世界太陽光発電パネル価格決定メカニズムに関する計量経済分析

Econometric study on the pricing mechanism of global solar PV panel

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This paper attempts to analyze the pricing mechanism of global solar photovoltaic (PV) system using learning curve (LR) as the tool to identify contributing factors to cost reduction of PV panel between 1988 and 2006. We began with estimation of the LR for 1988-2006 as a whole, and subsequently repeated the whole exercise by dividing the review period into three periods to examine changes in LR as industry/technologies mature. In each exercise, we considered also three other potential explanatory factors including silicon prices, in addition to cumulative production. Where applicable, we repeated the estimation using both data in nominal and real prices for comparison. We found that (1) LR results using only cumulative production denoted possible missing explanatory factor in the estimation; (2) Silicon prices should be considered; (3) Real prices data is preferred in order to account for inflation; (4) LR of energy technologies should be examined according to stages of industry/technology development. With consideration to the above findings, the estimated LR was 12% for 1988-1996, dropped to 10.7% for 1997-2001 and finally slowed to 10.2% for 2002-2006. We then utilized this estimated LR to project future module cost reduction pathways based on a range of solar deployment scenarios. Results indicated that module costs in real prices will drop from $3.8/Watt in 2006 to $1.68/Watt in 2030 in the most accelerated solar deployment scenario.

Keywords : Learning curve, solar photovoltaic, module cost

1. Introduction

The global solar PV industry has experienced unprecedented growth over the last decade with an average annual growth rate of 50%. In 2011, global solar PV market has reached a cumulative installed capacity of close to 70GW, up from 1.8GW in 2000 (EPIA, 2012), providing 0.1% of total global electricity generation (IEA, 2010). While still a dwarf compared with fossil fuels, the PV industry is expanding very rapidly due to dramatic cost reductions by a factor of nearly 100 since the 1950s, far more than any other energy technology in that period. Long-term scenario studies projected an increased role of PV in global electricity generation and positioned solar energy as one of the realistic options for future's energy mix. Though PV is still economically uncompetitive compared with conventional sources such as gas, coal, and even with other renewable sources, technology improvements, innovation, adequate incentives and support policies, such as the Feed-in Tariffs will bring further cost reductions for electricity from PV. Under the right policy and market conditions, electricity from solar energy could achieve grid parity in some European markets as early as 2013. In this paper, firstly we analyzed the pricing mechanism of global solar PV panel using LR as the tool to identify contributing factors to cost reduction of PV panel over the last few decades. We then utilized the estimated LR to project future module cost reduction pathways based on a range of solar deployment scenarios.

2. Methodology and data

In the estimation, we utilized world average PV module cost per watt as the performance measure instead of using prices as a proxy for a more accurate estimation of LR (Nemet, 2006; McDonald et al, 2001). In addition to cumulative global solar PV production, the following potential explanatory factors (1) silicon prices; (2) demand and supply gap of world PV market; and (3) Chinese share in world PV production were also tested to analyze their contributions to cost reductions in the production of PV module from 1988 till 2006.

Firstly, we estimated PV's LR for 1988 till 2006 as a whole using only cumulative production as commonly practiced in past studies in estimating technical progress of energy technologies (IEA, 2000; Harmon, 2000; Poponi, 2003). Subsequently, we included the above-mentioned other potential influential factors to analyzed their effects on cost reductions of PV module. Where applicable, we repeated the above exercises using both nominal and real prices for comparison.

In the next step, we divided the review period into the following three periods and repeated the above processes to examine changes in LR as technologies mature:

(1) 1988 – 1996: Preparation for takeoff – period where terrestrial application, mostly stand-alone become dominant over spaced-based applications.

(2) 1997 – 2001: Early commercial – which was characterized by rapid deployment of PV in member countries of the European Union, especially Germany, Spain and Italy following a series of government support programs and most importantly the implementation of FiTs.

(3) 2002 – 2006: Commercialization – a high growth period with increasing mass production of PV panels in a highly competitive global market with emergence of new and less costly PV technologies such as thin film.

In terms of the data used for the analysis, average silicon prices per kg of mono- and multi-crystalline silicon from 1988 to 2010 were collected from Trade Statistics of Japan by Ministry of Finance. These prices were adjusted to 2007 US dollars using gross domestic production deflator of United

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States. World annual and cumulative solar PV production data from 1975 to 2010, world average PV module cost per watt from 1975 till 2006 were obtained from database of Earth Policy Institute Data Centre. Nonetheless, global average PV module cost per watt from 2007 till 2010 were our own estimations. World annual and cumulative PV installed capacity data from 1995 to 2011 were compiled from EPIA (2008, 2012). For period beginning 1975 till 1994, world annual installed capacity was assumed to equal global annual PV production on account of the industry was still a niche electricity source at this stage, and there was no excess of production capacity.

3. Estimated results and discussions

3.1 LR for 1988-2006

3.1.1 Cumulative production

LR of both nominal and real prices was the highest when only cumulative production was considered. However, correlation coefficient, R^2 value, that expresses the quality of the fit between the data and the estimated LR were well below 0.95, hence an indication of possible missing explanatory factor in the estimation (McDonald et al, 2001). Where else, Durbin-Watson (DW) values were close to 0 and indicated evidence of positive serial correlation.

3.1.2 Silicon prices

We added silicon prices in addition to cumulative production and re-estimated the LR. R^2 and DW values for both nominal and real prices improved and LR dropped from 7.6% to 5.2% for nominal price as showed in equation S2-a, and from 14.2% to 8.1% for real price as per equation S2-b of Table 3. Improved R^2 and DW values denoted that silicon prices should be considered in estimating LR of solar PV, or risk the possibility of over-estimate the LR.

3.1.3 Influence of demand and supply gap of world PV market and Chinese share in world PV production to the pricing of world solar PV

Demand and supply gap of world PV market, and share of Chinese solar PV in world market were included in the estimation as potential explanatory factors to examine if there is any relationship between these factors with cost reductions of PV module. However, we were unable to establish meaningful relationship from our results regardless of whether the data was in nominal or real prices as showed in equation S3-a, S4-a, S3-b, S4-b in Table 3. Nonetheless, it is worth noting that in practice it is very difficult to separate effect of the many explanatory factors. For instance, the effect of Chinese share in annual world PV production could be covered as part of the silicon prices factor. Additionally, capacity instead of share to annual world production of PV might be a better explanatory factor in assessing changes in cost following rapid expansion of Chinese PV module in the market.

3.1.4 Comparisons of estimated LR using data in nominal and real prices

Comparing the LR results with data in nominal and real prices, generally, LR is lower when estimated using data in nominal prices. LR with data in nominal prices was approximately 3 percentage point lower than that of real prices as showed in equation S2-a and S2-b respectively, due to inflation. Additionally, LR estimations with data in real prices have higher R^2 and DW values than that of nominal prices, hence implies that the use of data in real prices is preferred in order to obtain the real rate of technical progress.

3.2 LR and stages of technology (industry) development

This section examined changes in LR as technology mature by diving the review period into three periods namely 1988-1996; 1997-2001; and 2002-2006. LR estimated with only cumulative production for both nominal (equation P1-a) and real prices (equation P1-b) again has a low R^2 value and a DW value close to 1.

Pertaining to demand and supply gap of world PV market, as well as share of Chinese solar PV in the world market, again, as denoted equations P3-b and P4-b in Table 3, we were unable to establish meaningful results to demonstrate their contributions to module cost reductions over the last 20 years. Nonetheless, these results need to be interpreted with care as discussed in section 3.1.1 above.

Comparing the LR results with data in nominal and real prices, again LR is found to be lower when estimated using data in nominal prices for the same reasons as discussed in section 3.1.4 above.

In equation P2-b, where LR was estimated with cumulative production and silicon prices, R^2 value was the highest at 0.9771 with a DW value of 2.08. Results denoted that LR dropped as industry develops and enter commercialization. LR was closed to 12% during 1988 to 1996, dropped to 10.7% in 1997 till 2001 and slowed to 10.2% from 2002 onward to 2006. This conformed to theory where young technologies learn faster from market experience than old technologies with the same progress ratios. The same absolute increase in cumulative production will have more dramatic effect at the beginning of a technology's deployment than it will later on.

Studies found that choosing the time period to use for calculating the LR differs substantially (Nemet, 2006) and that the analysis of the diffusion and adoption of new technologies using LR calls for careful interpretation as results showed that relatively small changes in the LR will result in significant changes in costs of electricity (Neij, 1997). Our methodology demonstrated that it is meaningful to examine LR of energy technologies according to stages of industry/technology development in order to obtain a more accurate estimation of recent LR. Nonetheless, a technology breakthrough, and further expansion of thin film modules into the market could bring faster cost reductions than indicated by our estimations for today's technology.

4. Sensitivity of PV module cost projections to solar deployment scenarios

In this section, we examined the sensitivity of PV module cost reductions to global PV deployment scenarios using our estimated LR results in section 3 above. We extrapolated PV module costs till 2030 using estimated LR of equation P2-b (see Table 3), where module cost is a function of cumulative PV production and silicon prices as showed in equation (1). We utilized global cumulative installed PV capacity projections as a proxy to global cumulative PV production, and assumed no changes to the price of silicon throughout the period.

$$MDCost = f\,(WPVCUM, PAVE2007) \qquad (1)$$

where MDCost is the global average PV module cost per watt in real prices; WPVCUM is global cumulative PV production; PAVE2007 is the average silicon prices per kg in real prices.

To explore sensitivity of PV module costs to solar deployment, three scenarios namely (1) *WEO2011 Current Policies scenario*; (2) *WEO2011 New Policies scenario*; and (3) *EPIA Solar Generation 6 – Accelerated scenario* were selected for the analysis. Global cumulative installed PV capacity for each of these scenarios was as summarized in Table 1.

Fig. 1 showed the results of the sensitivity analysis. In *EPIA Accelerated Scenario*, module costs in real prices will drop the fastest from $3.8/W in 2006 to $2.01/W in 2020 and $1.68/W in 2030. Overall, module cost reduction is projected to be in the range of 19% to 35% in 2030 against 2011 level for the three solar deployment scenarios analyzed. Nonetheless, these projections should be regarded as indicative of possible pathway of cost reductions, where with technology breakthrough and further expansion of less costly thin film modules into the market, module cost may drop faster than indicated by estimated LR for the same deployment level.

The averaged installed PV system prices in Japan was $6.5/W in 2009, with module costs accounted for up to 65% of total system costs and the rest from balance of system (20% of total) and installation (15% of total) (METI, 2011). Using the above module cost projections, we calculated the cost per kWh of PV-generated electricity in 2030 by assuming annual capacity factor of 12% over a life span of 20 years (NPU, 2011), and that module cost will account for 50%, 60%, and 65% of total system cost in 2030. Cost of a unit of PV-generated electricity in real prices are anticipated to be in the range of $0.12/kWh to $0.20/kWh in 2030 for the three scenarios analyzed as summarized in Table 2.

5. Conclusion

We assembled historical PV data from 1988-2006 to estimate and analyze its LR. Our analysis indicated that estimated LR using only cumulative production denoted possible missing explanatory factor in the estimation, and that other important explanatory factors such as silicon prices should also be considered. Real prices data is preferred for the estimation to account for inflation where applicable. Additionally, LR of energy technologies should be examined according to stages of development to reflect changes in LR as industry/technologies mature. With consideration to the above findings, we estimated that LR was 12% for 1988-1996, dropped to 10.7% for 1997-2001 and slowed to 10.2% for 2002-2006.

In sensitivity analysis of PV module cost projections using a range of solar deployment scenarios, results indicated that module costs in real prices will drop from $3.8/W in 2006 to $2.01/W in 2020 and $1.68/W in 2030 for the most accelerated solar deployment scenario. Overall, module cost reduction is projected to be in the range of 19% to 35% in 2030 against 2011 level for the three scenarios analyzed. Nonetheless, these projections should be regarded as indicative of possible pathway of cost reductions as technology breakthrough and further expansion of less costly PV modules may drive faster cost reductions than indicated.

Table 1 Long term scenario studies of global PV deployment to 2050.

Scenario	Global cumulative installed PV capacity (GW)						
	2011 (Actual)	2020	2025	2030	2035	2040	2050
IEA Solar PV Technology Roadmap	69.7	210	-	872	-	2019	3155
WEO2011 Current Policies Scenario		161	-	268	314	-	-
WEO2011 450-Scenario		220	-	625	901	-	-
WEO2011 New Policies Scenario		184	272	385	499	-	-
EPIA Solar Generation 6 - Reference Scenario		76.9	-	111.8	-	268.9	377.3
EPIA Solar Generation 6 - Accelerated Scenario		345.2	-	1081.1	-	2013.4	2988.1
EPIA Solar Generation 6 - Paradigm Shift Scenario		737.2	-	1844.9	-	3255.9	4669.1
JPEA Solar PV Outlook		340	776	1573	-	-	-
ETP 2012 6°C Scenario		-	-	-	-	-	556
ETP 2012 4°C Scenario		-	-	-	-	-	1,153
ETP 2012 2°C Scenario (Base)		-	-	-	-	-	2,655
ETP 2012 2°C Scenario -no CCS		-	-	-	-	-	3,237
ETP 2012 2°C Scenario-high RE scenario		-	-	-	-	-	4,822
ETP 2012 2°C Scenario-high Nuclear Scenario		-	-	-	-	-	2,639

Source: EPIA (2011, 2012); IEA (2010, 2011, 2012); JPEA (2010).

Figure 1 PV module cost reduction projections to 2030 under a range of solar deployment scenarios.

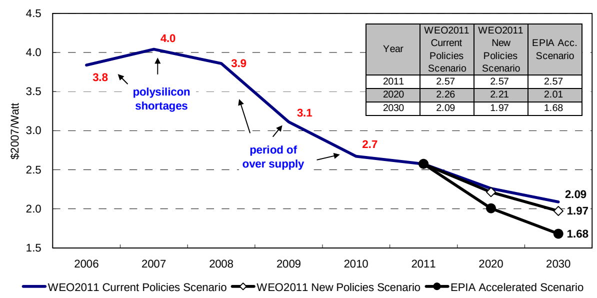

Table 2 Calculated cost of PV-generated electricity in 2030 under a range of solar deployment scenarios.

Case	65-Case	60-Case	50-Case
(a) Assumptions			
Share of module cost to total system cost (%)	65%	60%	50%
Capacity factor (%)		12%	
Life span of PV system (years)		20	
(b) Projected module cost in 2030 ($2007/W), this study			
- WEO2011 Current Policies Scenario		2.09	
- WEO2011 New Policies Scenario		1.97	
- EPIA Accelerated Scenario		1.68	
(c) Calculated cost of PV-generated electricity in 2030 ($2007/kWh), this study			
- WEO2011 Current Policies Scenario	0.15	0.17	0.20
- WEO2011 New Policies Scenario	0.14	0.16	0.19
- EPIA Accelerated Scenario	0.12	0.13	0.16

Note: (1) This calculation is based on estimated module costs from this study, and other assumptions as outlined in Table 2. Discount rate, O&M cost, which are often included in estimating levelized cost of electricity (LCOE) were not considered in our calculation.
(2) NPU (2011) considered four levels of discount rate – 0%, 1%, 3% and 5% in its estimation of LCOE for PV system in Japan. LCOE for residential PV system was estimated to be in the range of $0.12/kWh to 0.23/kWh in 2030 (at $1=85.74yen, as utilized throughout this study).
(3) O&M for PV system was assumed to be $0.002/kWh in Poponi (2003), and $0.02 to $0.1/kWh in Neij (1997).

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Table 3 Estimated learning rates of PV in this study.

	Variables		Country/ Region	Time period	Correlation coefficient, R^2	Durbin–Watson, DW	t-value				Learning rate (LR), %			Performance measure
							World cum prod (MW)	Silicon prices ($/W), ($2007/W)	World ann inst /world ann prod	Share of Chinese prod in world PV prod (%)	1988-1996	1997-2001	2002-2006	
Nominal Prices	P1(a)	LC	World	1988-2006	0.7076	0.838	-2.78				7.3	7.9	7.2	module cost per watt ($/W)
	P2(a)	LC + Silicon prices	World	1988-2006	0.9306	1.853	-6.17	7.01			9.3	8.2	7.7	module cost per watt ($/W)
	S1(a)	LC	World	1988-2006	0.6844	0.549	-6.33				7.6			module cost per watt ($/W)
	S2(a)	LC + Silicon prices	World	1988-2006	0.9122	1.391	-7	6.72			5.2			module cost per watt ($/W)
	S3(a)	LC + Silicon prices + Demand and supply gap	World	1988-2006	0.9073	1.425	-3.72	5.37	*-0.38*		5.7			module cost per watt ($/W)
	S4(a)	LC + Silicon prices + Share of Chinese prod in world PV prod	World	1988-2006	0.9072	1.385	-2.72	2.65		*0.35*	5.9			module cost per watt ($/W)
At $2007	P1(b)	LC	World	1988-2006	0.8858	0.756	-5.62				15.5	16.2	14.9	module cost per watt ($2007/W)
	P2(b)	LC + Silicon prices	World	1988-2006	0.9771	2.08	-7.38	7.8			11.8	10.7	10.2	module cost per watt ($2007/W)
	P3(b)	LC + Silicon prices + Demand and supply gap	World	1988-2006	0.9755	2.124	-5.2	6.68	0.26		11.6	10.4	9.9	module cost per watt ($2007/W)
	P4(b)	LC + Silicon prices + Share of Chinese prod in world PV prod	World	1988-2006	0.9754	2.061	-3.2	3.56		*0.06*	12	10.9	10.4	module cost per watt ($2007/W)
	S1(b)	LC	World	1988-2006	0.8652	0.429	-10.79				14.2			module cost per watt ($2007/W)
	S2(b)	LC + Silicon prices	World	1988-2006	0.9688	1.439	-7.53	7.57			8.1			module cost per watt ($2007/W)
	S3(b)	LC + Silicon prices + Demand and supply gap	World	1988-2006	0.9671	1.465	-4.14	5.64	*-0.43*		8.9			module cost per watt ($2007/W)
	S4(b)	LC + Silicon prices + Share of Chinese prod in world PV prod	World	1988-2006	0.9668	1.402	-2.81	3.14		*0.28*	8.9			module cost per watt ($2007/W)

Note: LC = learning curve; world cum prod = world cumulative production; world ann inst = world annual installation; world ann prod = world annual production; PV = photovoltaic; MW = megawatt; W = watt