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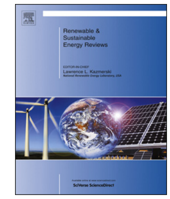

The dynamics of solar PV costs and prices as a challenge for technology forecasting

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ABSTRACT

An effective energy technology strategy has to balance between setting a stable long term framework for innovation, while also responding to more immediate changes in technology cost and performance. Over the last decade, rather than a steady progression along an established learning curve, PV costs and prices have been volatile, with increases or plateaus followed by rapid reductions. The paper describes, and considers the causes of, recent changes in PV costs and prices at module and system level, both international trends and more place-specific contexts. It finds that both module and system costs and price trends have reflected multiple overlapping forces. Established forecasting methods – experience curves and engineering assessments – have limited ability to capture key learning effects behind recent PV cost and price trends: production scale effects, industrial re-organization and shakeouts, international trade practices and national market dynamics. These forces are likely to remain prominent aspect of technology learning effects in the foreseeable future – and so are in need of improved, more explicit representation in energy technology forecasting.

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1. Introduction

The pressing need to decarbonize energy systems poses multiple policy challenges – high among them, developing and maintaining a support package for low carbon technological innovation [1–3]. In defining such policy support multiple technical, economic, political and societal forces have to be taken into account in order to deliver a balanced energy technology strategy and to enable emerging technologies to progress along the 'innovation chain' from R&D to large scale deployment. Crucial element in such challenge is a robust assessment of emerging energy technologies' cost-competitiveness, in particular by accounting for their possible future cost and performance trajectories. Indeed, a successful energy technology strategy must be able to balance between the need to set a stable long term vision for innovation as part of overall energy

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system change, while also being responsive to more immediate (and perhaps unexpected) changes in technology cost and performance.

This challenge is here considered and discussed in the context of solar photovoltaics (PV). Solar PV is a technology which has shown decades-long learning (in terms of reduced manufacturing costs and improved performance), under the benefit of sustained policy support; as such, it is seen a prime exemplar (along with wind) of a renewable energy technology learning curve [4]. Over the last decade, however, rather than a steady progression along its established learning curve, PV production costs have experienced increases followed by rapid reductions and PV prices have been increasingly volatile.. This volatility has created problems for policy, with 'PV bubbles' being seen in a number of European countries with strong market creation support measures [5,6]. The recent history of PV therefore highlights the dilemma of technology policymaking for long term system change, while being responsive to short term market fluctuations.

The paper considers this dilemma in terms of its implications for technology assessment and forecasting methods. It looks into recent changes in PV production costs and prices at module and system level (both international trends and more country-specific contexts) and it considers the causes of these changes – going beyond simple 'headline' causes to see cost and price trends in PV modules and systems as reflecting multiple overlapping forces. In particular, it addresses the technology forecasting methods available (both aggregated – experience curve - and disaggregated – engineering assessment - methods) and discusses the extent to which they have been able to describe and anticipate such cost and price trends.

The framing of the paper is mostly international/global, as is appropriate for a study of PV innovation dynamics given that PV modules are manufactured and traded on a global market. PV system prices are by contrast more affected by national/local implementation conditions, so for the discussion on PV system cost dynamics attention is given to selected specific PV markets, with a particular focus to United Kingdom.

Section 2 firstly provides an introduction to the two main cost forecasting methods considered and their use for PV cost assessment. Sections 3 and 4 discuss PV module and system cost and price trajectories, main drivers behind them and to which extent price trends have been predicted by the available forecasting methods. Finally, Section 5 draws some conclusions on the implications for technology forecasting methods and for policy making.

2. PV costs assessment and forecasting methods

There is a wide range of contributions to the PV cost reductions literature; these can be broadly grouped in two main categories. Firstly, *experience curves* (*or learning curves*), where cost reductions are analyzed as function of market and production capacity expansion, and future cost reductions are estimated by projections of historical trends, bearing in mind the likelihood of historic drivers continuing into the future. Secondly, *engineering assessments* (or system component analyses) are 'bottom up' analyses which use engineering-based estimates to assess the contribution of different technology system components to the overall costs, and how improvements in efficiencies and refinements in production processes affect their future trajectories. Each method and its use for PV cost assessment are now discussed in turn.

2.1. Experience curves and their use in PV technologies forecasting

Experience curves describe a quantitative relationship between cumulative production and the 'unit cost' of a given technology (measured as either capital cost or cost of energy produced). Experience curves are generated by measuring the effect of a doubling of cumulative production on the unit cost (or price). The resulting percentage change is called the *progress ratio*. A related and frequently used indicator is the *learning rate*, the complement to the progress ratio. Experience curves have been widely used to describe historical trends and performance of energy technologies [4,7–12] as well as for estimating the future costs of energy technologies based upon expected market development and future production capacity. A technology's future cost reduction potential can be inferred by applying a historically observed progress ratio/learning rate to projected market growth [8,13–16]. Alternatively, experience curves are sometimes used to assess the market expansion needed to achieve a certain target cost reduction (e.g. a 'break-even' cost target) as well as the total learning investment and the time needed to achieve the given cost target [4,11,13,17–19].

Experience curves are an effective mean of capturing long term historic cost trends and have been widely used to describe historical cost trends of technologies and to inform policy decisions. They can also facilitate the representation of progressive learning and technology change into energy modeling and scenario analysis – providing a quantitative illustration of cost reduction potential and the role of innovation in long term change.

However, the limitations of experience curves in technology forecasting have been repeatedly identified in the literature. At a basic conceptual level, learning by experience (the assumed primary learning effect in learning curves) can only partially explain cost reductions and the multiple, complex drivers of cost reductions cannot be fully captured by a simple functional relationship between capacity installed and unit cost [7,14,20–25]. In particular, experience curves are deemed ill-suited to predict discontinuities in learning due to e.g. technological breakthroughs, market structural changes, effect of knowledge spill over from outside the industry as well as possible future barriers to development [25]. Indeed, the tendency of experience curve-based forecasts is to project forwards historically observed cost/price trends – and implicitly therefore, the drivers behind historic trends. Even within an established design, however, significant changes of learning rate may be seen, reflecting different stages of maturity.

Particular concerns have been raised about projecting forwards learning rates in modeling exercises. Several studies have highlighted how discontinuities and uncertainties in the future learning rates can non-linearly propagate through energy policy models [26] and are not fully acknowledged when used to inform policy decisions [4,24,25,27]. Given demands for accelerated energy system transformation, there may well be an increased likelihood of future discontinuities and step-changes in the energy technologies, and the risk is that such changes are not fully captured and anticipated by energy modeling and policy decisions informed by them.

There is a wide range of studies applying experience curves to PV technologies. The majority of PV experience curves are built from data for *1st generation* crystalline silicon (c-Si) PV, which is historically the conventional PV technology (see also Section 3). However, other PV technologies such as *2nd generation* inorganic thin film or novel *3rd generation* PV technologies (which includes a range of novel technologies at pre-commercial stage: from demonstration, e.g. multi-junction concentrating PV, to novel concepts still at R&D stage e.g. polymer cells, quantum-structured PV cells [28]) are emerging and are likely to follow different learning path than conventional c-Si PV (see also Section 3.1). In principle, an aggregated experience curve could be developed to encompass conventional c-Si and emerging PV technologies. However, very little time series data exist for emerging PV technologies, so that experience curves cannot be built for them with any degree of confidence (other than in a highly speculative scenario fashion).