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Estimating the learning curve of solar PV balance–of–system for over 20 countries: Implications and policy recommendations

Amro M. Elshurafa [a, *], Shahad R. Albardi [a], Simona Bigerna [b], Carlo Andrea Bollino [a, b]

[a] King Abdullah Petroleum Studies and Research Center (KAPSARC), PO Box 88550, Riyadh 11672, Saudi Arabia
[b] Department of Economics, University of Perugia, 06123 Perugia, Italy

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ABSTRACT

Solar photovoltaic systems installed on homes and commercial building rooftops are deemed central for a low-carbon future. As capital costs of photovoltaics continue to fall, its role towards making buildings more sustainable and environmentally-friendly will continue to grow. Capital costs of a photovoltaic system comprise the module and balance-of-system costs. The latter refers to everything-else needed to make the photovoltaic system functional including cables, mounts, labor, etc. While modules are priced internationally, the balance-of-system cost is country-specific. Price developments of modules, which have been thoroughly studied in literature, followed an 80% learning curve. Research on the balance-of-system learning curve however, has not been as extensive. In this paper, we estimate for the first time the learning curve of balance-of-system costs in photovoltaics for more than 20 countries via an extensive dataset. Our calculations yield a global learning curve for the balance-of-system of 89%, which corresponds to a progress ratio of 11% compared with 20% for modules. Understanding the rate at which capital costs of photovoltaics are falling with such detail will aid in more effective renewable energy policy planning and budgeting. Finally, some steps requiring no financial commitment but can bring down balance-of-system costs are discussed, which greatly contribute to a cleaner and more sustainable future.

1. Introduction

One fundamental difference between conventional and renewable technologies is that conventional generation requires fuel. Renewables, however, boast (near) zero variable costs but are not dispatchable. This difference, among others, results in different cost implications as shown in Fig. 1, where the levelized cost of energy (LCOE) breakup for solar and a conventional combined cycle (CC) plant is illustrated. With CC plants, nearly three quarters of the costs are dominated by variable costs, including fuel, and is spread over the lifetime of the plant. In contrast, the LCOE of solar generation is dominated by its capital expenditure (CAPEX).

The cost structure of any photovoltaic (PV) system comprises mainly two components: (1) the module, which converts sunlight to electricity, and (2) the balance of system (BOS) costs, which is an all-encompassing term representing everything else needed for the solar system to be erected and functional including, inverter(s), mounts, cables, bolts, labor, permitting, grid connection, etc. Due to economies of scale, the costs, in dollars per watt, vary with the size of the solar facility, which may be residential (2 kW–10 kW), commercial (10 kW–500 KW) or utility (~1 MW and above).

In addition to the use of heat pumps (Esen et al., 2006), whether ground or air-coupled (Esen et al., 2007), residential and commercial PV in particular are considered essential contributors to energy conseravation (Esen and Yuksel, 2013) and lowering carbon emissions (Gustafsson et al., 2017). The importance of residential and commercial PV increases in countries where land is scarce, which does not enable installing utility-scale PV. Given the low operational and maintenance costs of PV, it is the CAPEX that constitutes the only financial hurdle for PV deployment (Asaee et al., 2017). The costs of PV have been historically following a downward trajectory, and this trend is expected to continue. The analysis of the overall profitability of PV deployment on buildings includes both technical (Ghazali et al., 2017) and economic (Ioannou et al., 2014) factors. However, there is not a specific

* Corresponding author.
E-mail addresses: amro.elshurafa@kapsarc.org (A.M. Elshurafa), Shahad.bardi@kapsarc.org (S.R. Albardi), simona.bigerna@unipg.it (S. Bigerna), carlo.bollino@kapsarc.org (C.A. Bollino).

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Nomenclature

β	Learning Coefficient
C_1	The cost of producing the first unit of a good or product
C_Q	The marginal cost of producing the Q-th unit of a good or product
cpi	Consumer Price Index
CAPEX	Capital Expenditure
CC	Combined Cycle
BOS	Balance of System
i	Subscript representing a country
LC	Learning Curve
LCOE	Levelized Cost of Energy
LR	Likelihood Ratio
O&M	Operational & Maintenance Costs
Oil	Oil Price
OLS	Ordinary Least Square
poly	Polysilicon spot price
PR	Progress Ratio
PV	Photovoltaics
Q	The cumulative quantity produced of a good or product
steel	Steel Index Price
SUR	Seemingly Unrelated Regression
t	Subscript representing time

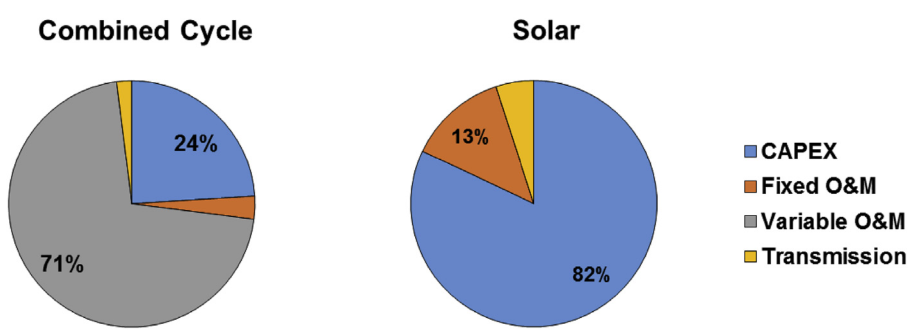

Fig. 1. LCOE breakup for combined cycle and solar. In CC plants, most of the costs are attributed to variable O&M costs through the lifetime of the facility. For solar, most of the LCOE is governed by CAPEX. Data based on DOE-EIA data 2015.

consideration of the BOS cost component pattern to the total capital cost development. It is therefore crucial to understand the rate at which capital costs of PV have been falling, disentangling the various cost components, to aid policymakers in formulating better policy interventions that can allocate reasonable financial support for effective deployment.

Throughout the literature, demonstrating that the economics of solar PV have been following a downward trajectory was achieved via the average selling price (ASP) of modules. As manufacturing experience accumulates, module manufacturers become more efficient and this enhanced efficiency translates into cost reductions. The latter concept is referred to as the learning curve (LC), and is a concept that can be applied to other industries also. Plotting the module prices can be done against time or manufactured capacity, though the theoretical definition of LC relates monetary values to manufactured capacity, not time.

Relying on selling prices of modules to be the benchmark for cost trends in the PV industry did not happen accidentally. Modules can essentially be treated as a commodity; several organizations track and publish the spot price of modules. As such, monitoring the module price evolution gives a global picture on how the industry is progressing. The same does not immediately apply to the BOS (Huenteler et al., 2016). Each country has unique industry, policy and energy environments, and because renewable targets vary across countries, it is expected that the BOS costs would also evolve differently between countries (Neij et al., 2017). Regional specificities associated with the BOS include tax rates and labor wages for example.

Furthermore, when trying to forecast PV system costs in a certain country, projecting how the cost of modules would develop globally and how the BOS costs would evolve regionally should be carried out simultaneously (Neij et al., 2017). The different CAPEX values prevailing in each country are mainly attributed to the variation in BOS, not in module costs.

As the prices of modules have declined at a faster rate compared with BOS, the BOS has grown to form a larger share of CAPEX (Stapersma, 2015). The latter observation warrants a detailed study of the evolution of the BOS globally. In this paper, we deduce for the first time the LC of the BOS component for more than 20 countries. With the aid of an extensive dataset that has been compiled, arriving at the LC for these countries was achieved econometrically via the ordinary least square method and the seemingly unrelated regression method. Another important aspect of this study is that it uses recent data covering years up to 2015 compared with previous studies that are mostly over a decade old. Such analysis identifies countries that have succeeded in reducing the BOS costs more effectively, and will aid in identifying best practices that can potentially be replicated in other countries.

The value of the LC concept is not to be underestimated: it gives a reasonable picture on how costs evolved. Hence, the objective of this paper is to serve as aid in better projection of future solar PV CAPEX costs. This is crucial for the development of PV installed on homes and commercial building rooftops, because these systems depend on the reaction of private market decisions to the policy framework while private investment decisions are obviously sensitive to local BOS cost conditions.

Further uptake of renewables, which is tied to a cleaner energy future, will depend on their costs and indeed the LC has been relied on to serve in framing and shaping this discussion within policy circles (Zou et al., 2016), including those related to incentives (Wand and Leuthold, 2011), market structure (Batlle et al., 2012), and interaction with conventional forms of generation (Kobos et al.,