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King Abdullah Petroleum Studies and Research Center

Reporting LCOE for Solar PV: Apples to Apples Comparisons

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Key Points

Solar energy is expected to be an integral technology in the creation of a low-carbon future. Hence, as photovoltaics (PV) installations continue to grow at an exponential rate, a better understanding of the generation costs of this relatively young industry is necessary in order to assess its competitiveness versus conventional sources. Using an extensive dataset of generation costs for solar technology, this study finds:

- Despite its inherent shortcomings, the levelized cost of energy (LCOE) is still the de facto metric used by research centers, private sector and government institutions to quantify electricity generation costs.

- The LCOE range for solar generation is significantly larger than that for conventional generation. This large spread for solar is mainly attributed to differences on how detailed the calculation of the LCOE is, the use of outdated or inaccurate assumptions, and/or not being explicit about the financial conditions including policy support.

- To compare different solar LCOEs equitably, we applied a ‘normalization’ procedure. The reported LCOE values were recalculated using numerical inputs stemming from global norms to fill gaps or deal with location-specific artefacts. Normalizing assumptions were applied to all the LCOE data points used in this paper. As expected, the spread decreases considerably.

- This normalization procedure, which leveled the playing field for reported LCOEs, suggests that the large variation in solar LCOE values that is generally accepted in literature is overstated. Furthermore, power purchase agreement prices for recent competitive bids should not be confused with LCOE and care is needed when comparing projects to ensure that a ‘new record’ was in fact achieved.

Executive Summary

It is generally accepted that electricity generation costs, or the LCOE of PV technology, vary widely and this variation is larger than that in conventional technologies. Due to regional differences in solar irradiation levels, labor costs and other factors, some variation is to be expected. However, the variation observed in literature is still considered large even after adjusting for regional specificities.

As solar players push to increase their market share, the competition with conventional technologies intensifies. Hence, solar not only seeks to reach parity with conventional generation sources, but aims to even surpass them on an LCOE basis to compensate for its intermittent nature. In the past two years, several LCOE and power purchase agreement (PPA) records in solar technology were set and then broken shortly thereafter. Some of these reported records are competitive with fossil-fuel generation and make the above-mentioned variation even larger. Yet, such anecdotal agreements cannot deem a technology to be universally competitive; the industry as a whole should be reaching and merging toward lower costs, not just confined to a few promised projects that have yet to become operational.

To validate competitiveness claims and be able to confidently provide insights to policymakers and investors, we compiled an extensive dataset of solar LCOEs for this study. The dataset allowed us to study the reasons behind this relatively large spread.

Inspecting the data, it was found that the reports do not consistently use the same assumptions when arriving at the LCOE. Furthermore, the level of detail adopted when calculating the LCOE is different across reports, contributing to a larger variation. Inclusion or exclusion of policy support (whether direct or indirect) particularly skews costs considerably.

Following these observations, a normalization procedure was performed. Essentially, the normalization procedure unifies the assumptions and parameters to be used for each LCOE, but keeps regional characteristics intact. As expected, the spread of the data decreased post-normalization, indicating that the accepted convention of solar costs being widely varying is overstated. Explicitly, the coefficient of variation narrows by almost 14 percent for the utility LCOE values. More realistic assumptions based on actual experiences and operational minutiae goes a long way toward reducing the LCOE data spread.

Accepting an LCOE figure without being aware of the underlying assumptions can result in erroneous conclusions. With the aid of the normalization exercise carried out in this paper, policymakers and investors are better versed on what lies behind reported LCOE values and can make more informed decisions. Policymakers can also look to formulate well-targeted budgets for renewable support, while investors can envisage a clearer picture of their expected revenues.

Costs of Generation Across Technologies

Each electricity generation technology has its strengths and weaknesses. Ideally, a generation system should, among other features, be environmentally friendly, easily ramped up and down to follow the load (responsive), reliable, safe and cost-effective. Currently, there is no technology that scores a perfect mark in all these criteria. Among the criteria mentioned above, however, cost is arguably the most influential factor that affects utility decisions when deciding on capacity expansions.

In the past two decades, many countries have shown significant interest in solar technology, and have taken firm steps to translate this interest into tangible action despite solar generation costs generally being higher than fossil fuel. Countries justify the premium paid for solar by citing many reasons including energy security or reducing carbon emissions. Figure 1 shows the generation costs in terms of levelized cost of energy (LCOE), of solar compared with coal and combined-cycle gas turbine (CCGT) technologies.

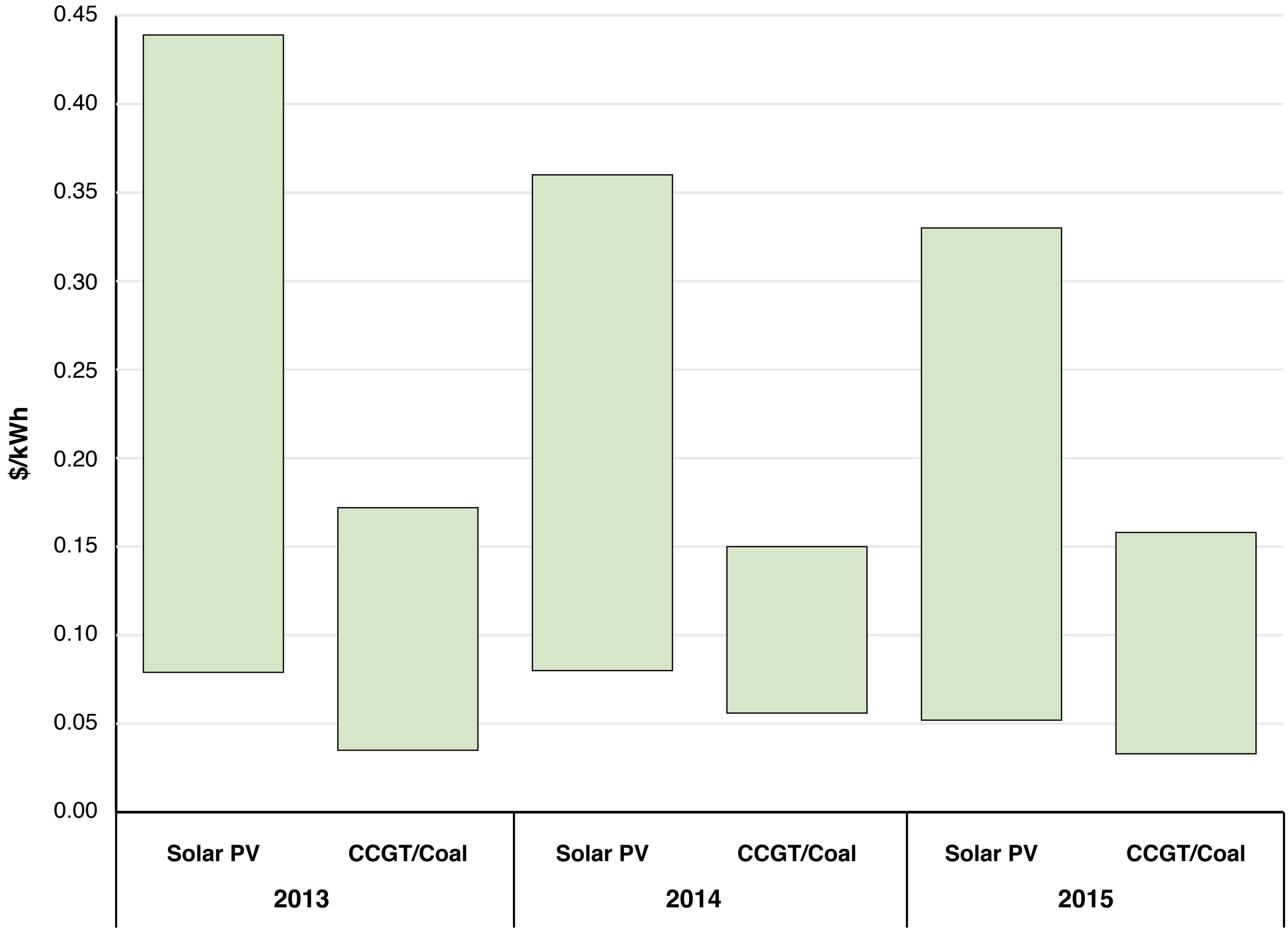

Figure 1. The LCOE of solar technology compared to coal and CCGT technologies.

Source: KAPSARC based on data from IRENA, BNEF and WEC.

It is clear from Figure 1 that the variation in generation costs of incumbent technologies is much smaller compared to solar. The relatively small variation in LCOE figures for fossil fuel technologies may be partially explained by technology maturity, and the fact that most of the costs of the incumbent technologies are related to the technology itself and not labor. On the other hand, a significant portion of the upfront costs in solar systems is attributed to labor costs, which are region-sensitive. At the same time, generation itself is highly affected by the quality of the solar resource, which is, once again, regional.

Although solar technology provides benefits, its intermittency and potential to provide energy only during daytime are two drawbacks that are difficult to ignore. Solar module costs have decreased considerably over the past 25 years, but these declines have yet to make solar fully competitive with conventional technologies globally and for all scales (i.e., residential, commercial and utility). With continued competition and pressure exercised on renewables given the intermittency disadvantage, several reports and news articles have announced the achievement of an LCOE or a PPA record, and often state that grid parity with conventional generation technologies has been reached (Borgmann, 2014; Shahan, 2015; Kenning, 2015 and Ayre, 2015). These records, which are reported and broken shortly thereafter, result in a further widening of the variation between the LCOE for solar and conventional generation. Using LCOE and PPA interchangeably can also be a source of confusion, and the difference between these two terms will be explicitly highlighted shortly.

Setting LCOE or PPA records for a technology that is fairly young might not be entirely surprising, as learning and development within the technology occurs at a fast rate during this phase. However, what raises eyebrows is that these generation cost records being set are distant from typical generation costs as will be shown shortly. To consider a technology competitive, it is not enough to cite a few future projects and then extrapolate them as the new industry norm since each project possesses unique features that may not be replicated elsewhere. For a technology to be considered competitive it means that the general trend of the costs in that industry is competitive with other technologies, and is not just confined to a few projects that have yet to be operational.

As mentioned earlier, variation is expected in reported LCOE values due to legitimate reasons including solar conditions and labor wages, which affect the amount of capital required for a particular project. Furthermore, depending on the level of detail that one wishes to include in calculating the LCOE and how accurate the assumptions are, the variation in the generation cost will also be affected. Hence, comparing these LCOEs that did not go through the same filter may lead to sub-optimal decisions as policymakers and investors may have been misguided by inaccurate information.

To substantiate claims of competitiveness and extract insights with confidence, an extensive time-series global dataset was compiled for solar PV LCOE values (Elshurafa and Albardi, 2016). Along with this dataset, an LCOE analyzer tool (i.e., an LCOE calculator) specifically tailored for PV technology was created, which enables fair comparisons to be performed across different solar PV projects. In other words, we would be able to effectively level the playing field and verify whether a reported LCOE is genuinely representative by ensuring that the underlying assumptions (i.e., discount rates, lifetime, operation, maintenance costs, etc.) fall within typical ranges that are accepted in the industry. This exercise is referred to in the paper as normalization. Consequently, it would be possible to identify the core reasons that contribute the most toward the skewing seen in the published LCOE figures.

The dataset holds time-series LCOE figures for residential, commercial and utility scale systems for dozens of countries from a variety of sources. It is published online and made freely available in an interactive manner. The LCOE analyzer tool is also available and is easy to use. For more information, see Elshurafa and Albardi, (2016). The dataset is available at:
https://www.kapsarc.org/openkapsarc/kapsarc-solar-photovoltaic-toolkit/

A Closer Look at the LCOE

The levelized cost of energy, abbreviated as LCOE, is still the prevalent metric used in the energy sector for cost comparison purposes. Conceptually, the LCOE is the ratio of all costs incurred throughout the lifetime of the power plant to overall energy generated. It is easy to understand and also relatively easy to calculate. Most importantly, it enables comparison of different generation technologies by capturing fundamental cost components including capital costs, operation and maintenance costs and discount rates.

Ironically, however, the simplicity of LCOE, which is seen as one of its points of strength, is simultaneously a source of criticism. Important characteristics of generation technologies such as dispatchability and ramping flexibility are not captured in the LCOE expression, which is a major reason why LCOE is not a reliable measure of the value of electricity to the power system. Furthermore, as the penetration levels of renewable technology increases beyond a certain threshold, utility operators incur balancing costs that are, again, not included. For that reason, investors, utilities and consumers would interpret LCOE differently based on their respective interests. Despite these shortfalls, and in the absence of a better metric, the LCOE continues to be the de facto measure of cost competitiveness and comparison across technologies for power generation.

In its simplest form, the expression of the LCOE can be written as:

$$LCOE = \frac{I + \sum_{i=1}^{n} \frac{O\&M}{(1+r)^i}}{\sum_{i=1}^{n} \frac{E_i}{(1+r)^i}} \qquad (1)$$

where I is the initial investment (in dollars), r is the discount rate (%), E is the energy output (in kilowatt-hours, or kWh), n is the lifetime of the plant (in years) and $O\&M$ is the annual operation and maintenance costs (in dollars). Conceptually, LCOE is the price at which electricity should be sold at in order for the project to break-even.

It is possible to arrive at the LCOE using equation 1 rather easily from a calculation viewpoint. However, the challenge that arises is to agree on the values that are to be used. Lifetimes of 25 years are considered typical, but that of 30 years and even longer are becoming increasingly accepted (Dunlop et al., 2005; Jordan and Kurtz, 2012). The classic question of 'what discount rate should be used?' is one that is asked when performing any financial assessment and the case at hand is no exception. It is these assumptions that are the points of contentions and also the source for the wide ranges seen in solar LCOEs.

But as mentioned, equation 1 is considered simplistic. Many organizations and researchers incorporate more parameters into the expression to arrive at a more representative figure. These additional parameters include, and are not restricted to: O&M cost escalator, panel degradation rate, de-rating (the overall losses of the solar system), decommissioning costs, insurance costs and policy support. As the costs of modules decreased over the past 20 years and in turn reduced upfront capital, the effect of these parameters on the LCOE increased.

The above argument suggests that there are at least two factors that exacerbate the variability in reported LCOE figures: (1) the level of detail that is to be included, i.e., the parameters to be included when calculating the LCOE, and (2) the numerical value associated with each parameter. In other words, even if the parameters to be included in the analysis are agreed upon, the actual numerical values may not. Furthermore, the LCOE is highly sensitive to some of the parameters. Hence, a small change in an input, such as the discount rate, can swing the LCOE values considerably. To reiterate, by variability, we mean the swings in the LCOE value that extends beyond the expected variability caused by legitimate regional factors such as solar conditions or salaries. Numerous publications in the literature have discussed this topic (Hutchby, 2014; Bazilian et al., 2013 and Branker et al., 2011).

How Normalization is Performed

The previous two sections summarized the status of the literature with respect to reporting solar PV LCOEs. In this section, we provide a tool to try and address this variability, and at least two elements are required to effectively normalize the data:

- An extensive compilation of LCOE data along with all the underlying assumptions used to calculate the reported LCOE

- A flexible tool that enables the calculation of the LCOE tailored to solar

Both the dataset and the analyzing tool (calculator) have already been developed (Elshurafa and Albardi, 2016). The dataset compiles LCOE figures from dozens of sources and converts all the costs to USD/kWh to enable comparison. Further, the LCOEs have been categorized into the classical system sizes: residential, commercial and utility. The LCOE analyzing tool was specifically tailored to solar PV technology and designed with the 'user in mind.' As such it is simple to use, yet does not compromise the inclusion of parameters that affect the LCOE.

With the aid of the dataset and the calculator, it will be possible to apply the same assumptions on all the reported LCOEs, i.e., perform an apples-to-apples comparison. We will refer to this exercise as 'normalization.' Essentially, the assumptions that stand behind each data point in the dataset will be scrutinized to ensure that it is consistent with typical global norms. If not, these assumptions will be amended according to values summarized in Table 1 below. For example, if a report uses a discount rate of 10 percent, it would be amended to 5 percent, as a discount rate of 10 percent is considered relatively high. Further, if an LCOE value was calculated assuming an ideal solar system (i.e., no losses), a loss of 15 percent would be assumed; thereby translating to an efficiency of 85 percent of the solar system. With this exercise, we ensure that all the projects are treated equally.

Note that there are some sources that have reported an LCOE value but did not report the assumptions that were made on how the LCOE was reached. These points are excluded from the analysis – we only include the points that have been reported with their underlying assumptions.

All the LCOE data points available in the dataset have been converted to nominal U.S. dollars, which allows the user to perform cost comparisons immediately. Hence, the normalization procedure that is performed in this paper is a second step that followed converting all the cost data collected into a single currency.

Table 1. Assumptions used in the normalization procedure.

Parameter	Value
Discount rate	5 percent
De-rating factor	85 percent
Annual panel degradation	0.5 percent
Operation and maintenance costs	$10/kW/year
Lifetime	25 years
Policy support	None
Insurance cost	None
Solar condition	Region-specific

Source: KAPSARC.

Normalization Results

As mentioned earlier, solar PV systems can be residential, commercial or utility. Given that the normalization procedure performed in this paper is identical for all three categories, we will show the steps and analysis for the utility category only, but provide the final results for all three categories.

In Figure 2a below, the collected data before performing any normalization is shown. The actual dataset contains a larger number of LCOE data points. However, the data that is shown here are only those that are tagged with assumptions. In Figure 2b, the normalized data are shown. Visually, it is immediately noticeable that the spread of the data has shrunk over the past few years. In 2008 for example, the maximum and minimum points were around $0.62/kWh and $0.07/kWh before normalization. After normalization, the maximum and minimum data points were approximately $0.50/kWh and $0.12/kWh.

It is best to explain how Figure 2b was created by providing an example of a normalization procedure for a single data point with some detail. In year 2008, Moore and Post (2008) reported a levelized cost of $0.062/kWh for a utility-scale solar farm in Arizona. This data point can be seen in Figure 2a, and is considered relatively low for an LCOE value in 2008. However, the authors, in their calculations, included federal income tax credits and state property tax reductions but excluded financing costs.

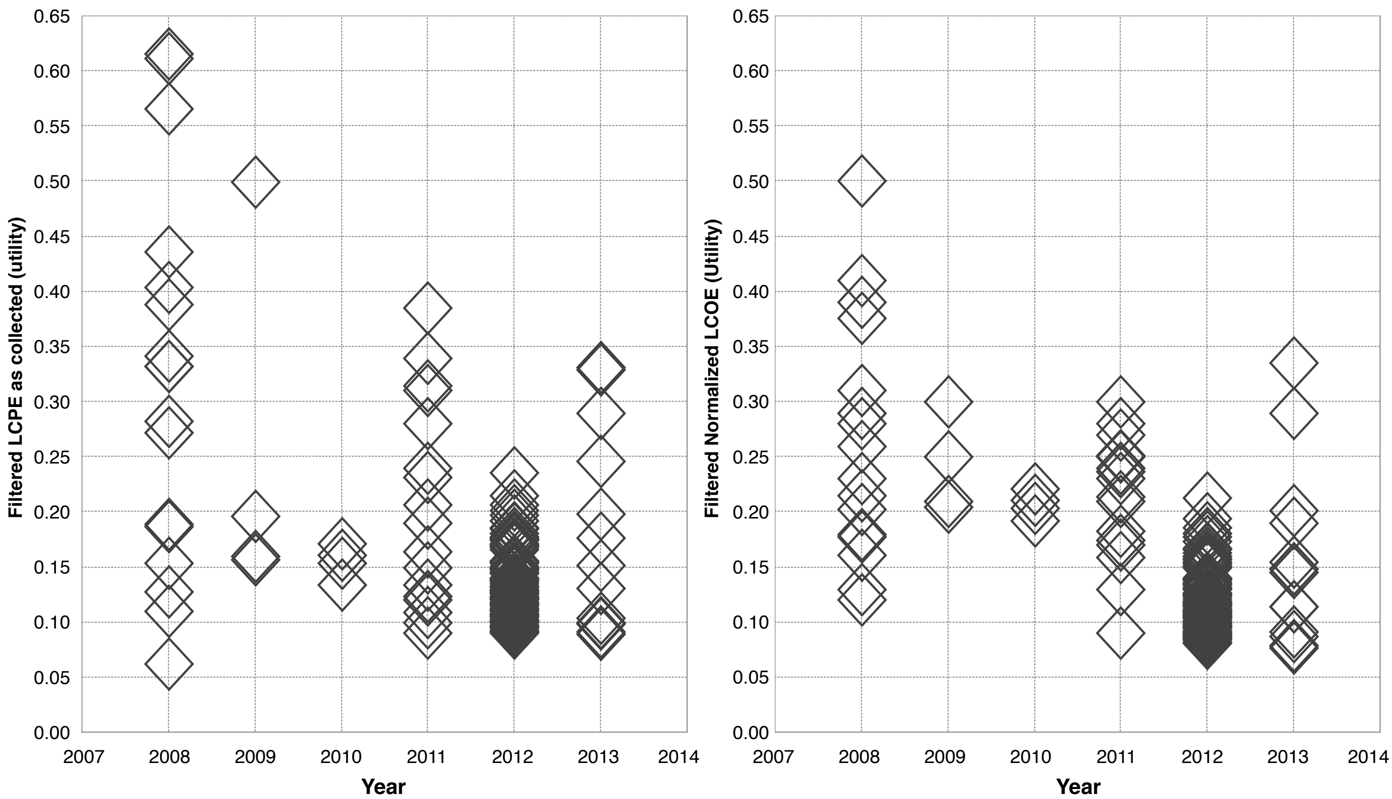

Figure 2. (a) The LCOE data points as collected from its respective sources before normalization, and the data after performing normalization (b).

Note: The spread of the data decreases after the normalization has been performed.

Source: KAPSARC.

This data point was normalized, i.e., the LCOE was recalculated by excluding policy support and using a discount rate of 5 percent. Consequently, the normalized LCOE rises to around $0.25/kWh. Note that Figure 2b no longer shows the previous cost of $0.062/kWh.

Using the same methodology, the normalization process was performed for the rest of the data points, with differences only in the details. One important note is that not all LCOE data points required normalization; if the assumptions being used to arrive at the LCOE in a report were reasonable, then these assumptions are kept intact. Changes to the assumptions occurred only if necessary. See Table 2 for a summary of three examples of reported LCOE that went through the proposed normalization filter. In the first example, the Arizona Project mentioned above is summarized, where the reported LCOE was $0.062/kWh. After excluding policy support and including financing, the normalized LCOE rises to around $0.25/kWh. In the second example, an LCOE of $0.61/kWh was reported for a project in Italy at a discount rate of 10 percent. However, when applying a 5 percent rate, the normalized LCOE drops to $0.42/kWh. Finally, Fraunhofer Institute reported an LCOE of $0.13/kWh with all assumptions being reasonable. Hence, the normalized LCOE stays the same since no assumptions were changed.

After performing the normalization for all available data points, the standard deviation was calculated for the sample and, as expected, the standard deviation was lower for the normalized data. Further, the coefficient of variation (COV, which is the ratio of the standard deviation to the mean) was also derived. Once again, the COV was lower for the normalized case and the least difference was observed in the residential scale. Although there is a considerable number of data points for the residential scale, data points with supporting assumptions were much less, as opposed to commercial and utility costs. The latter partially explains the negligible observable difference in variation (i.e., relatively low number of data points).

Table 2. A few examples showing how the normalization was performed and how the LCOE value post-normalization can become higher, lower or unchanged

Project	Reported LCOE ($/kWh)	Observation(s) on assumptions	Remedy	Normalized LCOE ($/kWh)
Arizona TEC **(Moore & Post 2008)**	0.06	Calculation included policy support and excluded financing	Exclude policy support and include financing	0.25
Italy **(IEA 2010)**	0.61	Assumed a discount rate of 10 percent	Use a discount rate of 5 percent	0.42
Germany **(Franhofer 2013)**	0.13	None – all assumptions reasonable	None required	0.13

Source: KAPSARC.

The results are shown in Figure 3. The difference in the standard deviation between the collected and normalized data was larger than the difference observed in the COV. This was to be expected since the COV is the standard deviation normalized by the mean.

Before ending this section, it is worthwhile to point out a qualitative observation related to Figure 2. By inspection, the data indicates that the spread of the LCOE values have become smaller in recent years. Learning-by-doing, decline in hardware costs and more standardized global practices are potential explanations for this shrinking.

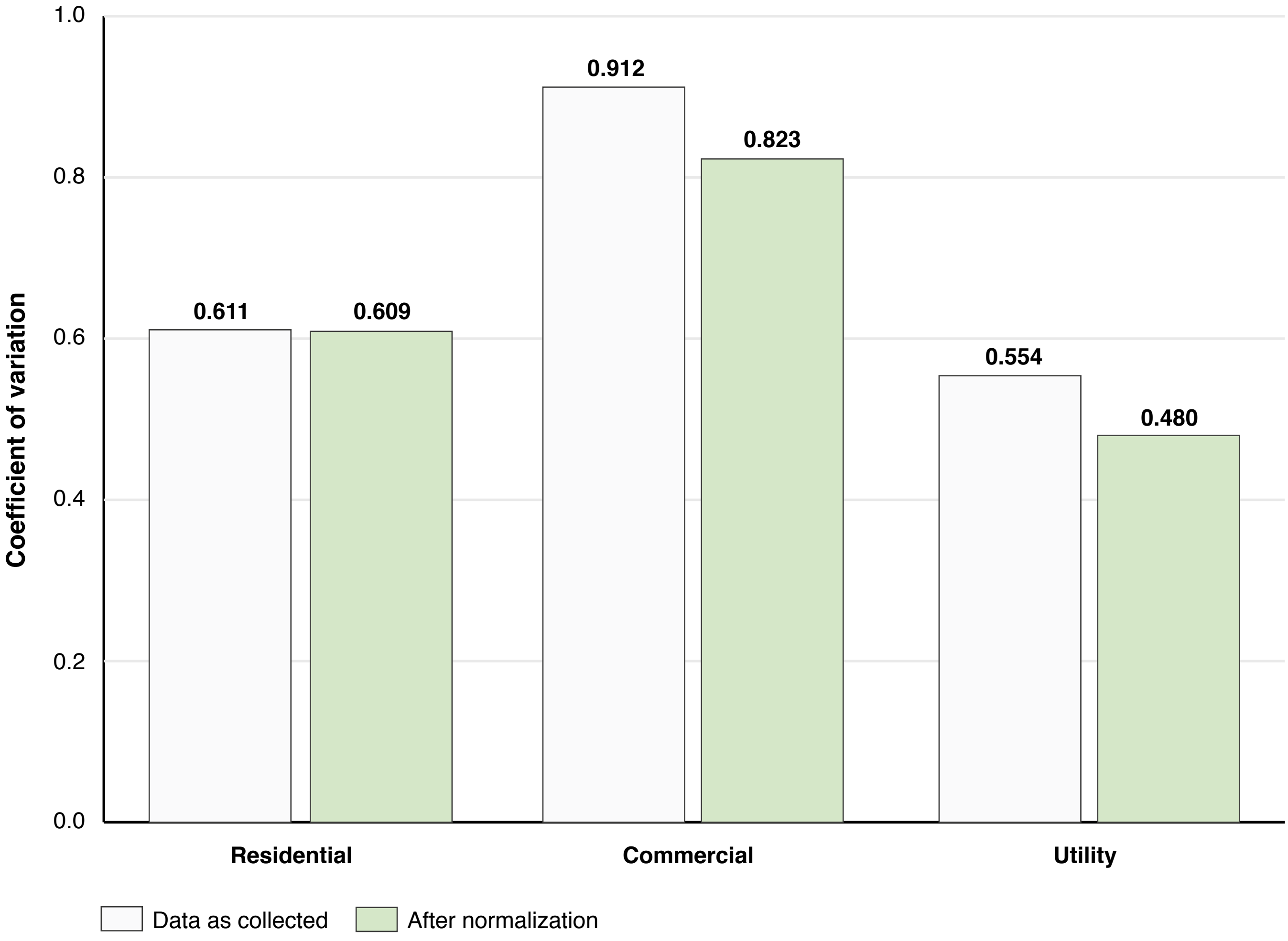

Figure 3. The coefficient of variation (COV, which is the ratio of the standard deviation to the mean) calculated for the collected and normalized data.

Note: The COV is always lower for the normalized case, but the least difference is observed in the residential scale.

Source: KAPSARC.

Discussion

Understanding reported LCOE and PPA values

When industry or research centers announce technology generation costs, they generally do so via the LCOE. However, when actual projects are launched, the utility (usually the buyer of electricity) or project developer (usually the seller of electricity) typically announce the price at which the electricity is going to be sold over a specified period. Such a contract is common in the renewable energy world as a form of support and is referred to as a power purchase agreement, or PPA. The PPA and LCOE, however, are not the same. A few differences should be noted:

> The LCOE is an estimated or modeled (virtual) number based on assumptions, while the PPA is an actual locked-in price.

> The LCOE represents current conditions prevailing in the industry, while the PPA is a promised price for a future project.

> The LCOE is a cost that represents breakeven conditions, while the PPA theoretically should account for a profit.

Typically, the PPA should be competitive for the buyer and profitable for the seller. In other words, it is likely that the LCOE will be lower than the PPA. The contract is made to the best of the parties' knowledge with no guarantees on how the future will unfold. In practice, some project developers may enter a bid with a boldly low PPA, maybe even lower than the project's LCOE, for other goals: they may want to set a record to gain media attention or use the project as a loss-leader. Nonetheless, and as a general rule, the LCOE can still serve as a proxy for the PPA and vice versa.

With the normalization procedure performed in this paper, it has been affirmed that reporting the LCOE with the appropriate assumptions enables the reader to put the numerical cost in perspective. Reporting a mere number without explaining how this number was derived can mislead readers or lead to inaccurate conclusions, and numerous examples can be provided to illustrate this issue. The previous section performed normalization on reported LCOE values and, for comprehensiveness, we will also do the same, briefly and qualitatively, on some reported PPA cases to show that the normalization procedure can apply to both LCOE and PPA values.

When the Dubai Electricity and Water Authority (DEWA) in the United Arab Emirates announced in early 2015 that they would buy electricity from ACWA Power – a Saudi holding company that is developing a solar farm in Dubai – for less than \$0.06/kWh, many were skeptical. This figure was considerably lower than the prevailing costs worldwide.

However, it is important to note that this new farm is earmarked to be built on the Dubai Solar Park as an expansion to an existing solar farm. In other words, the civil work and grid connection costs were already sunk. Further, DEWA, as a governmental institution, was able to secure low-cost borrowings compared with prevailing rates. Consequently, once all these factors are taken into account the announced PPA price is no longer a surprise. Factoring in these observations and recalculating the generation costs, one finds that the actual cost rises to around \$0.08-0.09/kWh – a number that is more in line with market levels at the time.

The Playa 2 project in the U.S. state of Nevada, which was developed by First Solar, announced that it will sell power at a price of less than \$0.04/kWh.

However, after further review, it was found that this price will increase by 3 percent per annum (Kenning, 2015). As for the recently announced ‘record’ in Chile of $0.0291/kWh (Mahapatra, 2016), it should be noted that this PPA is a contracted price for the year 2021 – the developers are betting on improvements in technology in order to deliver at such a low bid price. In other words, this PPA represents where the developers believe technology will reach, not where the technology cost is now. Other examples in the same spirit can be found in Ayre (2015) and Shahan (2015).

It is clear from these projects that each had unique characteristics tied to it. As a result, the final PPA value was significantly affected: hence claiming that a record has been set can be deceiving. While a detailed calculation can be carried out for each of these projects as was done in the previous section, the main message of this paper will not change. The chief recommendation put forward to policymakers, investors and other interested stakeholders in this study is to be wary when quoting LCOE values or accepting news regarding PPA contracts. Just because a project possesses the lowest reported PPA figure (in absolute value terms), it does not necessarily translate this figure to be a ‘new record.’ Unless the details and assumptions associated with these values are well documented and understood, comparisons are misleading.

Asking whether solar energy is competitive with other forms of fossil fuel is not a question that has a definitive global answer yet. In geographical locations such as islands, where both electricity prices and PV levels are high, solar can be viewed as competitive; examples of which include Hawaii. However, not all countries have the same favorable conditions. Note also that comparisons are usually held at the utility-scale level, since there are no commercially-available nuclear or coal generators for residential applications (at least, not yet). Solar competitiveness depends very much on where and when the comparisons are made.

Nonetheless, when receiving the answer (which will most probably always contain an LCOE number), it is important to remember that even if the solar technology and a conventional source reveal the same LCOE figure, this does not mean that both technologies are at parity. Although the LCOE is the same for both technologies in this virtual discussion, solar will only provide energy during daytime and when it is sunny. The conventional source, however, is available throughout the day and its output can be controlled depending on load demand.

The above discussion does not consider any externalities. Just as solar loses the battle of dispatchability every time against fossil fuels, solar will, on the other hand, win the battle on environmental-friendliness every time; yet another aspect to be taken into account when discussing whether solar is competitive with conventional forms of power generation. The U.S. Energy Information Administration encourages the use of the levelized avoided cost of energy, or LACE, in conjunction with the LCOE to be able to perform a comparison that accounts for externalities. The normalization procedure in this paper is also applicable on the LACE, with the appropriate modifications.

Conclusion

This paper provides a normalization framework and associated tools that aid in performing impartial comparisons of power generation costs in the solar PV industry. With the aid of an extensive LCOE dataset and a purpose-built calculator, it was shown that the reported variation in LCOE values is not as high as generally accepted in literature. The variation is exaggerated because of the different assumptions that are associated with computing the LCOE. After applying the same set of assumptions on the reported LCOEs, it was shown that the spread in the data narrows. Such a finding helps governments to formulate better feed-in-tariffs and allows investors to better anticipate their returns. Not only should comparing solar LCOEs to other technologies be done with caution, but also comparing LCOEs within the solar technology itself should also be done carefully.

Whenever an LCOE value is reported, it is best that the underlying assumptions are examined; particularly the financing assumptions and inclusion of any policy support that need to be explicitly mentioned, as they vary widely and are not standardized. Not reporting other parameters such as solar conditions or module costs, where a reasonable approximation can be obtained, could be considered less problematic – solar irradiation levels and module spot prices can be obtained from bona fide sources. This allows the reported LCOE to be put in perspective and enables a fair comparison with other reported values.

Another issue to look out for is whether the reported dollar per kilowatt-hour value is representative of the LCOE or a PPA. Although the proposed normalization is applicable to both the LCOE and PPA, it is important to note that the former is an approximate calculation for current conditions, while the latter is an actual number that is contracted for a future project guaranteeing a steady stream of income. Typically, the LCOE is a number that indicates a break-even point, whereas the PPA is one that entails some profit. Hence, comparing the LCOE to the PPA is not fully accurate. Yet, either of these parameters can be considered as a reasonable proxy for the other.

To account for tolerances in the assumptions, reporting the LCOE for a country, or even for a single project, as a range rather than a single value allows the observer to assess how the values drift and how sensitive they are given conditions that are most suitable for that specific country or project. The latter also includes capital costs. Some reports rely on published data of the previous year to calculate the LCOE for the current year, while in that time capital costs may have changed. Continuously following the developments in the cost of modules, inverters and other components and services is vital since capital costs have a significant effect on LCOE for solar projects in particular.

References

Ayre, James. 2015. "Another Low-Solar-Price Record: Saudi Electric Company Lands Solar PPA Under 5¢/Kwh." Cleantechnica. http://cleantechnica.com/2015/08/12/another-low-solar-price-record-saudi-electric-company-lands-solar-ppa-5%C2%A2kwh/.

Bazilian, Morgan, Ijeoma Onyeji, Michael Liebreich, Ian MacGill, Jennifer Chase, Jigar Shah, Dolf Gielen, Doug Arent, Doug Landfear and Shi Zhengrong. "Re-considering the economics of photovoltaic power." Renewable Energy 53 (2013): 329-338.

Borgmann, Moritz. 2014. "Dubai's DEWA Procures The World's Cheapest Solar Energy Ever: Riyadh, Start Your Photocopiers." Apricum. http://www.apricum-group.com/dubais-dewa-procures-worlds-cheapest-solar-energy-ever-riyadh-start-photocopiers/.

Branker, Kadra, M. J. M. Pathak, and Joshua M. Pearce. "A review of solar photovoltaic levelized cost of electricity." Renewable and Sustainable Energy Reviews 15, No. 9 (2011): 4470-4482.

Dunlop, E, D Halton and H Ossenbrink. 2005. "20 Years Of Life And More: Where Is The End Of Life Of A PV Module?." In Proceedings Of The 31St IEEE PV Specialists Conference, 1593-1596. DOI: 10.1109/PVSC.2005.1488449.

Elshurafa, Amro M and Shahad Albardi. 2016. The Solar Photovoltaic Toolkit. Riyadh: Publication number KS-1633-MP027A. https://www.kapsarc.org/wp-content/uploads/2016/05/KS-1630-MP024A-Solar_Photovoltaic_Toolkit.pdf.

Fraunhofer, 2013. Levelized Cost of Electricity Renewable Energy Technologies. Fraunhofer Institute for Solar Energy Systems. https://www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/study-levelized-cost-of-electricity-renewable-energies.pdf

Hutchby, James A. "A “Moore's Law”-like approach to roadmapping photovoltaic technologies." Renewable and Sustainable Energy Reviews 29 (2014): 883-890.

IEA, 2010. Projected Costs of Generating Electricity. International Energy Agency. https://www.iea.org/publications/freepublications/publication/projected_costs.pdf

Jordan, Dirk and Sarah Kurtz. 2012. Photovoltaic Degradation Rates - An Analytical Review. NREL. http://www.nrel.gov/docs/fy12osti/51664.pdf.

Kenning, Tom. 2015. "Buffett Project’S Record Low Cost Part Of Pricing ‘Trend’, Says First Solar." PV-Tech. http://www.pv tech.org/news/buffett_projects_record_low_cost_is_part_of_pricing_trend_says_first_solar.

Moore, Larry M., and Harold N. Post. "Five years of operating experience at a large, utility-scale photovoltaic generating plant." Progress in Photovoltaics: Research and Applications 16, No. 3 (2008): 249-259.

Mahapatra, Saurabh. 2016. “New Low Solar Price Record Set in Chile – 2.91 cents per kWh!”. Cleantechnica. https://cleantechnica.com/2016/08/18/new-low-solar-price-record-set-chile-2-91%C2%A2-per-kwh/

Shahan, Zachary. 2015. "World’S Cheapest Solar Power Lands In Austin, Texas — Under 4¢/Kwh! (Sort Of)." Cleantechnica. http://cleantechnica.com/2015/07/02/worlds-cheapest-solar-power-lands-in-austin-texas-under-4%C2%A2kwh-sort-of/

Notes

About the Authors

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About the Project

As solar PV installations continue to grow globally, a better understanding of the generation costs of this industry is important to assess its competitiveness versus conventional generation technologies. Using reported LOCE values for the solar industry, a normalization procedure which levels the playing field between reported values, was applied. The normalization procedure enables performing apples-to-apples comparisons between different projects. Accepting an LCOE figure without being aware of the underlying assumptions can result in erroneous conclusions. With the aid of the normalization exercise carried out in this paper, policymakers and investors are able to make more informed decisions: policymakers can look to formulate well-targeted budgets for renewable support, while investors can envisage a clearer picture of their expected revenues.

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