to deployment and learning, 2) practical specifications problems not sufficiently addressed in empirical estimations, such as, one, two or multifactor learning curves, functional form, sample choice, dynamics, possible data biases, reverse causation, simultaneity, etc.

Regarding point 2), there has been some work that should be mentioned: for example La Tour et al. [14], and other researchers have considered other explanatory variables. Zheng and Kammen [23], again tackle the issue of R&D on the estimation of the LR, and conclude that the oversupply of PV modules, and the decreased cost trend is unsustainable simply by increasing capacity deployed – the study was published in January 2014. They argue that policy support should focus on cost reducing R&D, so that PV technology could become competitive in 5–7 years. The empirical results are restricted to a sample of firms in the period 2000–2012. But to properly estimate the LR, a long span of observations is required, and besides, they still derive a sizable value for the LR. It has to be concluded that the empirical support for their implications is somewhat doubtful, and that the latest experience during 2014–2015 confirms the validity of the LR hypothesis. Yeh and Rubin [13] also consider this question, arguing that the specified models in practice have several deficiencies, in particular the functional form and the omission of key variables like R&D expenditures. They conclude by suggesting an inverted S shaped formulation for the LR equation as a function of capacity, and underlining the uncertainties in the estimated values, that should be accounted for in economic policy and simulations – these issues are also discussed in Ref. [24]; see Section 2.3.

The discussion about the underpinnings of the concept of 'learning-by-doing' – point 1) –, and the relevance of technical progress is reviewed next.

1.2. *Technical progress, deployment, and costs reduction*

It is frequently assumed that the spectacular and continued cost decline of PV modules in approximately the last 40 years, has