Near zero

TECHNICAL NOTE
Published Online: 15 July 2011

Is the solar photovoltaic learning curve flattening?

David W. Keith[1*] and Juan Moreno-Cruz[1]

Solar is one of the few low-carbon primary energy sources that could be scaled up to the 10's of terawatts (TW) needed to meet a substantial fraction of world energy demand over the century, so driving down the cost of solar is among the important enablers of decarbonization.

Two basic strategies are available to drive down costs: incent research directly or incent demand that will in turn motivate private sector research and generate production experience. We will call them Learning by Searching (LBS) and Learning by Doing (LBD). These strategies are, of course, intertwined as the market support strategies used for LBD also encourage research and there is ample evidence that LBS is ineffective without some market pull. We need both. The question is how to distribute resources between them. In this note we analyze returns to LBD.

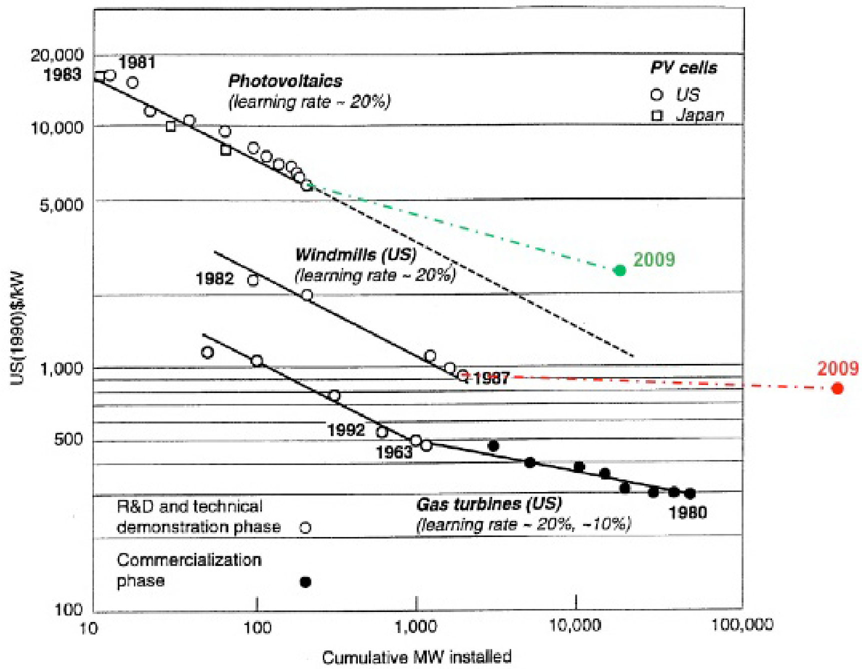


Figure 1. Breakpoints in learning curves adapted from Grübler et al. (1999). Assumptions that support the 2009 wind and solar points are given in Supplementary Note S2.

Estimates of future photovoltaic (PV) deployment often assume that costs decline with a single constant learning rate. (Learning rate defines the fraction by which costs decline for each doubling of installed capacity; see Supplementary Note S1). This may not be a good assumption as the learning rate often slows down as the technology matures (Fig. 1).

Have learning rates for PV begun to decline? We think this is a crucial question for policies aimed at reducing the cost of solar PV. The relatively slow cost declines in the last decade suggest that learning rates may be declining. In Figure 2 we fit 34 years of PV module price data using either a single learning rate or a bilinear fit as a simple test for the possibility that the learning rate has declined.

If future PV prices follow the linear fit then we will reach \$1/W at 180 gigawatts (GW) of installed capacity and it will require future expenditures of around \$200 billion to reach that capacity. If we are beyond the breakpoint and prices follow the bilinear fit then it will take 13,000 GW and \$15 trillion to reach \$1/W. Given PV's low capacity factor and intermittency we may need to get near \$0.3/W for PV to have a major share of the global primary energy supply; if this were the case then we will need \$3 trillion on the linear curve and \$5,000 trillion on the bilinear curve putting the goal out of reach.

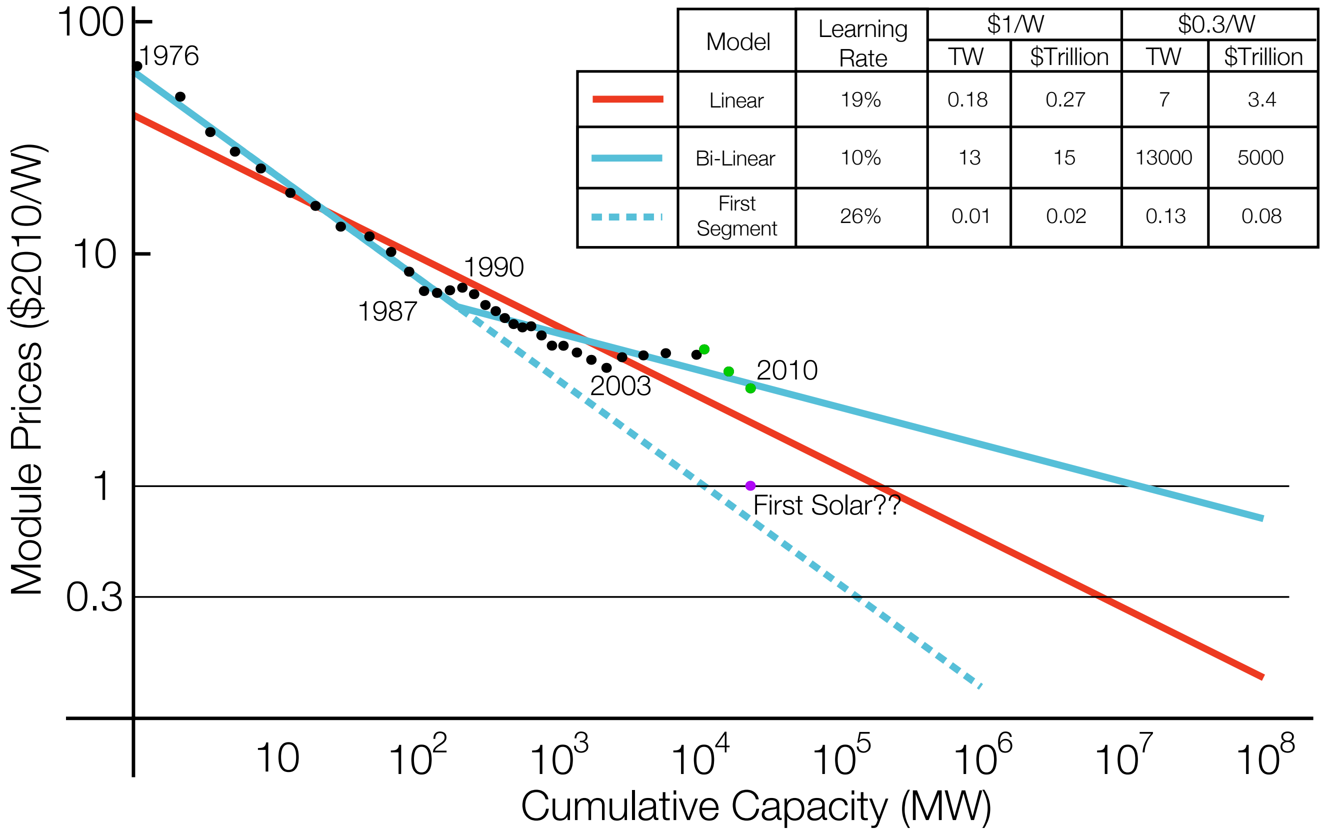
Caveats

We see two important ways in which this analysis may be flawed.

First, the data may be wrong. We could not find a single uniform source of data up to 2010, so we spliced together data from several sources as described in Supplementary Note S3. Perhaps the splicing procedure biased the result.

Second, the data is for prices, but power law learning curves were designed to describe declines in costs. Perhaps some companies have achieved cost well below current prices. Many sources suggest that companies such as First Solar have now achieved costs near \$1/W

[1] Energy and Environmental Systems Group, University of Calgary, Calgary, Alberta T2N 1N4, Canada *keith@ucalgary.ca



Model		Learning Rate	$1/W TW	$1/W $Trillion	$0.3/W TW	$0.3/W $Trillion
(red line)	Linear	19%	0.18	0.27	7	3.4
(blue line)	Bi-Linear	10%	13	15	13000	5000
(dashed blue line)	First Segment	26%	0.01	0.02	0.13	0.08

Figure 2. Linear and Bi-linear fits for solar PV cost vs. cumulative capacity. Data is Nemet (2009), EIA (2010) and Solarbuzz (2010) as described in Supplementary Note S3 and Fig. S1. The red line shows the best fit for the complete data, while the blue line shows a piecewise linear fit where the breakpoint is freely determined. The table shows the number of cumulative TW of cumulative capacity and integrated cost from 2010 required to reach $1.0 and $0.3/W targets shown by the horizontal grey lines.

(see, for example figure 3.17 of IPCC (2011) reproduced as Supplementary Fig. S2). It is not clear to us if these costs are marginal production costs or if they include full return on capital. As a caution: we have seen similar stories of cost breakthroughs before, they may be correct this time; yet, one would expect competition in a heterogeneous industry to quickly drive down rents so that marginal costs approach prices.

Tentative Conclusion

Excepting the dramatic cost declines in the last two years, there is evidence that learning rates declined over the last two decades. The learning rate over the last 20 years is 10% whereas many projections of future PV costs use rate closer to 20%, a value more appropriate to the first few decades of production. As the last 20 years encompass 99% of the cumulative PV shipments to date, it may well provide better guidance for learning rates as the PV industry enters a mature commercial phase.

The world has spent ~$70 billion in deploying PV over the last decade, a sum that vastly exceeds spending on research into high-risk high-payoff PV technologies. If PV learning rates have begun to decline then it will be very hard to get to cheap solar using a market driven LBD strategy and it may make sense to shift resources from LBD to a research-driven LBS strategy. If it's true that costs have jumped to near $1/W, a key question is: what will the learning rate be over the next decade?

References

Energy Information Administration. *Annual Energy Review*. Table 10.8. (2010)

IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. eds. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow, Cambridge University Press, Cambridge, UK and New York, NY, USA.

Grübler, A., Nakićenović, N. and Victor, D.G. Modeling technological change: Implications for the Global Environment. *Annual Review of Energy and the Environment* **24**, 545-69 (1999)

Nemet, G. F. Interim monitoring of cost dynamics for publicly supported energy technologies. *Energy Policy* **37**, 825-835 (2009).

Solarbuzz "Module Pricing" (2010); available online at: http://www.solarbuzz.com/Marketbuzz2010-intro.htm. Accessed October 2010 and May 2011.

Is the solar photovoltaic learning curve flattening?

David W. Keith and Juan Moreno-Cruz

S1. Power law learning curve

Discussion about the cost decline for PV is often framed around the power law learning curve which posits that costs should fall in proportion to cumulative production. That is $C_x = C_0 x^r$ where x is cumulative number of units produced and r is the learning rate, which typical value is -0.3. Rather than using r directly, it is more common to describe the progress ratio, the amount that costs decline for a doubling of total production. The progress ratio is $r = log_2 PR$, and a typical value is 80%, that is a cost decline of 20% for a doubling of investment.

S2. Breakpoints in learning curves

Figure 1 is adapted from Grübler et al. (2009). The horizontal axis is the globally cumulative installed in MW. We annotated the figure with current values for solar PV and wind. This suggests that solar PV and wind present a similar behavior to that observed in natural gas turbines (for a more detailed analysis of the slowdown in learning rates see Nemet (2009)).

The vertical axis is the cost per kilowatt in US(1990)$. The red dot shows the approximate point for the 2009 wind installed capacity. According to EWEA (http://www.ewea.org/index.php?id=1487), the total installed wind capacity is almost 160 GW and we are assuming a price of 1000 $/kW today which is equivalent to around 620 US(1990)$/kW (red point). According to Solarbuzz, the total installed capacity increased in 2009 by 7.5 GW which is equivalent to a 20% increase (http://www.solarbuzz.com/Marketbuzz2010-intro.htm). Hence, we assume global solar PV capacity to be around 38 GW. The average price in 2009 for modules is 4320 US(2010)$/kW (http://www.solarbuzz.com/Moduleprices.htm) which is equivalent to around 2700 US(1990)$/kW.

S3. Composite solar PV price and volume data

Our data is drawn from three sources (see main text references for full citations):

Nemet (2009);
Energy Information Administration (2010); and
Solarbuzz (2010).

We take Nemet (2009) data as the main source. These data give prices and (lag-)cumulative capacity up to 2007. From 2007 until 2009 we use cumulative capacity data from EIA 2010. However, EIA only considers US capacity while Nemet's data are global. To correct for this, we take EIA data from 1990 and calculate the share on US capacity to global capacity up to 2007 and then use the average yearly share to correct for US capacity in 2007-2009. We repeat the same procedure to calculate prices for the years 2008 to 2009. 2010 price data comes from Solarbuzz (2010) which gives us prices from June 2007 until December 2010.

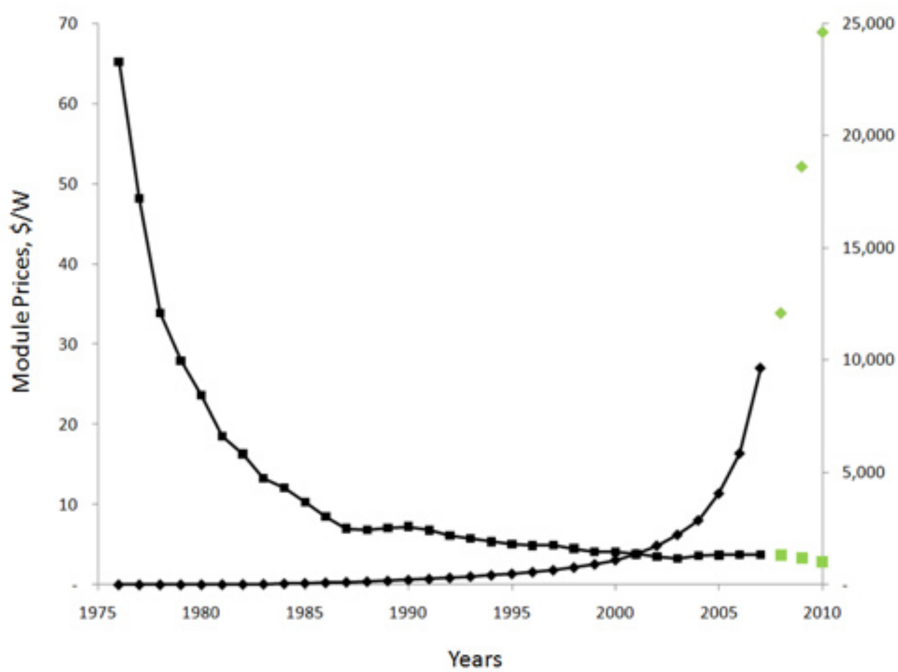


Figure S1. Composite data. Module prices in US$2010 [left vertical axis] and volumes in MW [right vertical axis], against years [horizontal axis]. Data is Nemet (2009) [black], EIA (2010) and Solarbuzz (2010) [green].

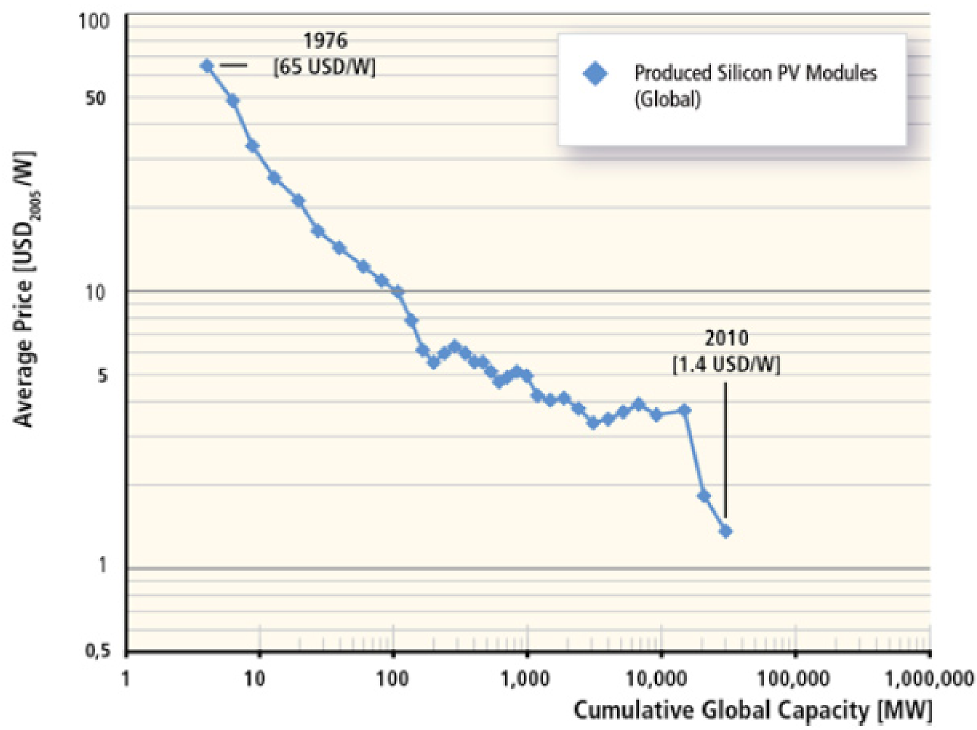


Figure S2. Average Module Prices in US$2005/W versus cumulative capacity in MW reproduced from IPCC (2011).