Deconstructing solar photovoltaic energy: Part 2

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ABSTRACT
This is the second and concluding part of a study on the solar photovoltaic market. In the first part, photovoltaic energy was contrasted with other energy sources used to generate electricity, and cost points necessary to produce a sustainable photovoltaic market were identified. In this second part, learning rates required to attain those cost points are provided. The paper concludes by examining a scenario in which 15% of the world's electricity in 2035 is generated using photovoltaic energy, and frames the challenge from both global investment and profitability perspectives.

Introduction

The previous edition of *Photovoltaics International* presented the first part of a study on deconstructing the PV market and its cost structure into logical components in order to bring some clarity to critical issues facing the industry, which is currently going through a turbulent period [1]. One critical question is what (and when) new disruptive technologies will be required in each of the three categories – cell, module and balance of system (BOS) – to maintain the necessary cost learning rates to continue to drive PV-generated electricity from today's US$0.20–0.40/kWh to ~US$0.10/kWh. The search for answers has led to investments in alternative thin-film technologies (primarily CdTe and CIGS) as well as monolithic and frameless methods for (automated) module construction, etc. Some of these technologies will become mainstream – most will not.

With the foundation having been laid in Part 1 of the study [1], Part 2 begins with a cost breakdown of the PV energy supply chain from system installation to cell manufacturing. The PV market evolution is then reviewed, and the likelihood of 15% of the world's electricity being generated by PV energy is discussed.

PV installation costs

The breakdown of installation costs (in terms of the average selling price ASP) is shown in Fig. 1; these costs represent the aggregation of the selling prices [2–4] relating to:

- BOS not including the inverter (BOS-I): 50–60%
- Inverter: 7–9%
- Module: 30–35%
- Cell: 60–70% of module

Historically the PV module has constituted 45–50% of the installation ASP, but this percentage has dropped recently into the low thirties, as module ASPs have fallen at a much faster rate than the BOS components.

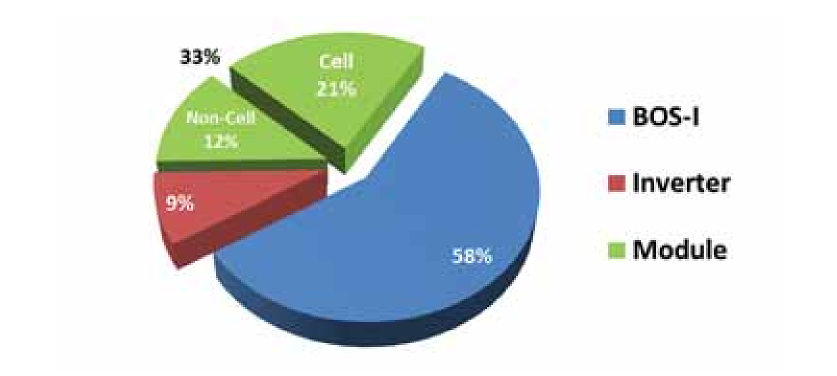

Figure 1. Breakdown of PV installation costs.

Between 2001 and 2011, installation costs in the USA dropped over 50% – from \$10/W to approximately \$4.5/W [4–6]. European installation costs, while ~25% lower because of higher volumes, exhibited a similar decline during the same period [7] (Fig. 2). In both cases, this translates into a learning rate of ~13%; in other words, on a dollar per watt basis, the price charged for a PV installation fell ~13% each time the installed capacity doubled. The price drop has been more dramatic since 2009 [7]. Isolating the period from 2009 to 2012 (extrapolated), installation costs had a learning rate of 28% – more than double the 10-year learning rate. The reason for the accelerated learning rate is primarily the precipitous drop in module pricing. On the basis of the market growth assumptions presented later in this article, the learning rate required to achieve a blended \$1.45/W installation price (equating to a levelized cost of electricity LCOE of ~\$0.10/kWh) within 10 years (2022) is 24%; this is significantly greater than that of the past 10 years, but less than the observed rate over the past three years. Given the economic challenges that the industry has had in digesting the past three years of 28% cost-reduction learning rates, maintaining a learning rate of 24% for the next 10 years appears daunting.

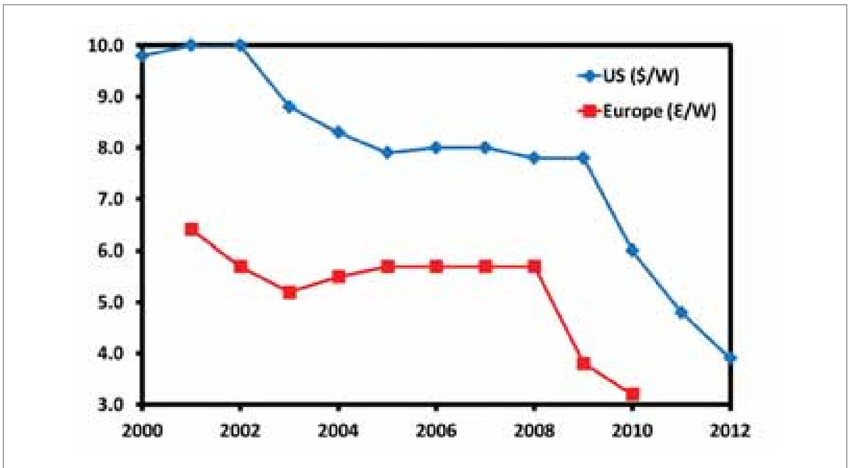

Figure 2. Historical installation costs in the USA and Europe.

> "The learning rate required to achieve a blended \$1.45/W installation price within 10 years (2022) is 24%."

In addition to the conventional volume-based learning rate, installation cost (not surprisingly) is a strong function of the market segment. Residential prices are considerably higher than commercial/industrial prices, which in turn are considerably higher than utility prices. This is primarily a function of scale and the ability to leverage BOS costs across a larger installation. At \$3/W, average PV utility installation costs at the end of 2011 were just above the \$2.50/W inflection point [1], and the best-in-class PV utility installations (>20MW) were already there [7,8]. The utility-scale installation average is likely to have achieved the \$2.50/W cost point in 2012.

PV BOS costs

PV BOS costs excluding the inverter (BOS-I) typically make up 50–60% of PV installation ASP. Over 65% of the BOS-I costs are hardware and labour related and consist of a combination of costs associated with racking, mounting, cabling, etc. (30%), labour (20%) and design/project management (13%) [2,9–11] (Fig. 3). While none of these items 'scale' in the conventional sense, there is a great deal of effort being placed, especially within the utility sector, in standardizing designs, reducing overheads and streamlining installations in order to further reduce costs. Improvements will come both in physical design (electrical systems, hardware standardization, structural design for low-labour installation, etc.) and in business processes (improved project management, standardization of installation best practices and system design, streamlining of the permit process and other overheads, site preparation standardization, etc.).

Over the period 2001 to 2011, worldwide BOS prices have been cut in half, from approximately \$5.0/W to \$2.6/W [6,7,9] (Fig. 4). This equates to a learning rate of ~12%: i.e. BOS prices dropped 12% each time the installed capacity doubled. However, costs varied significantly depending on the location and the type of installation: BOS costs for utility-scale installations, for example, were as low as \$1.40/W towards the end of 2011 [10].

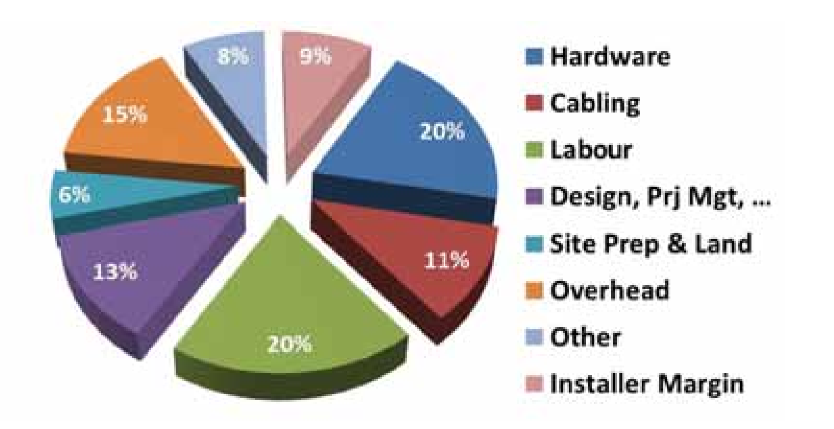

Figure 3. Breakdown of PV BOS costs (excluding inverter).

Source: Acero Capital compilation

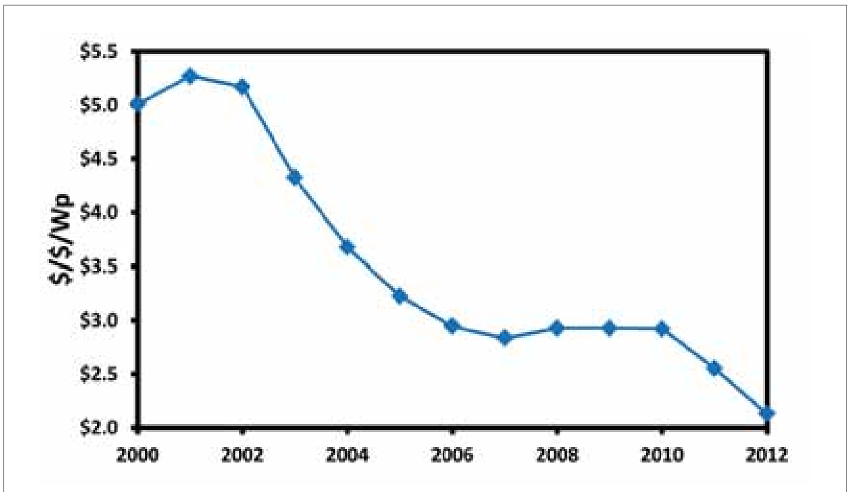

Figure 4. Historical BOS \$/W ASP.

Source: Acero Capital compilation

Under the assumption that the PV BOS recovers to 60–65% of installation ASPs going forwards, the BOS price required to support a \$1.45/W installed price point (equating to an LCOE of ~\$0.10/kWh) is \$0.80–0.94/W. The learning rate required to achieve this range of BOS price over the next 10 years is ~25%. Given the historical learning rate of ~12% and the makeup of BOS costs, achieving a 25% learning rate will be challenging and could well be the limiting factor in PV installation cost reductions. As a consequence, efforts have been made to systematically break down BOS costs in order to determine the necessary steps to achieve a BOS cost of \$0.88/W [11,12].

PV module costs

Historically, PV module ASPs have constituted 40–50% of the overall PV installation price. But, because of the precipitous drop in module ASP over the past three years, this percentage has fallen to 30–35%. Over 60% of the module cost is made up of the cost of the cells (Fig. 5). Most of the balance of the module costs (~25%) is attributable to basic materials such as EVA, backsheet, frame, glass, J-box, cable, ribbons, etc. [3,4,13]. The labour contribution tends to be relatively small, of the order of 1%. It follows that the focus for module cost reductions will be on material elimination (e.g. frameless modules) or reduction, and on material cost reductions (in particular reducing the cost of the backsheet and EVA). Nevertheless, given that the cell cost constitutes over 60% of the module cost, cell cost reduction and efficiency improvement need to be two of the major drivers in reducing module cost per watt.

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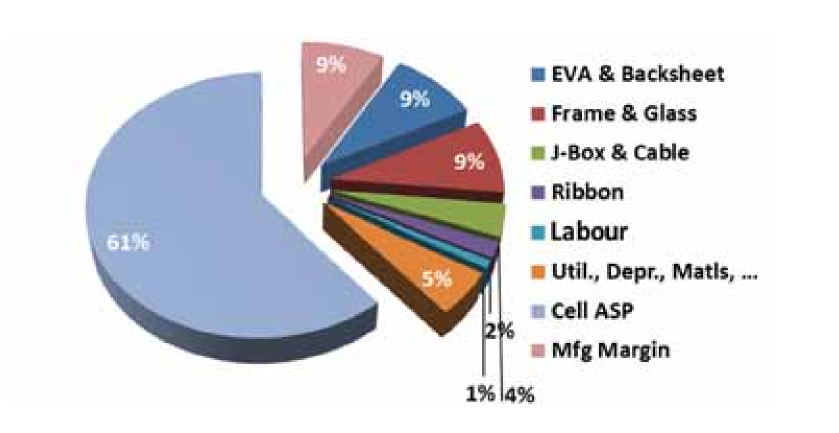
From 2001 to 2011, worldwide module ASPs fell by 60%, from approximately \$3.00/W to \$1.25/W [14,15] – a learning rate of ~13% (Fig. 6). However, almost all of the reduction in ASP has occurred since 2008, corresponding to a learning rate over the past four years of ~36% (or ~32% since 2009). The two main reasons for the recent doubling of the learning rate are:

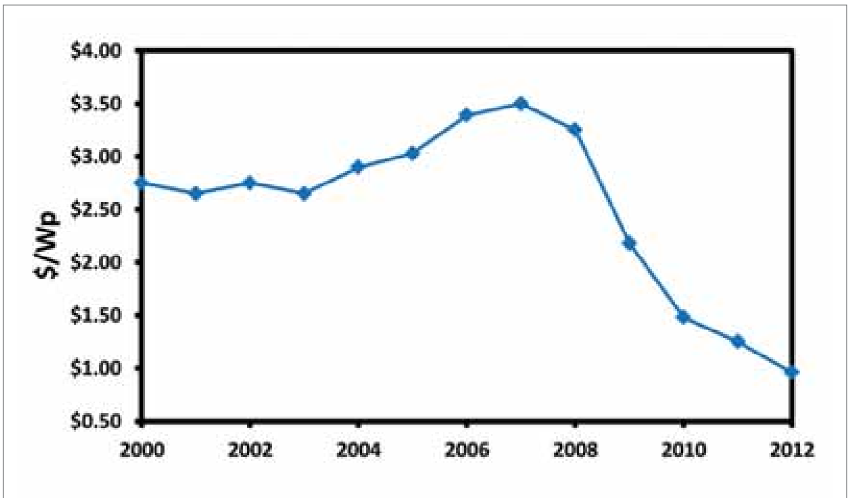
1. Polysilicon market price dynamics (undersupply to oversupply – prices held up and then dropped rapidly).

2. Competitive response to the PV market potential, resulting in overcapacity and a corresponding narrowing of the cost-to-ASP gap.



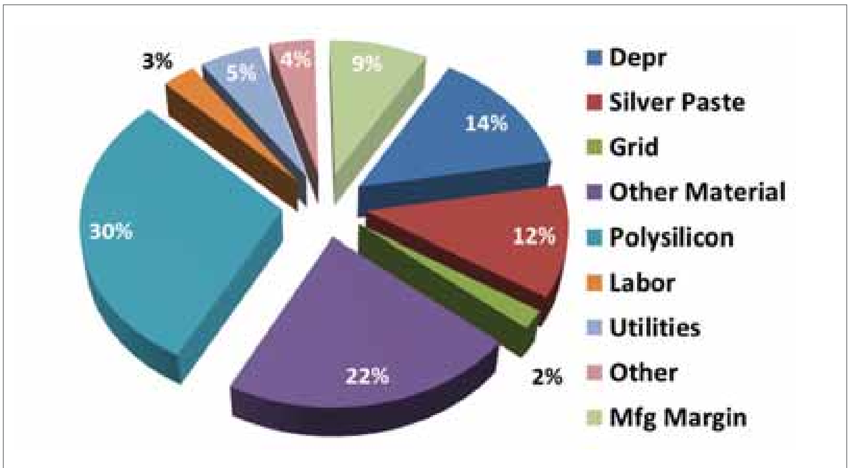
Source: Acero Capital compilation

Figure 5. Breakdown of PV module ASP.



Source: Mints [14,15]

Figure 6. Historical module ASP to first buyer.



Source: Acero Capital compilation

Figure 7. Breakdown of PV cell ASPs.

This market dynamic continued into 2012: as of May 2012, module prices had dropped to \$0.70–0.90/W [16]. Given the industry fallout and resulting low module margins, it is not clear how much longer this pricing rate decline can continue. Nonetheless, given the amount of capacity that is currently in place, it would not be surprising if the learning rate remained at ~30% through 2015 or 2016.

It is likely, however, that the longer-term cost learning rate will fall somewhere in between the last ten-year and the more recent three-year learning rates, i.e. ~22%, which turns out to be the 30-year learning rate [9]. Assuming that the PV module ASP rebounds to 35–45% of the installation price, the module ASP required to support a \$1.45/W installation price point (equating to an LCOE of ~\$0.10/kWh) would be \$0.51–0.65/W. The learning rate required to achieve the bottom range of this module price within the next ten years is ~18%. While this learning rate appears achievable, it will need to be driven primarily by reductions in cell cost and improvements in cell efficiency.

PV cell costs

PV cells typically make up 60–75% of PV module costs. Material costs, including polysilicon, account for approximately 65% of the cell cost [3,4,16] (Fig. 7). And, in spite of the recent drop in pricing, from well over \$100/kg to \$24/kg, polysilicon remains the largest component of cell cost at ~33%. Cell costs are typically broken down into substrate (\$0.15–0.18/W, depending on the cost of polysilicon), wafer (~\$0.18/W) and cell conversion (~\$0.19/W) costs [17]. Needless to say, cost reductions in all three areas are being aggressively pursued. These cost reductions fall into three general categories:

1. Efficiency improvements: minimizing photon, carrier or electrical losses [18].

2. Material cost reductions: use of poly-Si and minimizing wafer thickness if Si-based, material consumables, replacement or reduction of silver, etc.

3. Productivity improvements: equipment throughput/cost, yields, uptime, labour (e.g. operators and/or maintenance for each piece of equipment), floor space, etc.

In the case of Si-based cells, today's dominant technology, a variety of options can currently be found in prototype lines: selective emitters, textured front surfaces, heavily doped rear surfaces and rear-contacts, and increasing use of n-type substrates and, in more extreme cases, approaches such as emitter or metal wrap-through structures (EWT, MWT) [18,19].

Between 2001 and 2011, worldwide PV cell ASPs dropped by more than half, from approximately \$2.20/W to \$0.90/W; as of May 2012 they were down to \$0.51/W [16,20] (Fig. 8). This translates to a learning rate of ~15%: i.e. cell costs fell 15% each time the installed capacity doubled. From 2009 to 2012, however, this learning rate has more than doubled, reaching ~38%. Under the assumption that the PV cell price remains at ~70% of the module price going forwards, the cell price required to support a \$0.51–0.65/W module ASP point (or support an LCOE of ~\$0.10/kWh with the BOS cost assumed above) is \$0.36–0.46/W. The learning rate required to achieve the bottom range of this cell price within 10 years (2022) is ~11%, which is not particularly aggressive compared to historical learning rates. On the other hand, since improvements in cell cost and cell efficiencies drive downstream cost reductions, the pressure to achieve learning rates better than 11% will remain intense.

> "The cell price required to support a $0.51–0.65/W module ASP point is $0.36–0.46/W."

A summary of the various learning rates discussed above for the historical periods 2001–2011 and 2009–2012, as well as the learning rate required to achieve a $1.45/W installed ASP by 2022, is provided in Table 1 and graphically illustrated in Fig. 9. It is clear that the industry has not been characterized by a single learning rate in the past 12 years. Rather, there was a relatively slow learning rate from 2001 to 2008, followed by a rapid acceleration in the last four years. As discussed earlier, pricing in this recent period was driven by a precipitous drop in polysilicon pricing as well as a surge in capacity resulting in an imbalance between supply and demand. What is interesting is that using 2012 as the starting point, the learning rates required to achieve the $1.45/W installation ASP benchmark by 2022, consistent with an LCOE of $0.10/kWh, appear to be well within the capability of the front end of the industry (module and cell). But the learning rate requirements for BOS and therefore the complete system installations are significantly higher than what the industry has managed to deliver over the past 10 years. The implications are twofold. First, unless the BOS segment of the PV supply chain changes from 'business as usual,' it will be difficult to achieve the $1.45/W price point by 2022. Second, the pressure on reducing module and cell costs through accelerated learning rates will continue to offset what ideally would be a proportionate contribution from the BOS segment.

Deconstructing the total available PV market

The PV market has been growing at a compounded annual growth rate of ~30% over the past 10 years [21] (Fig. 10). However, a geographic deconstruction of this growth reveals that it has been fuelled by asynchronous growth of individual markets that have in turn been fuelled by starts and stops of subsidies [21] (Fig. 11). Thus, while on the surface the PV market appears relatively smooth and 'untroubled,' there has been considerable turmoil beneath the surface. Fortunately for the industry, the changes in individual country subsidies that have produced the underlying market turmoil have been offset in time, with the end result being that the overall industry has continued to grow at a rapid rate [22]. But to achieve continued growth, unsubsidized PV costs have to come down to the point that

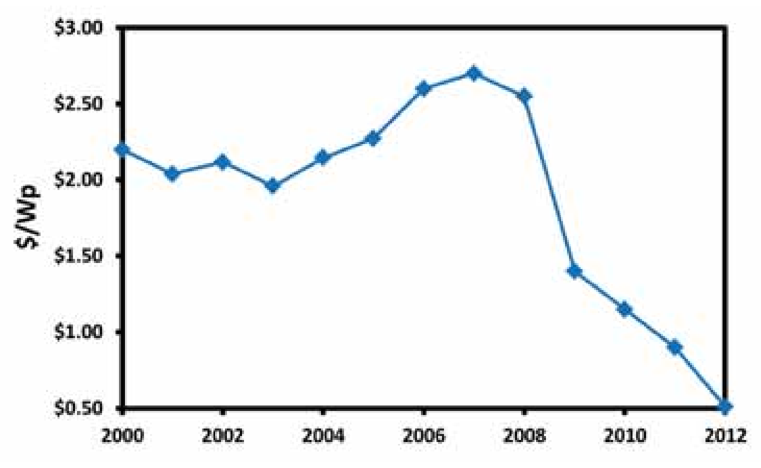


Figure 8. Historical PV cell ASP.

Source: Acero Capital compilation

	2001–2011 [%]	2009–2012 [%]	2012–2022 [%]
Install	13	28	24
BOSI	12	14	25
Module	13	32	18
Cell	15	38	11

Table 1. Summary of historical PV component learning rates and forward-looking learning rates required to achieve $1.45/W by 2022.

Source: Acero Capital compilation

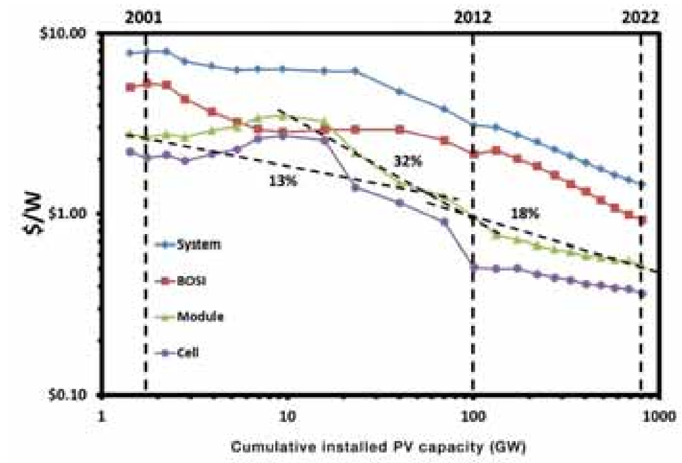


Figure 9. Graphical summary of PV component learning rates.

Source: Acero Capital

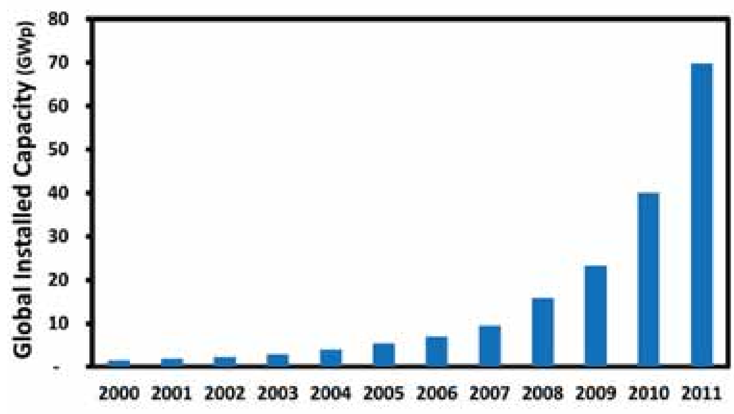


Figure 10. Evolution of the solar market.

Source: EPIA, May 2012

Market Watch

electricity generation from PV makes financial sense. The cost of subsidizing gigawatt levels of PV generation capacity has become prohibitive for most countries, especially in the light of the overall world macroeconomics. It follows that to achieve a self-sustaining growth trajectory, typical of most unsubsidized markets, the cost of PV electricity generation must stand on its own merits. As noted in the previous section, the industry is rapidly approaching a cost tipping point that will enable revenue sustainability, if not always profitability.

> "To achieve continued growth, unsubsidized PV costs have to come down to the point that electricity generation from PV makes financial sense."

Market Watch

Aside from geographic classification, the PV market is commonly divided into three segments: 1) residential, 2) non-residential (industrial/commercial) and 3) utility/ground-based. Residential installations tend to be rooftop systems, and in the USA these average ~6kW (Table 2). Utility-scale installations are typically ground-mounted and increasingly single-axis tracker systems, and have been getting larger over time. The 2012 US utility segment average (through May 9 2012) is ~10MW per installation – double the 2009 average installation size. Finally, industrial/commercial US installations average ~85kW.

Of the three installation types, the utility segment is the fastest growing, with a growth of ~760MW in 2011, and over 3GW of projects in construction [5] – almost three times that in 2010. Note that, from an installation cost perspective, in 2011 there was approximately a $1/W difference between the three segments. This translates to the residential segment having the smallest total available market (TAM) at ~$1.7 billion, with the non-residential having the largest at ~$3.9 billion [5].

Finally, the market can also be divided into grid-connected and off-grid segments. In the USA, as in most of Europe and increasingly Asia and the rest of the world, the bulk of the PV market is grid connected: more than 95% of the 2010 US installations and more than 80% of the cumulative US installations were grid connected [23].

How big can the PV market get?

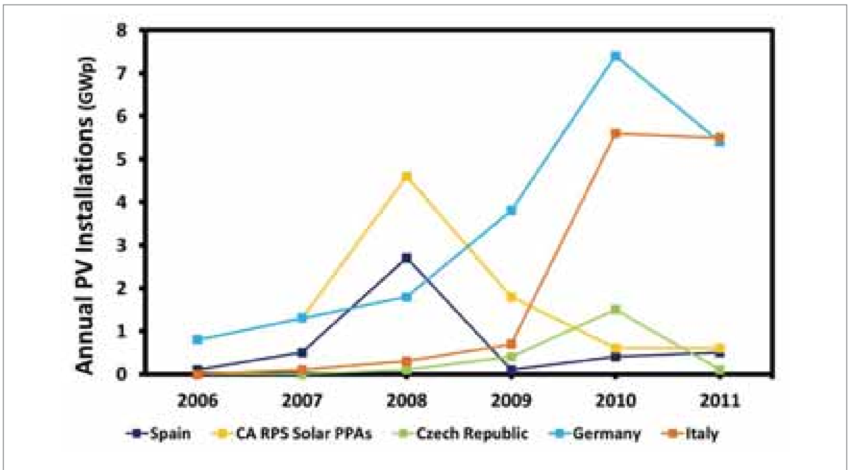
Rather than providing a PV market forecast (this has been demonstrated to be a losing proposition, with forecasts prepared over the past few years quickly becoming obsolete), the question has been turned around and now becomes: what investment would be necessary to achieve 15% of the world's electricity generation from PV by 2035? This scenario requires ~3800GW of installed PV generation capacity and a ~$4.9 trillion investment (Table 3). Annualized this would require building every year for 25 years the equivalent of ~1500 100MW PV power generating plants. This is no small task given that there are only a handful of 100MW-capacity PV power plants in existence today [26]. The resulting invested capital required averages out to ~$200 billion per year. From a market perspective, the result is a TAM growth from ~$100 billion to over $300 billion. At the module level this would translate to a TAM growth from ~$30 billion to ~$125 billion, and a cumulative spending of ~$1.6 trillion, equivalent to ~35% of the total investment in PV installations. Finally, at the cell level the TAM would grow from ~$20 billion to ~$90 billion, with a cumulative spending of ~$1.2 trillion, which is equivalent to ~70% of the total spending for modules. As an aside, the land mass required (assuming ~33km^2/GW) would be roughly 20% larger than either Cuba or South Korea. While not insignificant, this would still be a relatively small percentage (less than 0.1%) of the world's land mass.

Putting a 15% PV market into perspective

While a $4.9 trillion investment is enormous, it is important to put this expenditure into context. It is estimated that $10 trillion will be invested in incremental electricity generation over the period 2010–2035 [27] (Fig. 12). The relevant question is therefore: if the world's economies were to invest $4.9 trillion in PV electricity generation over this 25-year period to achieve the 15% PV metric, would this make economic sense compared with investments in alternative sources of electricity generation?

From an invested capital perspective, a simple breakeven argument would imply that, since the $4.9 trillion PV investment would be nearly half of the projected $10 trillion dollars to be spent in incremental electricity generation, PV should provide half of that incremental electricity capacity. With the PV cost roadmap cited, for $4.9 trillion, or 49% of the total investment in electricity production, in this model PV power plants would supply ~38% of the incremental electricity (Table 4).

Looking only at capital expenditure, either a $1.1 trillion 25-year subsidy (~$40 billion/year) or an installed cost lower



Source: EPIA, May 2012

Figure 11. Breakdown of the solar markets (CA RPS = California renewables portfolio standard).

	2010 Installations			2011 Installations			2010–2011 MW
	Number	Avg size [kW]	MW	Cost [$/W]	TAM [$bn]	MW	Growth [%]
Residential	45,570	6	266	6.00	1.67	279	5
Non-residential	4,486	85	367	5.00	3.93	785	114
Utility	30	8,500	255	3.50	2.65	758	197

Table 2. Summary of US grid-connected market segmentation by type.

Source: Acero calculations; SEIA (March 2012)

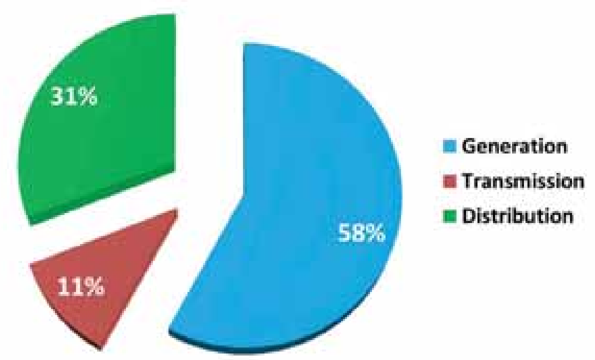
		2010	2015	2020	2025	2030	2035
WW electricity	T kWh	21.3	22.7	25.5	28.7	31.9	35.2
WW solar	G kWh	52	294	777	1,756	3,217	5,295
Solar %	%	0.25	1.3	3	6	10	15
Solar capacity	GWp	40	220	576	1,285	2,325	3,778
New 100MWp plants	-	n/a	1,807	3,558	7,087	10,397	14,532
New plants/year	-	n/a	361	712	1,417	2,079	2,906
Capital cost/year	$bn	n/a	107	135	192	237	304
WW land used	km^2	1,327	7,349	19,209	42,831	77,486	125,926
% of WW area	%	0.001	0.005	0.013	0.029	0.052	0.085
Cum. plants			1,807	5,365	12,451	22,848	37,380
Cum. capital ($bn)			533	1,206	2,168	3,355	4,874

Source: Acero calculations

Table 3. Required solar capacity to achieve 15% PV generation share of the market by 2035. Assumptions: 1) 2%/year growth in worldwide electricity generation [24]; 2) reduction in installed PV costs from $3/W to $1/W (~20% learning rate); and 3) improvement in capacity factor for PV-generated electricity from 15% to 16% [25].

Market Watch

than modelled ($0.77/W rather than $1.02/W by 2035) would be required to merit that 15% of the world's electricity be generated from PV on a purely invested capital basis. Obviously there are well-known arguments beyond invested capital alone as to why it can still make sense to invest at this level in PV generation capacity [28]. Nonetheless, a scenario (or goal) of meeting 15% of the world's 2035 electricity generation with PV will be quite challenging from both financial and logistical perspectives. Consequently, it should not be surprising that the US Energy Information Administration (EIA) forecast (Fig. 13) predicts 7% for *all* renewable generated electricity, a figure much less than the 15% PV scenario of Table 3. The end result will play out over the next 10–15 years, and most likely the actual figure will fall somewhere between these two extremes.



Sorce: World Energy Outlook 2012

Figure 12. Investments in power – total = $16.9 trillion (generation = $10 trillion).

Financial metrics and profitability expectations

While it is apparent that the revenue potential in the PV market is tremendous, the profitability outlook is less clear. Given the capital intensiveness of the PV power business, proper asset utilization is critical. A review of historical return on assets (ROA) percentage and earnings before interest, taxes, depreciation and amortization (EBITDA) margin from US, Chinese and German PV public companies provides insight into past performance and enables a simple model to be constructed that companies can benchmark against. For example, in order to achieve a positive ROA, a minimum EBITDA margin of 5% (and preferably 10%) is necessary (Fig. 14(a)). This in turn corresponds to a gross margin (GM) of ~20% (Fig. 14(b)). As the PV industry matures, these are likely to be metrics on which surviving companies will converge.

Since the gap between module ASP and cost is currently less than 20%, it is reasonable to assume that the module ASP learning rate in Table 1 for 2012–2022 applies equally well to module cost. It follows that the ~$0.67/W and $0.52/W module price points, corresponding to $2.50/W and $1.45/W installation prices, dictate a $0.54/W and $0.42/W module cost and a learning rate of ~18%+ in order to achieve 20% GM.

> "A scenario in which 15% of the world's 2035 electricity is generated by PV requires a cumulative $4.9 trillion capital investment in PV generation."

Conclusion

Electricity consumption in the USA starts to increase dramatically at a price point of approximately $0.18/kWh, and

		2010–2015	2015–2020	2020–2025	2025–2030	2030–2035	2010–2035
Incremental electricity	G kWh	1,400	2,800	3,200	3,200	3,300	13,900
Incremental PV	G kWh	241	484	979	1,461	2,078	5,243
PV % of increment	%	17	17	31	46	63	38

Source: Acero calculations

Table 4. Percentage of incremental electricity generated by PV.

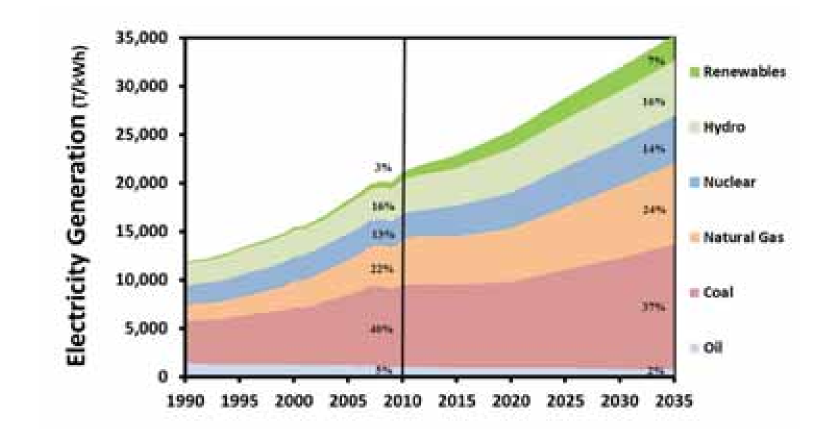


Figure 13. Forecast global energy sources for electricity generation.

Source: EIA, IEA, BP

approximately half of the USA's electricity is purchased at a price above \$0.10/kWh. Under some simplifying assumptions, the \$0.18/kWh and \$0.10/kWh translate into the following respective price points:

- ~\$2.50/W and \$1.45/W for installation
- ~\$0.67/W and \$0.52/W for modules
- ~\$0.47/W and \$0.36/W for finished cells

To provide a reasonable return on capital a 20% GM is required. This implies a \$0.54/W and \$0.42/W module cost for \$2.50/W and \$1.45/W installation costs respectively. The industry is expected to price modules at ~\$0.67/W by 2014 or 2015. The modelling carried out suggests that the second price point of \$0.52/W is achievable by 2022. PV module and/or wafer suppliers that survive must have credible paths to the upper end of these ranges within the next 18–24 months, and to the bottom end of these ranges by 2022.

From a supply chain perspective, the biggest challenge in achieving the necessary cost targets are in the installation/BOS segment. This will continue to put pressure on the cell and module portions of the PV supply chain to carry a disproportionate load of cost-reduction burden.

Finally, a scenario in which 15% of the world's 2035 electricity is generated by PV requires a cumulative \$4.9 trillion capital investment in PV generation (i.e. installations). This would be a massive infrastructure project, requiring the equivalent of ~1500 100MW PV plants be built each year through 2035. Annualized this would average out to ~\$200 billion per year. The PV module and cell spending to support this infrastructure build are ~\$67 billion and ~\$47 billion per year respectively. In order to realize the 15% scenario, either near-term cost reductions beyond what are currently modelled or significant continued subsidies will be required.

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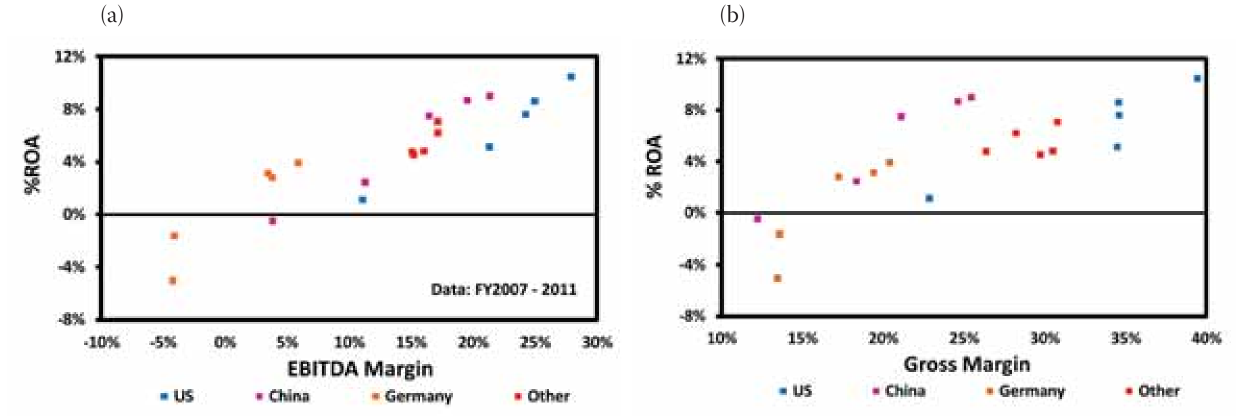

Figure 14. (a) EBITDA margin vs. % ROA; (b) GM vs. % ROA.

Source: Company information; Public filings

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