Deconstructing solar photovoltaic energy: Part 1

Antonio Alvarez & **Elisa Yoo**, Acero Capital, Menlo Park, California, USA

ABSTRACT
The PV industry is currently going through a turbulent period. By deconstructing the PV market and its cost structure into logical components, the aim of this two-part paper is to bring some clarity to critical issues facing the industry. The first part will discuss how PV compares to other energy sources for generating electricity. The second part, which will appear in the next edition of *Photovoltaics International*, will take a look at investments in technology that will be required to drive down the cost of PV-generated electricity.

Introduction

This paper begins with a basic review of electricity generation and supply and will lead up to a discussion of the global capital investment required to enable 15% of the world's electricity to be generated by photovoltaic (PV) energy by 2035 – and whether that makes financial sense. To link these two points together, a framework for understanding how PV compares to other energy sources for generating electricity is first constructed. The cost of electricity, along with the consequential cost points that PV-generated electricity must achieve to be economically competitive, is then reviewed. Another section will cover the limitations to PV market growth that are imposed by the way in which existing electrical grids are operated.

To bridge the gap between how electricity consumers and PV component manufacturers measure cost, a simple levelized cost of energy (LCOE) to dollars per watt translator is presented. This lays the foundation for a cost breakdown of the PV energy supply chain from cell manufacturing to system installation. In the final sections the PV market evolution is reviewed. The likelihood of 15% of the world's electricity being generated by PV energy is discussed from a financial perspective, and industry profitability requirements are proposed.

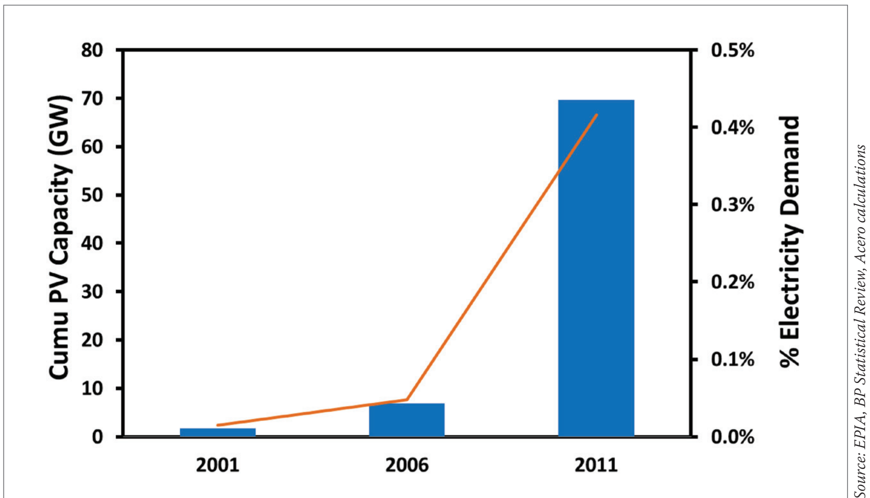


Figure 1. Worldwide electricity produced by PV energy.

> "Although the PV market has grown impressively, it still produces only a little over 0.4% of the world's electricity."

The PV market in perspective

As is typical of most nascent markets, especially those in the technology sector, the PV market has experienced a great deal of upheaval and even chaos during its formative years. This has been clearly demonstrated over the past two to three years, as the pricing dynamics, investment outlook and regulatory incentives have been in constant flux. The net result is an over-capacity situation that has led to bankruptcies, distressed acquisitions, capacity slowdowns, factory shutdowns and a precipitous drop in the market capitalization of public PV companies. While certainly cause for concern, this current state needs to be kept in perspective. Although the PV market has grown impressively – by a factor of 10 in the past five years (and a factor of 40 in the past 10 years) – it still produces only a little over 0.4% of the world's electricity [1,2] (Fig. 1).

It follows that the PV market is just getting started and, despite its recent setbacks, will continue to grow rapidly. Possibly the most pertinent question at this time is how to grow the industry in a profitable manner. To answer this question it is necessary to look at: 1) energy sources used to produce the world's electricity; 2)

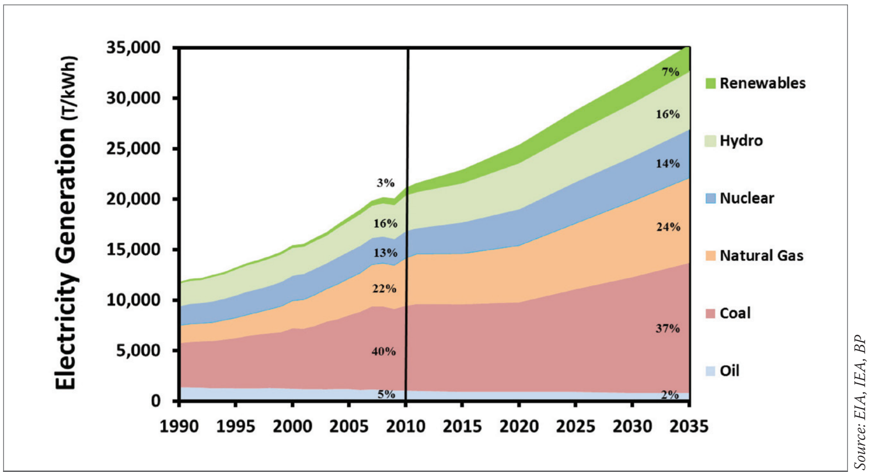


Figure 2. Forecast global energy sources for electricity generation.

price points resulting from these different energy sources; and 3) prices at which electricity is bought.

Deconstructing the energy sources for generating electricity

Over 60% of the world's electricity today is generated from coal and natural gas (Fig. 2), while nuclear energy generates approximately 13% [2,3,4]. Hydropower is by far the largest renewable energy source, contributing 16% to global electricity generation and making up ~80% of total renewable energy [4]. The PV portion is ~12% of non-hydroelectric renewables, or, as noted earlier, ~0.4% of the world's total electricity generation. Looking forward, the expectation is that, while renewables – including PV – will be the fastest growing segment of the overall electricity generation market, they will still constitute under 10% by 2035 [2].

Deconstructing the cost of electricity

The use of different energy sources results in electricity with a range of price points (Fig. 3). Nonetheless, the energy sources that make up the bulk of the electricity market in Fig. 2 – coal, natural gas, hydroelectric and nuclear – are all able to produce electricity at US$0.10/kWh or less in the USA [5]. Utility-scale PV in the USA today is only competitive with electricity generated from crude oil, which accounts for ~1% of electricity production (~5% worldwide), or with gas-peaking generators, which are only used a fraction of the time. The cost for unsubsidized residual PV installations is even higher – ranging from US$0.28/kWh to over US$0.50/kWh. Fortunately, there is no single price at which electricity is consumed (Fig. 4(a)) and therefore PV-generated electricity does not need to sell for US$0.05/kWh to US$0.10/kWh before it becomes competitive with other sources (conventional or renewable) of electricity.

> "The energy sources that make up the bulk of the electricity market are all able to produce electricity at US$0.10/kWh or less in the USA."

Retail electricity prices refer to the prices paid by consumers. These prices can be compensated by savings generated from the electricity production of residential PV systems. *Wholesale electricity prices* refer to the prices that utilities pay or receive.

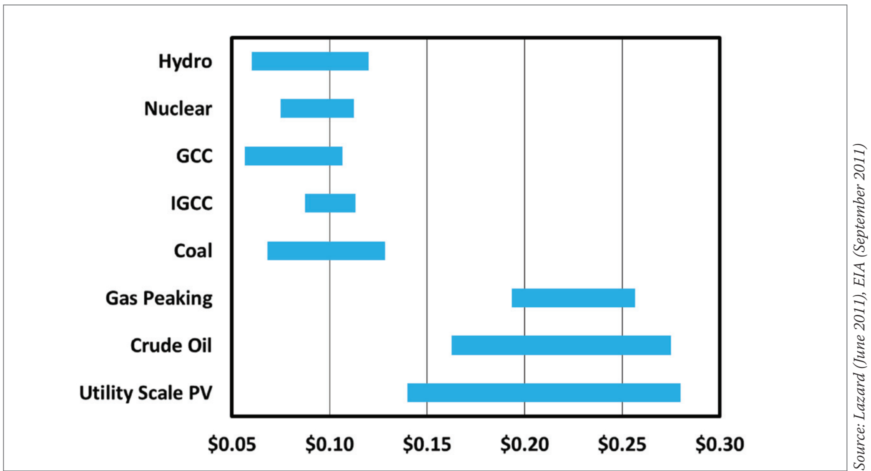


Figure 3. Cost of electricity produced from different energy sources (GCC = gas combined cycle, IGCC = integrated gasification combined cycle). Note: carbon capture is not assumed.

Market Watch

In addition, there is not a one-to-one correspondence between the price at which electricity is bought and sold, and the cost of producing that same electricity at a given time. Setting aside the impact of wholesale vs. retail electricity markets, the amount of electricity purchased depends not just on the source of electricity, but also on:

1. Location – USA (Texas vs. California vs. Hawaii) vs. France vs. Korea vs. China.
2. Type of customer – residential, commercial, industrial.
3. Time of day – the cost varies by time of day even though not all customers see time-of-day charges.
4. Regulated pricing, tariffs, etc.
5. Geopolitical factors, national security, etc.

This dependence is illustrated in Fig. 4(a), which shows the amount of US

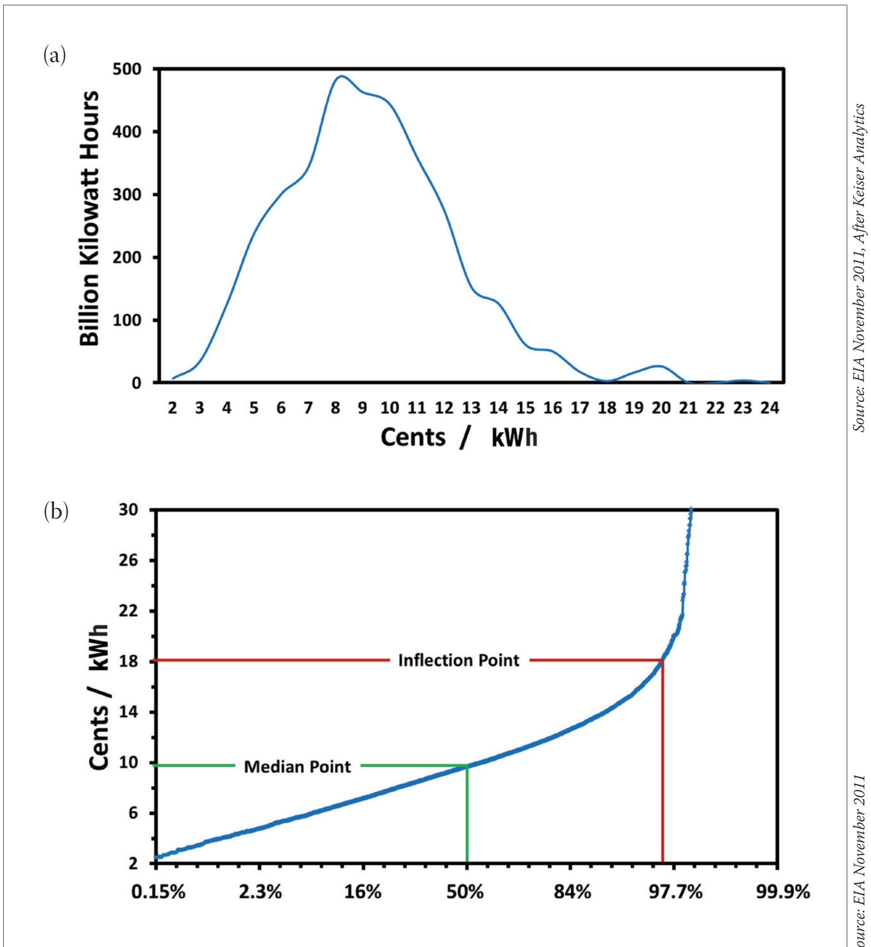
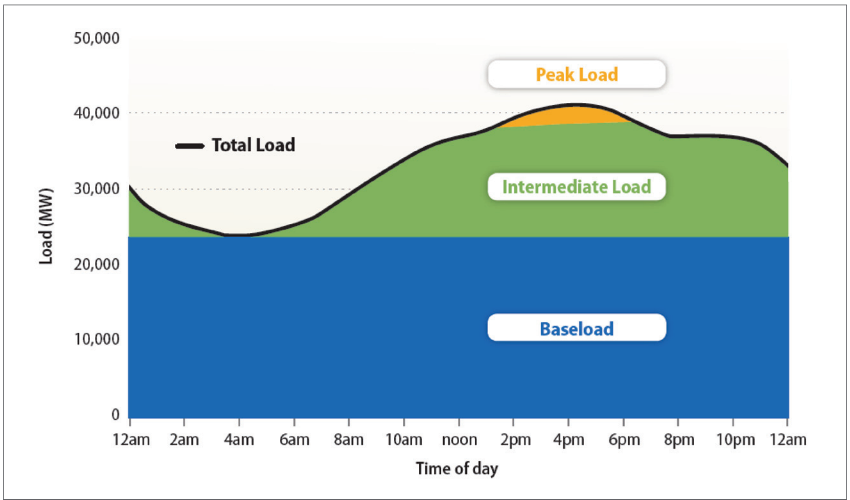


Figure 4. (a) US electricity consumed in 2010 vs. prices; (b) probability plot of the US electricity prices in 2010 from Fig. 4(a).

electricity consumed at different price points [6,7]. Transforming the data in Fig 4(a) into a probability plot provides insight into the costs that PV needs to achieve in order to provide electricity at a competitive rate (Fig 4(b)). While in practice the analysis would need to be done on a location-specific basis, the aggregate US data is used in this work as a proxy for the industry.

When PV suppliers can sell electricity (profitably and without subsidies) at ~US$0.18/kWh, an inflection or tipping point occurs (Fig. 4(b)). As the industry continues to reduce costs beyond this point, electricity generated by PV becomes increasingly economical and is therefore pulled into the electrical grid on a more *sustainable* basis. While 2011 US unsubsidized installed residential PV costs were, for the most part, off this chart, the recent fall in PV module and balance of system (BOS) costs has resulted in the median utility PV unsubsidized installation cost approaching the US$0.18/kWh inflection point [8].

The other critical point, often called 'grid parity,' is the median of the distribution, or ~US$0.10/kWh, as shown in Fig. 4(b). When the PV industry can achieve this metric, it becomes cost-competitive with half of the electricity produced by the aggregation of power sources. But cost is not the only criterion that determines market share in the electricity market. As will be discussed in the next section, an important criterion pertinent to the PV industry is energy source reliability or dispatchability with respect to the electrical grid.



Source: NREL, March 2010

Figure 5. Electricity demand load over a 24-hour period.

Deconstructing the electrical grid

The way electrical grids are constructed and operated today dictates a requirement for power sources with different characteristics. Electricity demand fluctuates over the course of a day, throughout the week and seasonally [9] (Fig. 5). In response to fluctuating demands the electric grid has evolved to consist of three distinct supply/load segments: base, intermediate and peak [10].

The suitability of a power source in addressing the load demands in each of the three different categories depends on its specific characteristics [11,12]. Base-load power plants, for example, must generate dependable power to consistently meet demand around the clock in an efficient, reliable and inexpensive manner regardless of demand fluctuations. Base-load plants designed to meet these characteristics are typically large, run continuously at full capacity (except for major preventive maintenance), and are not very efficient in responding to rapidly fluctuating loads. In typical grid systems, base-load power is 40–50% of the maximum load in order to insure that the plant runs continuously.

Intermediate-load power plants are designed to be responsive to fluctuations in load and are often known as 'load-following' power plants. They are smaller than baseload plants, operate 30–60% of the time and are therefore more expensive to run.

Finally, peak-load, or 'peaker,' plants are designed to be highly responsive to changes in electrical demand. They can be started up and shut down quickly and can vary the quantity of electrical output by the minute. Since peak-load plants are only required for peak demand (in the USA this typically occurs during hot summer afternoons), they tend to have smaller output and only operate 10–15% of the time. As a consequence they are also the most expensive to operate. Table 1 gives a summary of the different generating plants. The electrical grid structure is one of the reasons why different types of power plants and sources have been developed over time and is also one of the reasons for the broad range of electricity cost/pricing.

Renewables such as wind and solar do not fit neatly into this simple construct. Before the advent of renewables, increasing demand for power (up to a point) was satisfied by generating plants increasing their output, typically by consuming more fuel. In a system without any renewables, generating units are put on-line (i.e. dispatched) in order of lowest variable cost [11]. With renewables, however, the procedure is reversed. Most renewable

	% of annual max load target	% of annual electricity provided	Type of plant	Ability to cycle/ demand response	Capacity factor	Size	Operating time	Typical cost ($/kWh)
Base	40–50%	50–60%	· Coal · Natural gas · Nuclear · Large hydro	Poor	70%+	Large: 500MW–1GW+	· Almost always on (except pm)	Low: 0.06 – 0.10
Intermediate	30–50%	20–40%	· Combined cycle CT · Steam turbine · Hydropower	Acceptable	35–55%	Medium: 200MW+ typical	· Follow demand during the day · On 30–60% of the time	Medium: 0.08–0.12
Peaking	Balance	5–10%	· Combustion turbine (CT) · Small hydro	Best	25%-	Small: < 50MW typical	· Only on very hot summer days · On 10–15% of the time	High: > 0.15

Source: Acero Capital

Table 1. General characteristics of electricity generation plants.

generating plants, and PV plants in particular, ramp up and down of their own accord, and grid operators must adjust to accommodate their outputs. In other words, grid operators need to use the power supplied by PV plants when available and then balance the grid system by reducing output from an existing conventional generating plant. Ideally, within a given interconnected grid, a PV plant's electricity would displace the output of the conventional plant with the highest variable cost [13–15]. Some advocates of renewable energy characterize this existing grid makeup as outdated and claim that the onset of greater grid intelligence will make the concept of base-load power obsolete [16,17]. For better or worse, however, given the huge infrastructure in place, this change, if it happens at all, will take place over several decades.

To get a feeling for an electrical grid's complexity, consider the US national electric power system. It consists of three independently synchronized grids (Eastern, Western and Texas) linked by a small number of relatively low-capacity lines. Within these areas are 107 balancing authorities in eight regions, coordinated by the North America Electric Reliability Corporation (NERC). The authorities are responsible for balancing the supply and demand for power in real time within specified areas. Combined, the three independent grids serve over 143 million residential, commercial and industrial customers through more than six million miles of transmission and distribution lines owned by more than 3000 diverse investor-owned, government-owned and cooperative enterprises. At the generation level, investor-owned utilities and independent power producers each account for ~42% of the electricity generation (84% total). Cooperatives and federal systems account for an additional ~4% each (8% total), while publicly owned systems organized at the state or municipal level account for the remaining 8% [18]. This system, which took decades to put in place, will not change overnight.

Even setting aside transmission issues, it follows that for the near term there are challenges in integrating PV generation into a conventional electric grid. In addition to the limited dispatchability of PV-generated electricity, there is the issue of intermittency or variability/uncertainty associated with dependencies on the weather and cloud coverage. For up to 10% of PV generation grid penetration, the system load during high demand is reduced while having little or no appreciable impact on the minimum (base) load. As PV penetration reaches 10–15%, greater steps need to be taken, but still the intermittency problem can be managed with a combination of better planning, increased flexibility of conventional generating plants, greater cross-region grid integration, increased operating reserves, mixed-mode generation plants (i.e. combinations of PV, wind and IGCC co-located or integrated) and some limited degree of storage. Above 20% PV penetration, it becomes increasingly difficult to maintain system reliability. Even achieving 10 to 15% PV penetration comes at a cost: estimates of the additional cost burden range from 10 to 20%, increasing as the penetration of PV in the electric grid increases [14]. All solutions to the intermittency problem – be they storage, or maintaining back-up or redundant conventional power sources, or even adding additional grid intelligence – come at a cost.

So where does PV-generated electricity best fit into this grid structure? With respect to system planning, a key characteristic of PV's generation profile is its correlation with periods of high electricity demand. This has obvious benefits: the presence of PV as part of the grid implies that expensive peaker plants are not required to run as often or may even be taken off-line, which in turn lowers the overall system operating cost. On the other hand, this period of high electricity demand is also when the system is most vulnerable, so greater care needs to be taken in load management. (Note: as grid penetration increases, the midday summer demand peak will most likely be eliminated and a new demand peak – late afternoons or winter evenings – may prevail. If this comes to pass, additional PV will produce power at off-peak demand.)

Aside from serving to reduce the need for electricity from peaker plants, PV-generated electricity can also fill part of the role served by conventional intermediate power plants. Since these intermediate plants can respond to load fluctuations in a relatively efficient manner, a portion of the conventional intermediate power plant generation can also be reduced by integrating PV into the overall system planning, and it may be possible to reduce the percentage of load covered by baseload plants to 35%.

"PV currently best fits into the grid for peaking and intermediate load applications."

In conclusion, PV currently best fits into the grid for peaking and intermediate load applications. The PV-served available market is therefore limited to approximately half of the total electricity generation required, but also does not force PV to compete directly with the lowest-cost power sources. From a practical perspective, in the absence of low-cost storage (not likely in the near term) and modest penetration by other renewable energy sources, the figure of 15 to 20% is a likely upper limit of PV grid penetration over the next 20–30 years. This, as will be shown later, is still an enormous market opportunity.

Translating LCOE to dollars per watt

Even though PV suppliers take into account the levelized cost of energy (LCOE = total lifecycle costs divided by total lifetime energy production) in their positioning and pricing strategies, the industry discourse and benchmarks are given in price (or cost) per watt (US$/W), i.e. the cost of energy generation. Electricity consumers on the other hand talk in terms of cents per kWh, i.e. the cost of power consumption. What is needed is a way of translating between the two.

The LCOE can be a relatively complex calculation [19], as it depends on:

1. Total life cycle costs:
   - Cost of the project/system
   - Amortization or financing costs (discount rate, loan duration, amount financed, etc.)
   - Operating and maintenance (O&M) costs
   - Residual system value
   - Tax rate

2. Total lifetime energy production:
   - Average daily insolation, i.e. the amount of sun the system receives
   - Energy harvest (panel efficiency, sensitivity to temperature and to low or diffused light, etc.)
   - System losses (inefficiencies, soiling, etc.) and downtime (inverter or other malfunction or failure point)
   - System degradation over time (guaranteed <1%/year for most PV systems and typically 0.2–0.5%)

By using a few simplifying assumptions, the cost per watt of PV installation is translated into the LCOE as shown in Fig. 6. Since irradiation is a major driver of the LCOE, three levels are shown: 1) 1100kWh/m^2/year (representative of Germany); 2) 1800kWh/m^2/year (representative of much of the USA and portions of Spain); and 3) 2400kWh/m^2/year (representative of the US southwest). The US$0.18/kWh inflection point previously noted corresponds to an installed PV price point of ~US$2.50/W (unsubsidized) at a nominal irradiation of 1800kWh/m^2/year (red star). Similarly, US$0.10/kWh (median point) corresponds to ~US$1.45/W (green star). These are key points to keep in mind. The three vertical dashed lines correspond to average US PV installation costs for residential (~US$5.90), non-residential

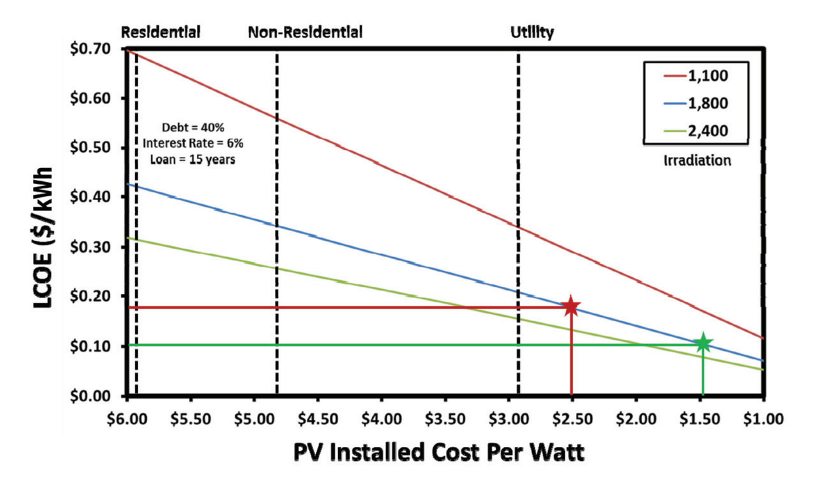
(~US$4.80) and utility-scale (~US$2.90) projects as of the first quarter of 2012 [8]. As noted previously, only utility-scale installations are approaching the US$0.18/kWh inflection point and then only at the highest levels of irradiation. As the industry drives towards profitability at US$0.18/kWh and subsequently at US$0.10/kWh, a large, sustainable and attractive PV electricity market will emerge. The question is, when will suppliers hit these cost points?

PV system installation costs are commonly divided into two categories: BOS and module. But, to better illustrate the critical cost-driving components of the PV value chain, installation costs have been divided into three categories: BOS, module and cell. While cost extrapolations are often done at the installation or module level it should be obvious that learning rates associated with each of these three categories will be fundamentally different and it is critical to differentiate between them (Fig. 7). Comparisons with Moore's law for integrated circuits, which are often done, are not applicable here. The main reason is that, in all three categories, raw materials make up 50–70% of the total cost and they do not 'scale' down. Nevertheless, there are volume learning rates associated with all three categories, and it is possible to ascertain the relative learning rate for each category by breaking it down into major components:

1. BOS: power conditioning/inverter, structural components (racking material, hardware, wiring, etc.) and items associated with the actual installation such as project management, permitting, site development, labour, etc.
2. Module: materials (~70%: EVA, backsheet, glass, frame, cell interconnect, glue), junction box, depreciation, utilities, labour, etc.
3. Cell:
   (a) Substrate: polysilicon (~50% in Si cells), glass, metal film, processing, depreciation, labour, etc.
   (b) Wafer: materials (~60% in Si cells: slurry, wire saw), depreciation, labour, etc.
   (c) Cell conversion: raw materials (~55%: silver paste, screen, process materials, etc.), processing, depreciation, labour, etc.

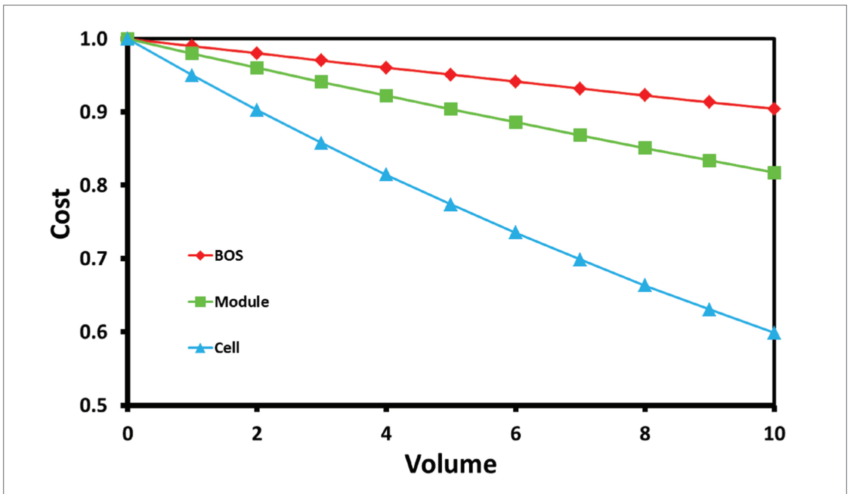
Intuitively, BOS costs – especially at the residential or small commercial level – would be expected to have the lowest learning rate. Installation tends to be relatively labour-intensive, extremely site specific and highly dependent on factors such as commodity price fluctuations in steel, copper and aluminium. Only the inverter is subject to a reasonable learning rate. And, since the inverter is basically a power component, even it does not lend itself to the same cost-reduction learning rates associated with digital technology.

Materials, including the cost of cells, make up the largest portion of module costs. Owing to its 'economic' immaturity relative to other material components, the cell has the highest potential for cost reduction. For a contrasting example, consider the front glass used in module construction. Glass is a fairly mature technology – it is not going to have the 30%/year cost-reduction learning rate that has characterized recent module cost reductions. Unless it is eliminated completely, the same can be said for the aluminium frame. It is not obvious that



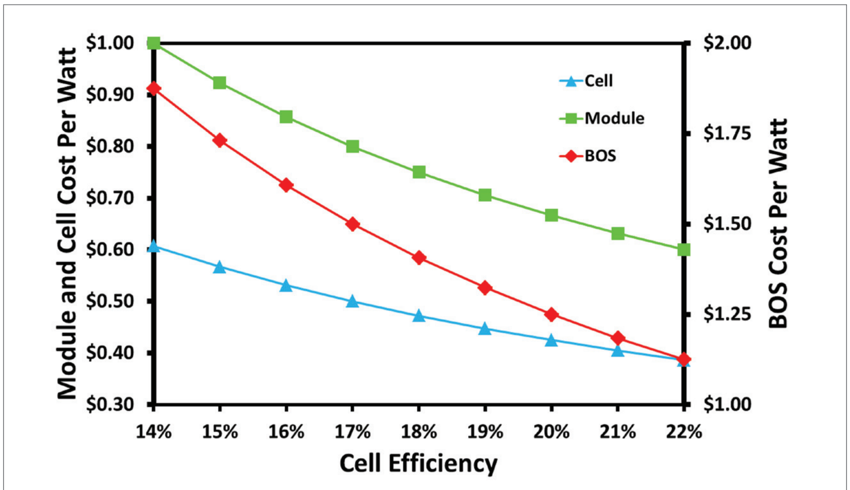
Source: Acero Capital (after Keiser Analytics)

Figure 6. LCOE (US$/kWh) vs. installed price (US$/W) (red star = US electricity pricing inflection point; green star = US electricity pricing median point).



Source: Acero Capital

Figure 7. Relative learning rates for PV component absolute costs.



Source: Acero Capital

Figure 8. PV component cost in US$/W vs. cell efficiency at fixed absolute cost.

labour is going to get much cheaper. It follows that the portion of the PV value chain that can exhibit the highest learning rate is the cell.

> "The portion of the PV value chain that can exhibit the highest learning rate is the cell."

Cell innovation drives costs in two ways: first, through normal component cost reduction characterized by production efficiency increases and economies of scale; second, through increased efficiency characterized by continuous technology improvements. Since PV costs are normalized by watts generated, any increase in cell efficiency gets leveraged through the value chain, i.e. BOS and module costs. This impact can be quantified by calculating the cost per watt for a cell, module and BOS assuming a fixed dollar cost for each component at nominal cell efficiency (17% in this example), and then calculating the cost per watt as the cell efficiency varies (Fig. 8). The impact of cell efficiency on PV component dollar per watt cost ranges from 8% at lower efficiencies to 5% at higher efficiencies for each absolute per cent improvement in cell efficiency. In a world where profits are measured in single-digit percentages, this is a significant impact.

Conclusion

Accounting for just 0.4% of the world's electricity generation in 2011, the PV power generation market is just getting started. The industry is exhibiting the fits, starts and growth pains typical of any nascent industry. Subsidies have up until now driven the PV market and enabled a rapid reduction in PV cost, especially in the last three years as the industry achieved critical mass: ~$100 billion total available market (TAM). While electricity produced through PV is still, in general, not cost-effective compared to conventional sources of electrical power generation, its cost is approaching a tipping point.

One critical question is what new disruptive technologies will be required (and when) in each of the three categories – BOS, module and cell – to maintain the necessary cost learning rates in order to continue to drive the cost of PV-generated electricity down from today's US$0.20–US$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 in monolithic and frameless methods for (automated) module construction, etc. Some of these technologies will become mainstream – most will not. In an attempt to answer the question above, each technology will be examined separately in detail in the second part of this article, which will appear in the next edition of *Photovoltaics International*. Beginning with a cost breakdown of the PV energy supply chain from system installation to cell manufacturing, Part 2 will review PV market evolution and will discuss, from a global financial perspective, the likelihood of 15% of the world's electricity being generated by PV energy, as well as industry profitability requirements.

References

[1] EPIA 2012, "Global market outlook for photovoltaics through 2016".

[2] DOE/EIA 2011, "International energy outlook 2011".

[3] BP 2012, "Statistical review of world energy 2012".

[4] IEA 2012, "Medium-term renewable energy market report 2012".

[5] Lazard 2011, "Levelized cost of energy analysis".

[6] EIA 2011, "Electric sales, revenue, and average price" [available online at http://205.254.135.7/electricity/sales_revenue_price/].

[7] Keiser Analytics 2011, "Quantifying the U.S. solar PV potential using retail electricity prices".

[8] SEIA, GTM Research 2012, "US solar market insight report: Q1 2012".

[9] NREL 2010, "Solar power and the electric grid".

[10] Public Service Commission of Wisconsin 2009, "Electric power plants".

[11] Kaplan, S. 2008, "Power plants: Characteristics and cost", CRS report for Congress.

[12] National Energy Technology Laboratory 2010, "Investment decisions for baseload power plants".

[13] SunShot Vision Study 2012, "Integration of solar into the US electric grid".

[14] NREL 2006, "Very large-scale deployment of grid-connected solar photovoltaics in the United States: Challenges and opportunities".

[15] NREL 2008, "Production cost modeling for high levels of photovoltaics penetration".

[16] Diesendorf, M. 2010, "The baseload fallacy", Energy Science Coalition briefing paper 16.

[17] German Renewable Energies Agency 2010, "Renewable energies and base load power plants: Are they compatible?".

[18] MIT 2011, "The future of the electric grid".

[19] Velosa, A. 2010, "What is inside your LCOE assumptions?", SEMI PV Group, The Grid [available online at http://www.pvgroup.org/NewsArchive/ctr_036226].

About the Authors

Antonio (Tony) Alvarez is a venture partner at Acero Capital and the COO at Aptina, a developer of CMOS image sensors, as well as a member of the Boards of MEMC and ChipMOS Technologies. Prior to joining Aptina, he served as the COO of Advanced Analogic Technologies, the COO of Leadis Technology, and the senior vice-president of the Memory Products Division as well as of R&D at Cypress Semiconductor. In addition to having edited *BiCMOS Technology & Applications*, Tony has over 20 publications and several patents in the area of semiconductor technology. He has B.S. and M.S. degrees in electrical engineering from the Georgia Institute of Technology and is currently a member of its Advisory Board.

Elisa Yoo is an associate at Acero Capital and focuses on investments in both IT and clean energy. To date she has participated in Acero's investments in Banyan Energy, Bitzer Mobile and Splash. Prior to joining Acero, Elisa worked at Deutsche Bank Securities in the technology investment banking group, where she worked on several M&A and corporate finance transactions in IT (SaaS and Mobile) and clean energy (Solar). Elisa has a B.A. from Stanford University in human biology with a focus on bioinformatics.

Enquiries

Acero Capital
2440 Sand Hill Road
Suite 101
Menlo Park, CA 94025
USA

Tel: +1 650 316 8597
Email: tony@acerovc.com
Website: www.acerovc.com