Re-considering the Economics of Photovoltaic Power

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Abstract: We briefly consider the recent dramatic reductions in the underlying costs and market prices of solar photovoltaic (PV) systems, and their implications for decision-makers. In many cases, current PV costs and the associated market and technological shifts witnessed in the industry have not been fully noted by decision-makers. The perception persists that PV is prohibitively expensive, and still has not reached 'competitiveness'. We find that the commonly used analytical comparators for PV *vis a vis* other power generation options may add further confusion. In order to help dispel existing misconceptions, we provide some level of transparency on the assumptions, inputs and parameters in calculations relating to the economics of PV. The paper is aimed at informing policy makers, utility decision-makers, investors and advisory services, in particular in high-growth developing countries, as they weigh the suite of power generation options available to them.

Keywords: Photovoltaics; Energy economics; Energy policy

1. Introduction

In this paper we seek to provide a measure of clarity and transparency to discussions regarding the present status and future potential of PV system economics. In particular, we review a broad and recent range of academic, government and industry literature in order to highlight the key drivers and uncertainties of future PV costs, prices and potential, and establish reasonable estimates of these for decision makers.

Whilst recent dramatic changes in the underlying costs, industry structure and market prices of solar PV technology are receiving growing attention amongst key stakeholders, it remains challenging to gain a coherent picture of the shifts occurring across the industry value chain around the world. Reasons include: the rapidity of cost and price changes, the complexity of the PV supply chain, which involves a large number of manufacturing processes, the balance of system (BOS) and installation costs associated with complete PV systems, the choice of different distribution channels, and differences between regional markets within which PV is being deployed. Adding to these complexities is the wide range of policy support mechanisms that have been utilised to facilitate PV deployment in different jurisdictions. In a number of countries these policies have become increasingly politically controversial within wider debates on public subsidies and climate change action. As such, the quality of reporting and information on the PV industry economics can vary widely.

PV power generation has long been acknowledged as a clean energy technology with vast potential, assuming its economics can be significantly improved. It draws upon the planet's most abundant and widely distributed renewable energy resource – the sun. The technology is inherently elegant – the direct conversion of sunlight to electricity without any moving parts or environmental emissions during operation. It is also well proven; PV systems have now been in use for some fifty years in specialised applications, and for grid connected systems for more than twenty years. Despite these highly attractive benefits and proven technical feasibility, the high costs of PV in comparison with other electricity generation options have until now prevented widespread commercial deployment. Much of the deployment to date has been driven by significant policy support such as through PV feed-in tariffs (FiTs), which have been available in around 50 countries over recent years (REN 21, 2011).

Historically, PV technologies were widely associated with a range of technical challenges including the performance limitations of BOS components (e.g., batteries, mounting structures, and inverters), lack of scale in manufacturing, perceived inadequate supply of raw materials, as well as economic barriers - in particular high upfront capital costs. While the industry was in its infancy - as recently as five years ago global cumulative installation was about 16 GW - this characterisation had merit (EPIA, 2011a). Now, with rapid cost reductions, a changing electricity industry context with regard to energy security and climate change concerns, increasing costs for some generation alternatives and a growing appreciation of the appropriate comparative metrics, PV's competitiveness is changing rapidly. As an example, large drops in solar module prices have helped spur record levels of deployment, which increased 54 percent over the previous year to 28.7 GW in 2011. This is ten times the new build level of 2007.

At least some of the confusion over the economics of PV has stemmed from the way PV costs (and prices) are generally analysed and presented. Primarily, this has been done using three related metrics, namely: the price-per-watt (peak) capital cost of PV modules (typically expressed as $[1]/W), the levelized cost of electricity (LCOE) (typically expressed as $/kWh), and the concept of 'grid parity'. Each of these metrics can be calculated in a number of ways and depend on a wide range of assumptions that span technical, economic, commercial and policy considerations. Transparency is often lacking in published data and methodologies. Importantly, the usefulness of these three metrics varies dramatically according to audience and purpose. As an example, the price-per-watt metric has the virtue of simplicity and availability of data, but has the disadvantages that module costs do not translate automatically into full installed system costs, different technologies have different relationships between average and peak daily yields, and there is always the question of whether costs quoted are manufacturers' underlying costs versus wholesale costs or retail price[2].

LCOE and 'grid parity' are of special relevance to government stakeholders but require a wider set of assumptions. They vary widely based on geography and on the financial return requirements of investors, and do not allow for robust single-point estimates. Instead, sensitivities are normally required (yet rarely presented), as are explicit descriptions of system boundaries. The financial case for PV depends on the financing arrangements and terms available, as well as estimates of likely electricity prices over the system lifetime. And often the distinction between wholesale and retail prices is not made clearly. Further, the capabilities of key decision makers

[1] We use the symbol $ to mean US dollars.

[2] There are further potential complexities between cost and price – in one common definition of these terms, for a seller price is what you sell a product or service for, and cost is what you paid for it. For a buyer, price is often used to mean what you pay for a good or service while cost includes ongoing expenditure over its life. Clearly there are considerable opportunities for confusion.

vary greatly in different PV market segments, spanning utility investors for large-scale PV farms to home owners contemplating whether to install roof-top PV systems. There is, thus, a clear requirement for greater transparency in presenting metrics so that they can be usefully compared or used in further analysis.

The aim of this paper is two-fold: first, we attempt to highlight some of the issues that are most critical for decision-makers using the common metrics. Second, we aim to inform policy and investment decision-makers about the best estimates of current costs of PV. This short paper does not address the more general power system issues which need to be dealt with in order to achieve significant PV deployment (e.g., integration, ancillary service provision, or power storage), or does it address the context or impetus behind the drive for increased renewable energy usage (e.g., climate change, or energy security).

The remainder of the paper begins with Section 2, in which a narrative of the dramatic shifts the PV industry has experienced in recent years is presented. Section 3 previews the cost of PV power as described in the literature and compares this to updated estimates. In section 4 we highlight the sensitivity of the LCOE metric to input parameters and assumptions. Section 5 considers complexities surrounding the concept of PV 'grid parity'. Section 6 suggests cause for optimism in the PV industry and briefly discusses policy implications. Section 7 concludes.

2. A dramatic shift

From 2004 to Q3 2008, the price of PV modules remained approximately flat at $3.50-$4.00/W, despite manufacturers making continuous improvements in technology and scale to reduce their costs. Much of this can be attributed to the fact that the German, and then Spanish, tariff incentives allowed project developers to buy the technology at this price, coupled with a shortage of polysilicon that constrained production and prevented effective pricing competition. The 18 largest quoted solar companies followed by Bloomberg made average operating margins of 14.6%-16.3% from 2005 to 2008[3].

Consequently, both polysilicon companies and downstream manufacturers expanded rapidly. When the Spanish incentive regime ended abruptly at the end of September 2008, global demand stayed roughly flat at 7.7 GW in 2009, from 6.7 GW in 2008, while polysilicon availability increased at least 32%; enough to make 8.5 GW of modules, with an additional 1.6GW of thin film production. As a consequence of this sudden need to compete on price, wafer and module makers gave up some of their margins, and the price fell rapidly from $4.00/W in 2008 to $2.00/W in 2009. The ability of manufacturers to drop their prices by 50%, and still make a positive operating margin, was due to the reductions in costs achieved over the previous four years, driven by scale and advances in wafer, cell and module manufacturing processes, as well as to improved performance resulting from better cell efficiencies and lower electrical conversion losses (Wesoff, 2012).

Since 2004, regardless of module prices, system prices have fallen steadily as installers achieved lower installation and maintenance costs due to better racking systems (IPCC, 2012), and falling BOS costs (Bony et al., 2010). In addition, financing costs have fallen, due, in part, to an improved understanding ofand comfort with, PV deployment risk (NEA et al., 2005; WEF, 2011). It is important to highlight the impacts of recent excess production capacity. In such situations,

[3] Much of the data and graphs in this paper were provided by Bloomberg New Energy Finance (BNEF) and are not otherwise disclosed to the public.

prices can fall to the level of marginal production costs, or even below - the Coalition for American Solar Manufacturing, claimed that, "Chinese manufacturers are illegally dumping crystalline silicon solar cells into the U.S. market and are receiving illegal subsidies" and brought a case resulting in US import tariffs being levelled on China modules in 2012 (Bradsher and Wald, 2012). Regardless of the subsidy situation, there is at least 50 GW of cell and module capacity globally, and an estimated 26-35 GW of demand, for 2012. The implications for future PV pricing are potentially significant, as industry participants fail or consolidate (Sarasin, 2011). In Germany alone, two major solar companies have announced bankruptcy between December 2011 and end of April 2012 (Q-cells and Solon). US firm First Solar closed its European operations in April 2012, and the media has focused on the high profile US based thin film start-up Solyndra bankruptcy in August 2011.

For the first time, in late 2011, factory-gate prices for crystalline-silicon (c-Si) PV modules fell below the $1.00/W[4] mark (Bloomberg, 2012); moving towards the benchmark of $1.00/W installed cost for PV systems, which is often regarded in the PV industry as marking the achievement of grid parity for PV (Lushetsky, 2010; U.S. DOE, 2010, 2012; Yang, 2010; Laird, 2011)[5]. These reductions have taken many stakeholders, including industry participants, by surprise. Many policy makers and potential PV buyers have the perspective that that solar PV is still far too costly on an unsubsidized basis to compete with conventional generation options, and this confusion is exacerbated by the solar industry positions, which, when consulted by policy-makers and regulators, have generally recommended high tariffs. Some have argued that prices are currently below sustainable levels and might even have to rise slightly as the industry consolidates and seeks to return to profitability (e.g., Mints, 2012b); however technological advancements, process improvements, and changes in the structure of the industry suggest that further price reductions are likely to occur in coming years.

3. Price per watt

The most fundamental metric for considering the costs of PV is the price-per-watt of the modules. PV module factory prices (Figure 1) have historically decreased at a rate (price experience factor) of 15-24%[6][7] (IEA, 2010; Zweibel, 2010; IPCC, 2012); the higher figure refers to an inflation-indexed calculation. If one assumed a $3.00/W average 2003 price, experience curves would suggest prices might have fallen to $1.01/W by early 2012[8]. However, primarily because of silicon shortages, module prices temporarily increased to $3.88/W in 2008 before declining to below $2.00/W by December 2009 in some instances. They then fell a further 14% in 2010 (REN 21, 2011). As of April 2012, the factory-gate selling price (ex-VAT) of modules from 'bankable' or "tier 1" manufacturers was $0.85/W for Chinese multicrystalline silicon modules, $1.01/W for non-Chinese monocrystalline silicon modules, with thin film modules and those from less well-

[4] Throughout the text, W is synonymous with W_p (watt-peak), which is defined as the DC watts output of a solar module as measured under specified laboratory illumination conditions (Green, 1998). We do not discuss the varying affects of temperature on different cell technologies on PV performance.

[5] There is still at least another $1.00/W or so BOS and installation costs.

[6] This means that the price reduced by 15-24% for each doubling of cumulative sales.

[7] Production costs vary among the different PV module technologies but these cost differentials are less significant at the system level; they are expected to converge in the long-term (IEA, 2010).

[8] The anticipated experience curve is represented by the linear regression fit in Figure 1. Note, however, that in reality the data points between around 2003 and 2010 were not on that line, for the most part due to the cost impact of silicon shortages.

known suppliers even cheaper. Depending on the market, distributors of these modules can take a considerable margin, buying at the factory-gate price and selling at the highest price the market can support ('value-based pricing').

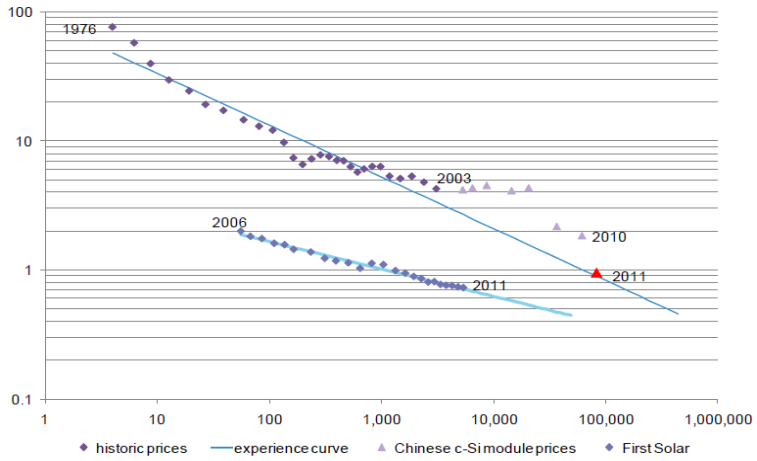

Figure 1: PV module experience curve 1976-2011 (BNEF, 2012a).

A closer look at one type of module (Chinese c-Si) shows the dramatic change in the price curve since 2008 (Figure 2). Historically, modules had a share of around 60% of the total PV system cost (Wang et al., 2011), but due to the extraordinary decline in module prices since 2008, its share in the total installed system cost has since decreased (Hoium, 2011). BOS components are now the majority share of the total capital cost-per-watt and therefore represent one of the main potential sources of further PV system cost reductions (Farrell, 2011a).

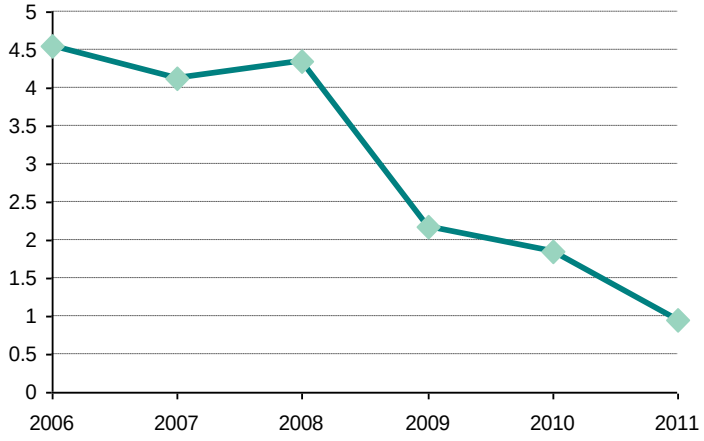

Figure 2: Chinese c-Si PV module prices ($/W): Note the change in the slope of the curve since 2008.

In order to provide further granularity, Figure 3 shows a typical breakdown of a Chinese multicrystalline silicon module in April 2012. (This price is nearly $0.10/W lower that than that

of international multicrystalline silicon modules, mainly due to significantly lower processing costs per watt of ingot and wafer, cell and module.)

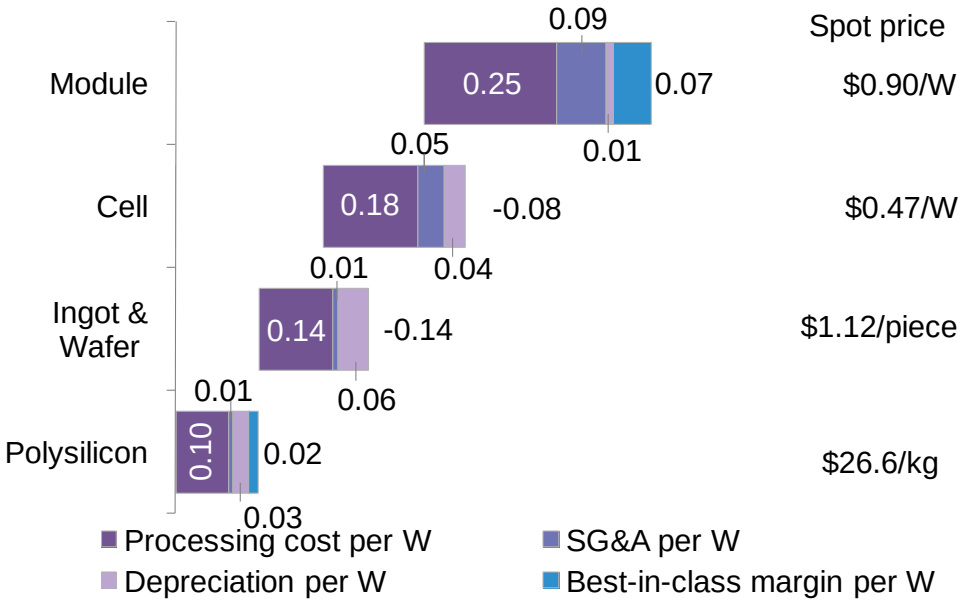

Figure 3 Chinese multicrystalline silicon module cost build-up (assuming 6.0g of silicon per watt of wafer), April 2012 (BNEF, 2012a).

Silicon costs, making up about 20% of the total module cost today, have had a significant impact on PV cost declines as they dropped from temporary highs of more than $450/kg in 2008 to currently (Q1, 2012) less than $27/kg (see Figure 4, and Fessler, 2012).

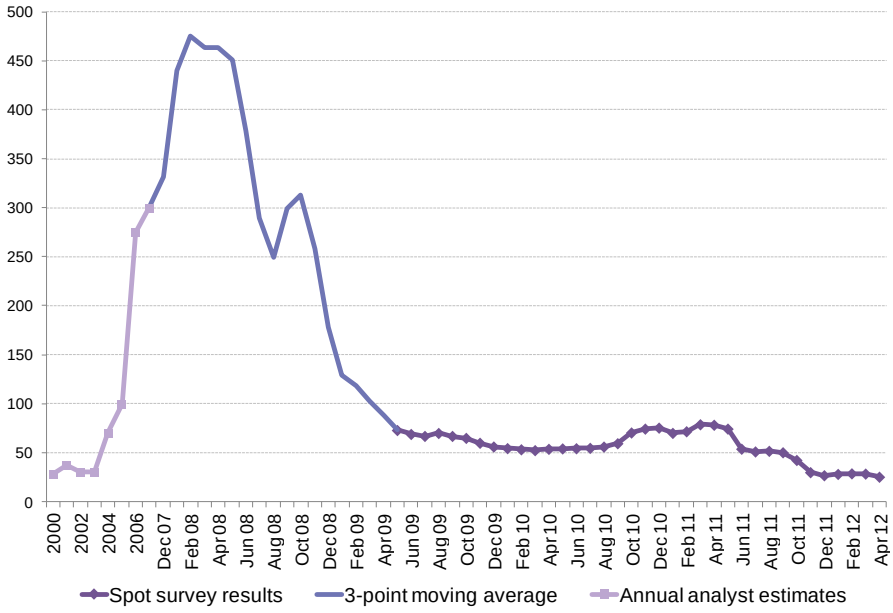

Figure 4: Spot price of solar-grade silicon ($/kg) (BNEF, 2012a).

On average, prices of wafers dropped from just below $1.00/W in 2009 to $0.35/W in Q1 2012, and those of cells declined from $1.30/W in 2009 to $0.55/W in Q1 2012. The BOS components experienced a 19% to 22% learning rate (IPCC, 2012). The price of its single largest component, the inverter, dropped from an average of $0.29/W in 2007 to under $0.20/W in some cases in Q1 2012 (IPCC, 2012; BNEF, 2012). Note the price difference in scale: inverters for a residential system currently still cost around $0.29, while those for commercial and utility scale systems cost $0.19/W and $0.18/W, respectively. According to Bony et al. (2010) the average cost of BOS (including installation) in 2010 ranged from $1.6/W for a ground-mounted system to $1.85/W for a rooftop system. The BOS cost for a 10 MW, fixed tilt, multi c-Si project in the US is reported to be $1.43/W and for a 10 MW, fixed tilt, CdTe project $1.54/W (Greentech Media, 2011). These examples show how many descriptors one needs to cite in order to provide full transparency in any presentation of this seemingly simple metric.

Our discussion so far has focused on crystalline and multicrystalline products, however the thin film PV industry raised its market share from 6% in 2005 to 20% in 2009 (IPCC, 2012). Its share was subsequently reduced to 13% in 2010 and further to 11% in 2011 (REN 21, 2011; Shiao, 2012). Thin film production increased by a record 63% to reach 2.3 GW in 2010. *PVxchange* module retail spot market reports March 2012 thin film module prices between $0.79/W for CdS/CdTe to $0.92/W for a-Si/µ-Si modules (pvXchange, 2012). Modules from First Solar, based on cadmium telluride (CdTe) and making up the bulk of global thin film shipments, have been successful due to a low cost position, but have also come under pressure in 2012 as crystalline silicon prices dropped.

4. Levelized Costs

If keeping up with fast-paced PV equipment cost and price changes is challenging, even more care is required in interpreting levelized cost of electricity calculations. There is a large literature on this subject (see e.g., Pollard, 1979; Rosenblum, 1983; Pouris, 1987; Landis, 1988; Thornton and Brown, 1992; Roth and Ambs, 2004; NEA et al., 2005; Canada et al., 2005; Moore, 2005; Simons et al., 2007; Bazilian and Roques, 2008; Bishop and Amaratunga, 2008; Myers et al., 2010; Singh and Singh, 2010; Yang, 2010; Zweibel, 2010; IEA et al., 2010; Ramadhan and Naseeb, 2011; Branker et al., 2011; Wang et al., 2011; Darling et al., 2011; Eldada, 2011; Timilsina et al., 2012; Mandhana, 2012). While the economic feasibility of a particular energy generation project is typically evaluated by metrics, such as ROI or IRR, the LCOE is most commonly used by policy makers as a long term guide to the competitiveness of technologies[9]. LCOE analysis considers costs distributed over the project lifetime and as such supposedly provides a more accurate economic picture, which system operators prefer over a simple capital cost-per-watt calculation[10]. A particularly important extension is that LCOE requires an estimate

[9]Long Run Marginal Cost (LRMC) is another metric used to calculate economic feasibility of a PV project. Many utilities use LRMC instead of LCOE. For an example of the use of LRMC, please refer to Simhauser (2010). What tool is used depends on the time horizon and perspective of the potential decision-maker. The differences between short-run and long-run marginal costs are covered in NEA et al. (2005).

[10]Useful references for recent, more elaborate work on LCOE calculation methods and/or analysis include: NEA et al. (2005); Lazard (2008); IEA et al. (2010); Singh and Singh (2010); Zweibel (2010); Branker et al. (2011); Darling et al. (2011); Wang et al. (2011).

of long-term PV system performance – a very context-specific outcome, driven by factors including solar insulation at the site, component technologies and specifications, overall system design and installation, and maintenance.

The LCOE for PV c-Si has declined by nearly 50% from an average of $0.32/kWh early 2009 to $0.17/kWh early 2012, while that for PV thin film experienced a drop from $0.23/kWh to $0.16/kWh in the same period. According to BNEF, the current (Q1, 2012) levelized cost ranges from $0.11/kWh to $0.25/kWh. Since the sharp drop in module costs in 2008, the literature on LCOE estimations for PV has grown substantially – we present some of it here. Under a range of financing assumptions and locations, the U.S. DOE estimated a PV LCOE of approximately $0.10/kWh to $0.18/kWh[11] for utility-scale, $0.16/kWh-$0.31/kWh for commercial systems and $0.16/kWh-$0.25/kWh for residential PV systems (NREL, 2009). The U.S. Energy Information Administration's (EIA) estimates range from $0.16/kWh to $0.32/kWh. Zweibel (2010) calculates a cost of PV electricity in the U.S. Southwest of $0.15/kWh. Running the Solar Advisor Model (SAM), Wang et al. (2011) obtain a LCOE of $0.11/kWh. Calculating LCOE for PV based on input parameter distributions feeding a Monte Carlo simulation, Darling et al. (2011) find an average LCOE of $0.09/kWh, $0.10/kWh and $0.07/kWh for Boston, Chicago and Sacramento, respectively. The US DOE Solar Program's Technology Plan aims at making PV-generated power cost-competitive with market prices in the USA by 2015. Their energy cost targets are $0.08-$0.10/kWh for residential, $0.06-$0.08/kWh for commercial and $0.05-$0.07/kWh for utility-scale solar PV (Asplund, 2008; IPCC, 2012). Branker et al. (2011) estimate a PV LCOE range for Ontario, Canada, of $0.10/kWh-$0.15/kWh[12]. LCOE estimates for PV in Africa by Gielen (2012) range from $0.20/kWh to $0.51/kWh. Schmidt et al. (2012) estimate PV LCOEs for six developing countries ranging from approximately $0.20-$0.35/kWh in 2010. In general, the LCOE range found in the literature extends from around $0.10/kWh to $0.30/kWh for most contexts.

Despite the substantial drop in PV costs, many commentators continue to note that PV-generated power is prohibitively expensive unless heavily supported by subsidies or enhanced prices (see e.g., Asplund, 2008; IEA et al., 2010; Singh and Singh, 2010; IPCC, 2012; Lomborg, 2012; Neubacher, 2012; Timilsina et al., 2012). Outdated numbers are still widely disemminated to governments, regulators and investors. Yang (2010), for example, calculates PV with a levelized cost of $0.49/kWh. Timilsina et al. (2012) find that the minimum values of LCOE for PV are $0.19/kWh. This sort of data often contrasts sharply with prices submitted in response to Dutch auctions for solar projects around the world, where developers bid to supply solar power at the lowest price. As an example, $0.12/kWh was bid in the Peru tender in August 2011, $0.11/kWh in China in September 2010 and $0.15/kWh in India in April 2012. At the end of March 2012, both SCE and PG&E in the US filed advice letters asking for approval of contracts: of the winning bids for 11 contracts, 9 were for PV, with the highest executed contract price of $0.09/kWh[13] (PG&E, 2012; SCE, 2012). In interpreting these auction results it is important to note that their results may reflect the impact of fiscal incentives and not be directly comparable to LCOEs. In addition, it is not always clear if the backers of these projects intend to make normal

[11] Note that some LCOE figures from the US quoted in this paper may be post-Federal tax rebates and may also include local capex rebates in some cases.

[12] The majority of estimates (presented here and) found in the literature are for the North American region. See Branker et al. (2011) for a comprehensive summary of LCOE estimates from various sources in North America.

[13] While this is the highest clearing price and individual contract prices could be even lower, note that federal tax credits likely make these prices look lower than they would otherwise be.

financial returns. As we will discuss, the fossil fuel or nuclear generation costs that are often used in comparisons may not be equivalent, for a wide range of reasons.

Standard definitions have been proposed for the LCOE method, such as those by IEA (NEA et al., 2005) or NREL (System Advisor Model (SAM)[14] and Levelized Cost of Energy Calculator[15]). Nevertheless, as discussed by Branker et al. (2011), the method "is deceptively straightforward and there is lack of clarity of reporting assumptions, justifications showing understanding of the assumptions and degree of completeness, which produces widely varying results". Darling et al. (2011) suggest using input parameter distributions rather than single numbers in order to obtain a LCOE *distribution*, rather than a single number, as a means of increasing transparency by reflecting cost uncertainty associated with solar projects. Other, more sophisticated methods exist (see e.g., Bazilian and Roques, 2008), but LCOE persists as a widely-used metric[16].

There is ample variation in the underlying LCOE assumptions found in the literature (Queen's University, 2011). For example, the capital cost for PV systems in the more current literature can range from $5.00/W[17] to $2.00/W[18]. While PV modules are generally warranted for 25 or more years (Zweibel, 2010), research suggests that a 40 year lifetime has been demonstrated and that 50 years may be within reach with today's crystalline technology (IEA, 2010). O&M costs for a utility-scale PV plant can range from $10/kW/year to $30/kW/year; this range may be partly due to differences in the scope of services provided under an O&M contract. (see e.g., Lazard, 2008; Darling et al., 2011; NREL, 2011). The Weighted Average Cost of Capital (WACC)[19] is normally used as a discount rate to determine the net present value of the PV power generation cost[20] but it can vary widely with the type of project owner, the nature and stability of regulatory regimes, and regional differences in cost of capital.

BNEF (on behalf of WEF (2011)) identify the most important determining factors of the levelized cost as being capital costs, capacity factor, cost of equity, and cost of debt. Sensitivity results presented by IEA et al. (2010) draw similar conclusions (see Figure 5), showing that levelized costs of power generated by PV exhibit a particularly high sensitivity to load factor variations, followed by variations in construction costs and discount rate. Singh and Singh (2010) analyze the impact of the choice of loan method on LCOE, identifying the loan repayment method as one high-impact assumption. The results of a rank correlation analysis undertaken by Darling et al.

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[14]https://sam.nrel.gov/.

[15]http://www.nrel.gov/analysis/tech_lcoe.html.

[16]LCOE is especially problematic for fossil fuel based generators as assumptions have to be made around future costs of fuel, and costs of associated volatility and uncertainty. Methodologies such as Real Options are beyond the scope of this paper, but are very useful in providing better understanding decision-making in power markets.

[17]Stuart (2011) reports $5.60/W on the high-end for a 5 to 20 MW system between 2008 and 2010. The summary of recent solar PV installed system costs compiled by Branker et al. (2011) ranges from $3.52/W to $5.02/W for utility-scale PV. See Goodrich et al. (2012) for a comprehensive study on residential, commercial and utility-scale PV systems in the US. Barbose and Wiser (2011) report installed costs in 2011 for large-scale PV projects in the range of $3.80/W to $4.40/W.

[18] Figures as low as $1.80/W are appearing (the reputed installed cost in India for 5MW projects according to EPC data from AnSol and SunEdison).

[19] See NEA et al. (2005) for a discussion of technology specific discount rates. For references on the cost of capital, see e.g., Ogier et al. (2004) or Pratt and Grabowski (2010).

[20] Note that this assumption is location and time-dependent as it includes prior assumptions on figures, including real risk free debt, debt risk premium, real and nominal cost of debt, equity risk premium, equity beta, real pre- and post-tax cost of equity, etc. Analyses in the literature abstracting from financing issues often assume 5% and 10% discount rates.

(2011) indicate that financial uncertainties (e.g., variation of discount rate) are a major determining factor of LCOE, followed by system performance (including geographical insolation variation), which equally represents a major contributor to the uncertainty in LCOE.

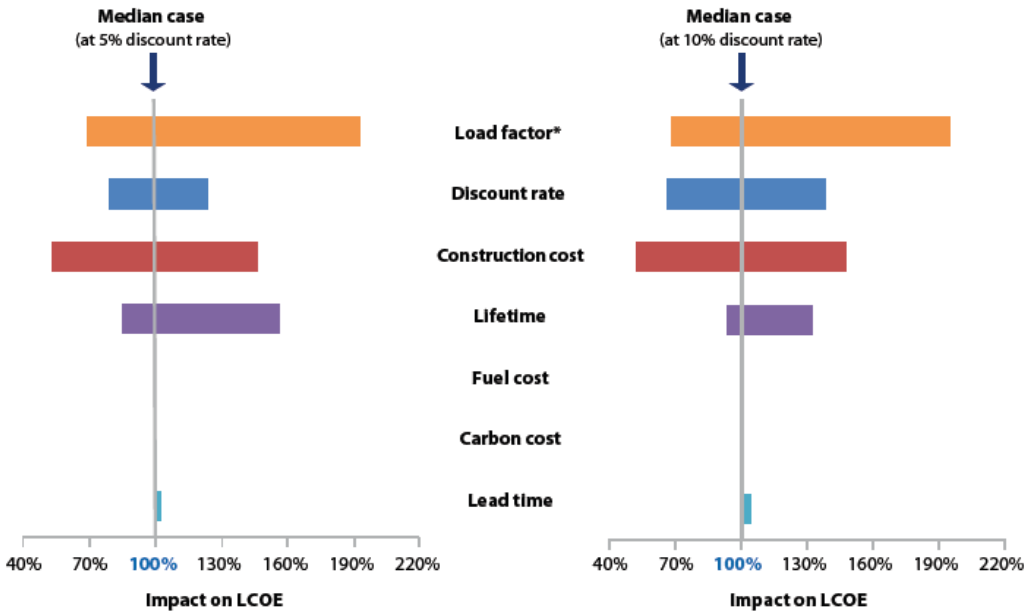

Figure 5: Tornado graph PV LCOE (IEA et al., 2010).

4.1. Power system comparisons

In addition to the complexities of providing clear PV LCOE figures, significant discrepancies between the underlying characteristics and economics of different power generating technologies, as well as of the markets they serve, make it difficult to directly compare project-by-project on a levelized basis. As an example, the Emirates Solar Industry Association (ESIA, 2012) show that based on current market rates, the LCOE from solar PV in typical MENA climates is estimated to be $0.15/kWh. At this level, PV is cheaper on a simple LCOE basis than open-cycle peaking units at gas prices higher than $5.00/MMBtu[21]. PV has, in fact, already replaced some peaking plants. In 2009, the California Energy Commission (CEC) rejected a contract for a new plant in San Diego in favour of a PV solar system that would lower the cost of electricity for ratepayers (Ahn and Arce, 2009). The key challenge lies in establishing the underlying place of different technologies within the power dispatch curve, and in the differing ways in which the resulting economics flow through into wholesale and retail electricity prices.

The primary focus within the electricity industry is on what value a particular technology brings to a power system. This can depend on the nature of demand, the network, and the mix of existing generation and its operating rules. Rapidly dispatchable peaking plant has a particularly high value for electricity networks with infrequent periods of very high demand. PV generation, in some locations, matches periods of higher demand and hence can be of high value, but its output

[21] That might appear as a surprising result given the significant investments underway in gas-fired peaking plant around the world including very sunny regions.

is generally variable and only somewhat predictable – a considerable disadvantage in an industry where supply must precisely meet demand (and losses) at all times and locations within the grid (IEA et al., 2010; Joskow, 2010; MacGill, 2010). The coherence of underlying economics and commercial returns for different technologies within an electrical grid adds further complexity for investment analysis, as italso depends on electricity market design and the design of any supporting PV policies.

Even at comparable levelized costs and with commercially proven technologies, differing risk profiles of different technologies also have a large impact on the viability of the project (NEA et al., 2005). The perceived risk of a technology is directly related to how, and at what costs of capital, projects are financed. Similarly, uncertainty in future fuel and electricity prices impacts differently on the profitability of different technologies (Bazilian and Roques, 2008). While gas-fired technologies, for instance, are particularly sensitive to fuel prices and price volatility (since fuel costs constitute the majority of generation costs), capital-intensive renewables, such as PV, are more sensitive to electricity prices, risk adjusted interest rates, maintenance costs and insolation levels[22].

5. Moving beyond grid-parity

The confusion surrounding the concept of grid parity is perhaps even more significant than either of the other two metrics we have highlighted, yet it remains a cornerstone of PV-related messaging. A new wave of discussions about grid parity has been set off by the recent non-linear price drops (See e.g., Parkinson, n.d.; Yang, 2010; Breyer and Gerlach, 2010; Baillie, 2011; Branker et al., 2011; Hickman, 2011; Seba, 2011; Farrell, 2011b; Shanan, 2012; Trabish, 2012; Carus, 2012; Goffri, 2012; Mints, 2012a). Depending on the scale of the PV project, grid parity normally refers to the LCOE of PV by comparison with alternative means of wholesale electricity provision – often an inappropriate metric as discussed previously. While for large-scale PV, these alternatives may indeed be assessed as alternative wholesale generation projects utilising different technologies, for small-scale domestic or commercial PV systems, the appropriate alternative should be the purchase of electricity at a relevant residential or commercial tariff. The latter case is where grid parity actually took its name – such PV applications are not competing against wholesale generation but, instead, the delivered price of electricity through the grid. Grid parity is not a term that is used for other generation technologies except those that are potentially deployed at small customer premises such as, for example, domestic-sized fuel cells.

As noted with LCOE, however, behind the relatively simple concept of grid parity lies considerable complexity and ambiguity. A particular challenge is the disconnect that is often seen within an electricity industry between underlying economic value, and the actual price for electricity at different points of the supply chain. For example, in wholesale electricity markets the price generally varies over time and by location, and is subject to a range of uncertainties related to the cost of ancillary services, transmission congestion, short-term load regulation, longer-term unit commitment, and contingency management. The competitiveness of large-scale PV in such markets by comparison with other generation options can then depend in large part on how well its intermittent production matches these prices by comparison with other, often dispatchable, plants, what short-term ancillary service implications it poses, and the ability to forecast future production. By contrast, the prices in many retail electricity markets are better

[22] For a detailed discussion of methodologies incorporating risk into cost calculations, see NEA et al. (2005).

described as 'schedules of fees' involving flat or relatively simple Time-Of-Use (ToU) tariffs that often smear energy and network costs for end-users, and smear overall costs across customer classes through simple accumulation metering and regulated pricing regimes (Elliston et al., 2010). The competitiveness of PV then depends in large part on its LCOE in particular contexts by comparison with the relevant tariffs that system owners and operators would otherwise be paying (Hoke and Komor, 2012)[23]. Additional complexities include the likely trajectory of future retail tariffs (and potentially underlying changes), and the potential challenges of financing small-scale installations by often poorly informed and relatively unmotivated energy users.

Contrary to the view that the arrival of grid parity is still decades away, numerous studies have concluded that solar PV grid parity has already been achieved in a number of countries/regions (see e.g., Breyer and Gerlach, 2010; Zweibel, 2010; Branker et al., 2011; Darling et al., 2011). This discrepancy is not difficult to understand, given the definitional issues we have presented. As mentioned, it is often difficult to ascertain whether the term refers to grid parity, also known as 'busbar parity' (i.e., competitiveness with wholesale prices), or 'socket parity' (i.e., competitiveness with electricity user prices). Calculations by Bhandari and Stadler (2009) suggested that grid parity of wholesale electricity in Germany will occur around 2013-2014. Branker et al. (2011) find that for Canada, PV grid parity is already a reality (under specific circumstances). Breyer and Gerlach (2010) estimate that grid parity of large industrial segments would start between 2011 and 2013 and occur at the same time in Europe, the Americas and Asia. Similarly, EPIA (2011) forecasts that 'dynamic' grid parity[24] could occur around the year 2013 in the commercial segment in Italy, after which it would spread out across the rest of Europe to reach all types of installations and market segments by 2020.

Figure 6 presents data around when certain countries reached and will reach grid parity. It shows, for example, that countries with higher electricity prices, such as Germany, Denmark, Italy, Spain and parts of Australia have already reached socket parity, defined here as the point where a household can make 5% or more return on investment in a PV system just by using the energy generated to replace household energy consumption, while countries like Japan, France, Brazil or Turkey are expected to reach it by 2015[25]. Such a 'busy' and non-intuitive graphic serves to demonstrate how difficult a concept it is to communicate – and this places PV at a disadvantage at a time when the industry is seeking to send clear messages on competitiveness in its political communications and government affairs.

[23] Note that although competitiveness is evaluated prior to build out and installation of PV, it has very little to do with how or when PV is dispatched into a market, if in the wholesale system, or aggregated from distributed generation (if allowed). So, while LCOE represents an average cost, the actual price that PV gets is the spot market price - unless under bilateral contracts, offsets ToU retail prices, or fixed rate prices at the distributed generation level.

[24] In EPIA (2011), 'Dynamic grid parity' is defined as "the moment at which, in a particular market segment in a specific country, the present value of the long-term net earnings (considering revenues, savings, cost and depreciation) of the electricity supply from a PV installation is equal to the long-term cost of receiving traditionally produced and supplied power over the grid".

[25] For more detailed information, see Roston (2012).

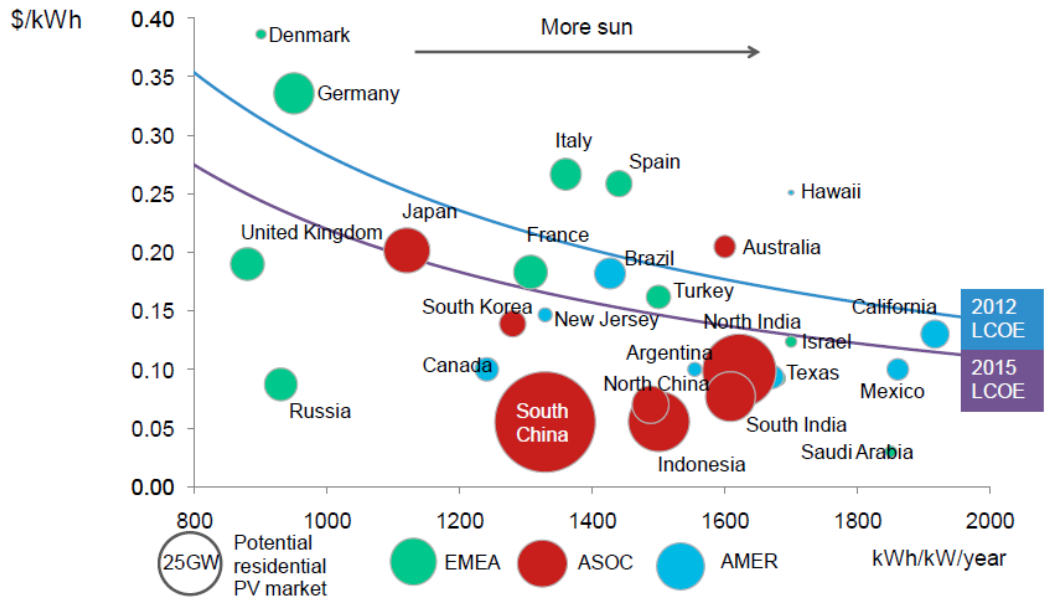

Figure 6: Residential PV price parity (size of bubbles refers to market size) (BNEF, 2012a).
Note: LCOE based on 6% weighted average cost of capital, 0.7%/year module degradation, 1% capex as O&M annually, $3.01/W capex assumed for 2012, $2.00/W for 2015.

6. Cause for optimism

Grid parity is now largely an outdated concept stemming from an industry that has traditionally been used to being an "underdog" of small scale, and constantly fighting for a "level playing field". While the term has served some usefulness as an abstract metric for R&D programmes to strive for, it is not useful in real-world power sector decisions (Mints, 2012b). Since it does not take into account the value of solar PV to the broader electrical industry, and is often used to compare a retail technology against a wholesale price, it implicitly provides a tool for proponents of other technologies to use against PV. Of course standard concepts and practices of assessing commercial viability rely on real data in contracts, financial spreadsheets and bids, remain the norm in transactions – these should replace grid parity in public discourse as well.

Developing countries in particular offer a huge potential market for PV systems. While historically the primary market for PV systems in developing countries has been off-grid applications - mainly individual solar home systems (Hoffmann, 2006; Moner-Girona et al., 2006), a larger market is expected to emerge in the near future for grid-connected PV. For decades, it has been recognised that PV was a good economic alternative in remote (off-grid) industrial applications that rely on diesel power generation, especially to power small electrical loads of up to hundreds of kilowatts (Solarbuzz, 2012). Data from IRENA now indicate that grid-connected PV in Africa has already become competitive with diesel-generated power, with an LCOE between $0.30 and $0.95/kWh, based on size, local diesel subsidies, and pilferage (IRENA, 2012). BNEF (2011) concludes that falling costs in PV technology mean that solar power is already a viable option for electricity generation in the Persian Gulf Region, where it can generate good economic returns by replacing the burning of oil for electricity generation[26].

[26] As long as the unburnt oil is valued at the international selling price, rather than extraction cost.

Similarly, power produced from PV in India is already competitive with power obtained by burning diesel (Pearson, 2012). These and other findings highlight the huge potential of PV in developing countries and indicate that, if not already competitive, PV is rapidly becoming competitive with alternative power generation technologies.

Still, the impacts of decision-makers not understanding the real costs for PV often has led to inefficiencies in, *inter alia*, tariff schemes. If PV power is perceived to be too costly, governments are less likely to take on the financial burden. This was the case in China in 2010, where the anticipated national PV FiT was dropped because solar PV costs were deemed too high[27] (EPIA, 2011b). Other governments introducing new FiT programs are confronted with the challenge of striking the right balance. The Japanese government, for instance, recently adopted a renewable FiT scheme (starting in July 2012) and faced the difficulty of picking an appropriate rate that will stimulate PV investment without overpaying for clean electricity[28] (McCrone and Nakamura, 2012). Alternative mechanisms such as tenders can offer options for addressing the dynamic cost environment, although may have higher risk for development (see e.g., Couture et al., 2010; Elliston et al., 2010; Kreycik et al., 2011). For example, the ACT government recently adopted a reverse auction process for large-scale solar through which developers will be paid their nominated FiT price less the market spot price. This means that as the spot price increases over time, the actual FiT payment will decrease. Collectively ratepayers will pay less FiT throughout the FiT period, although individual households will nonetheless incur higher energy charges as the spot rates increase (ACT Parliamentary Counsel, 2011).

7. Conclusions

The PV industry has seen unprecedented declines in module prices since the second half of 2008. Yet, awareness of the current economics of solar power lags among many commentators, policy makers, energy users and even utilities. The reasons are numerous and include: the very rapid pace of PV price reductions, the persistence of out-of-date data in information still being disseminated (occasionally by those with an interest in clouding the discussion), the misconceptions and ambiguity surrounding many of the metrics and concepts commonly used in the PV industry, and ambiguities regarding underlying PV costs due to the numerous policy support measures that have been put in place over the last decade.

We have presented a large body of academic and industry literature in an attempt to inform policy makers about the current costs and prices of PV, and to lend some clarity to those struggling with understanding the metrics generally used in assessing PV investments. Our main conclusions are that LCOE metrics in the PV industry can be misleading and should therefore be applied with caution as they require careful interpretation and transparency. Furthermore the term ‘grid parity’, the long-sought goal of the PV industry, has become outdated and is generally misleading.

Current PV module prices are considered by some to be below manufacturing cost, and consequently, as unsustainable, in large part because several leading non-Chinese firms in the industry have recently announced losses cutbacks or massive write-downs or filed for bankruptcy (Daily and Steitz, 2011; Daily and Das, 2012; Mints, 2012a, 2012b; Montgomery, 2012; Wesoff,

[27] The Chinese national PV FiT was subsequently announced in August 2011 (see e.g., Gifford (2011)).
[28] Early 2012 Japan decided that solar will receive JPY 42/kWh for 20 years (Quilter, 2012).

2012)[29]. Ultimately, the shift in prices of solar technology carries major implications for decision makers and policy designers, especially for the design of tariff, fiscal and other supporting policies (see e.g., Ahearn et al., 2011). The challenge is to elegantly transition PV from a highly promising and previously expensive option, to a highly competitive player in electricity industries around the world.

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[29] Perhaps there is an analogy to this in the telecommunications industry that experienced sharp falls in telecoms prices in the early 2000s, resulting in several major bankruptcies. Eventually, though, the excess broadband capacity paved the way for an explosive growth in the internet and communications industries. Similarly, whether prices are sustainable today or not, the abundant capacity in the PV industry may likely be laying the foundation for an enormous increase of PV power.

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