The economics of solar photovoltaic (PV) energy

Amro M. Elshurafa, Kapsarc, Shahad Albardi, Kapsarc, Carlo Andrea Bollino, University of Perugia and Kapsarc, and Simona Bigerna, University of Perugia

Abstract

From virtually no installations in 1990, the solar PV industry rested on a formidable 177 GW of installed capacity worldwide by the end of 2014 (IEA 2014). It is widely accepted, and indeed true, that costs of solar technology have considerably declined simultaneously with this expeditious installation growth rate. Learning and expanding supply chains, buoyed by policy support, allowed for such a cost drop to occur.

From a cost perspective, power generation technologies, whether conventional of renewable, can generally be analyzed using the concept of the capital costs, also known as CAPEX. CAPEX includes turn-key costs or overnight costs, refer to the upfront costs required to build the generation plant assuming the plant can be built overnight. We consider the cost structure of any PV system comprises mainly two components: (i) the module, which converts sunlight to electricity, and (ii) the balance of systems (BOS) costs, which is an all-encompassing term representing whatever else is 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 (2kW – 10kW), commercial (10kW – 500KW), or utility (~1MW and above).

The aim of the paper is to compute and estimate the learning rate (LR) for PV. The paper offers three novel contributions. First, the LR is computed for both CAPEX and BOS. Second, the LR analysis is country specific for a large number of countries, exploiting a new data base (Amro El Shurafa et al 2016). Third, the paper investigates the change in the learning rate after the 2008 crisis, finding some new structural determinants.

Relying on selling prices of modules to be the cursor for cost trends in the solar PV industry did not happen coincidentally. Modules can essentially be treated as a commodity, and several organizations worldwide follow and publish their spot prices on a regular basis – much like the oil price. 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. Unlike modules, regional specificities associated with the BOS like tax rates and labor wages for example, impede formulating a global norm for the BOS and an associated global learning curve. The different CAPEX values prevailing in each country are mainly due to the variation in BOS, not in module costs. Each country has unique circumstances, and because renewable targets vary across countries, it is expected the BOS costs would evolve differently between countries as well. In other words, when trying to forecast what system costs would be in a certain country, projecting how the cost of modules would develop globally and how the BOS costs would develop regionally should be carried out in parallel.

As mentioned, the module price developments have received significant research attention. However, the BOS segment did not receive the same attention. As the prices of modules have gone down at a faster rate compared to BOS, the BOS is currently responsible for a larger share of CAPEX compared to the module (CIEP 2015). The latter observation warrants a detailed study of the evolution of the BOS globally. In this paper, we deduce, econometrically, learning rates for the BOS component for nearly 20 countries with the aid of an extensive data set. Such analysis enables us to classify which countries have succeeded in reducing the BOS more effectively, and will consequently aid in identifying best practices that can potentially be exported to other countries.

The learning curve of modules has been determined by the evolution of the average selling price (ASP), or spot prices, as seen in Figure 1. The module industry followed an LC of approximately 80%, or a 20% progress ratio.

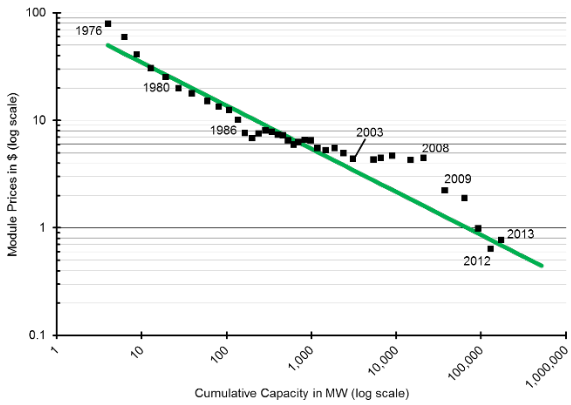

Figure 1. The learning curve of the solar PV module.
Source: KAPSARC based on data from BNEF.

Although the costs of solar cells have fallen precipitously and followed an 80% learning curve, BOS costs have not declined as fast and today remarkably represent the majority of the capital costs for this form of renewable energy. Costs associated with BOS include: land acquisition, site preparation and civil works, mounting structures, cables, legal costs, permitting, zoning, grid connection, charge control devices, labor, taxes, profits, marketing, etc. Formal definitions of BOS vary but generally refer to the costs required to erect a solar system with the exception of modules and inverters (Fraunhofer 2015), which is the definition we adopt in this paper.

According to industrial reports from the United States, BOS had become the majority of capital costs according to Green Tech Media (GTM, 2012). Similar trends are also found in Germany as shown in Figure 2 below.

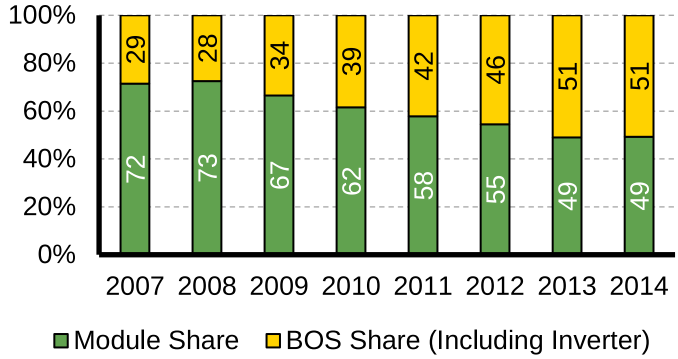

Figure 2. Shares of modules and BOS (including inverter) of the average price for rooftop solar systems in Germany. Note how the BOS is becoming increasingly responsible for a larger share of capital costs. Source: KAPSARC based on data from Fraunhofer ISE 2015.

We estimate the Learning Rate, which can also be referred to as The Learning Curve (LC) or The Experience Curve, with the following mathematical form:

$$C_Q = C_1 \cdot Q^{-\beta} \tag{1}$$

where C_Q is the cost of producing the Q-th unit, C_1 is the cost of producing the first unit, Q is the quantity produced, and β is the learning parameter.

Conclusions and policy implications will follow.

References

Elshurafa, Amro M. and Shahad R. Albardi. 2015. The KAPSARC Solar Photovoltaic Toolkit. KAPSARC. Publication number KS-1630-MP024A. Accessed: June 16, 2016. https://www.kapsarc.org/wp-content/uploads/2016/05/KS-1630-MP024A-Solar_Photovoltaic_Toolkit.pdf

Fraunhofer ISE. 2015. "Current and Future Costs of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility Scale PV Systems." Accessed November 30, 2015. https://www.ise.fraunhofer.de/de/weblinks/links-zu-externen-webseiten/current-and-future-cost-of-photovoltaics-long-term-scenarios-for-market-development-system-prices-and-lcoe-of-utility-scale-pv-systems

Ardani, K. and Margolis, R. 2015. "Decreasing Soft Costs for Solar Photovoltaics by Improving Interconnection Process: A Case Study of Pacific Gas and Electric." National Renewable Energy Laboratory. Accessed December 8, 2015. http://www.nrel.gov/docs/fy15osti/65066.pdf

Baumgartner F. , (2017). Photovoltaic (PV) balance of system components: Basics, performance, The Performance of Photovoltaic (PV) Systems Modelling, Measurement and Assessment, Pages 135–181

BNEF. 2016. "Q1 2016 PV Market Outlook." Bloomberg New Energy Finance.

Bony, L. et al. 2010. "Achieving Low-cost Solar PV: Industry Workshop Recommendations for Near-Term Balance of System Cost Reductions." Rocky Mountain Institute. Accessed December 15, 2015. http://www.rmi.org/Content/Files/BOSReport.pdf

Calhoun, K. et al. 2014. "Lessons from Australia." Rocky Mountain Institute. Accessed December 9, 2015. http://www.rmi.org/Knowledge-Center/Library/2014-11_RMI-AustraliaSIMPLEBoSFinal

Colver, I. 2014. "UK Hits 5 GW Solar PV Capacity." PV Magazine. Accessed December 9, 2015. http://www.pv-magazine.com/news/details/beitrag/uk-hits-5-gw-solar-pv-capacity_100016065/#axzz3tF9u58w7

Chase, J. 2015. "Cost Reductions and Scale Economies in Residential PV." Bloomberg New Energy Finance.

Chase, J. 2011. "The PV Experience Curve." Bloomberg New Energy Finance.

Feldman, D. et al. 2015. "Photovoltaic system pricing trends – Historical, Recent, and Near-Term Projections: 2015 Edition." National Renewable Energy Laboratory. Report number: NREL/PR-6A20-64898. Accessed November 26, 2015. https://emp.lbl.gov/sites/all/files/pv_system_pricing_trends_presentation.pdf

Fraunhofer ISE. 2015. "Photovoltaics Report." Accessed February 21, 2016. https://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

Cross, D. 2015. "Take My Solar Panel, Please!" Slate. Accessed December 20, 2015. http://www.slate.com/articles/technology/the_juice/2015/09/solar_panels_from_cps_energy_the_san_antonio_utility_s_brilliant_new_business.html

GTM. 2012. "Solar Balance-of-System Costs Account for 68 percent of PV System Pricing." (Accessed December 7, 2015. http://www.greentechmedia.com/articles/read/Solar-Balance-of-System-Accounts-for-68-of-PV-System-Pricing-New-GTM-Repo

Handleman, C. 2015. "Do big leaps in solar module efficiency mark the beginning of solar without subsidies?" *Renew Economy*. Accessed November 30, 2015. http://reneweconomy.com.au/2015/do-big-leaps-in-solar-module-efficiency-mark-the-beginning-of-solar-without-subsidies-61977

IRENA. 2012. "Renewable Energy Technologies: Cost Analysis Series – Solar Photovoltaics." Accessed February 21, 2016. https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-SOLAR_PV.pdf

Jager-Waldau, A. 2013. "PV Status Report 2013". European Commission. Accessed December 16, 2015. http://iet.jrc.ec.europa.eu/remea/pv-status-report-2013

MIT. 2015. "The future of Solar Energy." MIT Energy Initiative. Accessed January 12, 2016. http://mitei.mit.edu/system/files/MIT%20Future%20of%20Solar%20Energy%20Study_compressed.pdf

Neij Lena, (2008. Cost development of future technologies for power generation—A study based on experience curves and complementary bottom-up assessments, Energy Policy 36 (2008)2200–2211

Papaefthimiou, Spiros, Manolis Souliotis, Kostas Andriosopoulos, (2016). Grid Parity of Solar Energy: Imminent Fact or Future's Fiction?, Energy Journal, vol. 37, SI 2, 263-276.

Partridge, Ian , (2013). Renewable electricity generation in India—A learning rate analysis Energy Policy 60, 906–915

Peters, M., T.S. Schmidt, D. Wiederkehr, and M. Schneider (2011). “Shedding light on solar technologies: A techno-economic assessment and its policy implications.” Energy Policy 39: 6422–6439. http://dx.doi.org/10.1016/j.enpol.2011.07.045

PVInsights Website http://wap.pvinsights.com/

PROMES. 2015. “Solar cells under very high concentration.” Accessed November 30, 2015. http://www.promes.cnrs.fr/index.php?page=solar-cells-under-very-high-concentration#prettyPhoto

Randal, T. 2015. “Fossil fuels just lost the race against renewables.” Bloomberg. Accessed 23 November 23, 2015. http://www.bloomberg.com/news/articles/2015-04-14/fossil-fuels-just-lost-the-race-against-renewables.

Reichelstein, S. and Yorston, M. 2013. “The prospects for cost competitive solar PV power.” *Energy Policy*, 55*:*117-127.

REN21. 2014. “Renewables 2014 - Global Status Report.” Accessed August 25, 2014. http://www.ren21.net/REN21Activities/GlobalStatusReport.aspx

Rubin Edward S., Inês M.L. Azevedo, Paulina Jaramillo, Sonia Yeh, (2015). A review of learning rates for electricity supply technologies, Energy Policy 86 (2015) 198–218

Seel, J. 2012. “Making Photovoltaics Competitive in the U.S. – A Comparison of Residential PV Prices in Germany and the United States.” MSc Thesis. University of California at Berkeley

Shaw, V. 2015. “China: PV Installed Capacity Grows to almost 30 GW in 2014.” PV Magazine. Accessed February 21, 2016. http://www.pv-magazine.com/news/details/beitrag/china--pv-installed-capacity-grows-to-almost-30-gw-in-2014_100018231/#axzz40mnSqW3v

Shockley, W. and Queisser, H. 1961. “Detailed balance limit of efficiency of pn junction solar cells.” *Journal of Applied Physics*, 32:510-519.

Stadler, I. 2008. “Power grid balancing of energy systems with high renewable energy penetration by demand response.” *Utilities Policy*, 16:90-98.

US Department of Energy – EIA.. “Sunshot Initiative.” Accessed November 29, 2015. http://energy.gov/eere/sunshot/sunshot-initiative.

US Department of Energy – EIA, Levelized Costa and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2015. http://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf

Sean Ong, Clinton Campbell, Paul Denholm, Robert Margolis, and Garvin Heath, Land-Use Requirements for Solar Power Plants in the United States, US Department of Energy – National Renewable Energy Laboratory (2013) http://www.nrel.gov/docs/fy13osti/56290.pdf

The International Energy Agency (IEA),. 2014. A Snapshot Of Global PV (1992-2014). IEA PVPS. https://goo.gl/PR6Wy6.

Woodhouse, Michael, Rebecca Jones-Albertus, David Feldman, Ran Fu, Kelsey Horowitz, Donald Chung, Dirk Jordan, and Sarah Kurtz. 2016. 'On the Path to SunShot: The Role of Advancements in Solar Photovoltaic Efficiency, Reliability, and Costs'. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65872. http://www.nrel.gov/docs/fy16osti/65872.pdf.

Ezysolare,. 2016. Trend Analysis On Solar PV Module Prices. Ezysolare. https://goo.gl/6pZO8s.

Stapersma, Pier. 2015. Solar PV In A Strategic World: Recent Developments In The Solar PV Value Chain. Clingendael International Energy Programme (CIEP). http://www.clingendaelenergy.com/inc/upload/files/CIEP_paper_2015-04_web.pdf.

Witajewski-Baltvilks Jan, Elena Verdolini, Massimo Tavoni. (2015). Bending the learning curve, Energy Economics 52 (2015) S86–S99