Levelized Cost of Energy (LCOE) is billed as the new metric for PV system evaluation—the replacement for cost per watt.

What is it and how can PV system designers and developers use it?
Levelized cost of energy (LCOE) is a widely used term in the PV industry. It is often used as a marketing tool by PV equipment manufacturers or in discussions regarding utility-scale projects. How is it calculated and what are its uses? Is it purely an external metric, something the industry can use to compare its costs to that of other energy sources, or can it be an internal metric employed by developers, engineers and customers in making PV system investment and design decisions?

In this article, we discuss what LCOE is, how it is used and how it is calculated. We then focus on how it can and should be applied in the PV industry. In addition, we analyze some example PV systems and explore appropriate uses for the metric. We also discuss some of the pitfalls associated with LCOE and the limitations of its use.

LCOE Defined

LCOE is used to compare the relative cost of energy produced by different energy-generating sources, regardless of the project’s scale or operating time frame. As Thomas Holt and his co-authors define it in A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies (see Resources), LCOE is determined by dividing the project’s total cost of operation by the energy generated. The total cost of operation should include all costs that the project incurs—including construction and operation—and may incorporate any salvage or residual value at the end of the project’s lifetime. Incentives for project construction and energy generation can also be incorporated.

\[
LCOE = \frac{\text{Total Life Cycle Cost}}{\text{Total Lifetime Energy Production}}
\]

As presented in Equation 1, LCOE is a metric that describes the cost of every unit of energy generated by a project in $/kWh (or €/kWh or $/MWh).

As will be shown directly, this basic definition of the LCOE can be expressed mathematically in more complex ways to account for all of the variables that impact the life cycle cost and total energy production for a PV system.

LCOE Uses

LCOE is most commonly used for evaluating the cost of energy delivered by projects utilizing different generating technologies. Specifically, it is used to rank options and determine the most cost-effective energy source. LCOE may also be used to compare the cost of energy from new sources to the cost of energy from existing sources. In this context, it is useful to
policy makers deciding how future energy needs will be met and which technologies to support, and to utilities and project developers selecting technologies. It should be noted that energy-efficiency projects may also be evaluated using the metric.

Because it captures total operating costs, LCOE enables comparisons between significantly different technologies, but it may also be used to compare the cost of energy from variations of the same technology. Options related to components or system design can be evaluated to see what impact they have on LCOE. For example, a developer of a new PV module technology that is more efficient, but also more expensive, could use LCOE to determine performance or cost benchmarks that would need to be met in order for the technology to be competitive and adopted in the market. Similarly, LCOE could be used to identify areas where cost-savings research would be most valuable.

While LCOE is useful for comparing the cost of energy from multiple technologies or evaluating the differences between sources utilizing the same technology, it should not be the only metric that is considered when doing so.

Determining LCOE

Equation 1 may be rearranged mathematically to state that the LCOE—the cost of every unit of energy generated by the project—multiplied by the total units of energy generated by the project is equal to the total cost of operation for the project. The total cost of operation of the project is typically known as the total life cycle cost (TLCC). This revised expression is shown in Equation 2:

\[
\text{LCOE} \times \text{Total Lifetime Energy Production} = \text{Total Life Cycle Cost} \tag{2}
\]

(Equations 2 through 6 are also drawn from A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies by Holt and his colleagues.)

In LCOE calculations, costs are discounted to present day (see Sidebar below) to allow direct comparison between projects with differing cost structures or cash flows. Thus, both the TLCC and the value of the energy generated are considered.

Key Financial Concepts

While it is beyond the scope of this article to thoroughly explain the financial theory behind the LCOE equation, there are two key concepts that you need to understand.

**Cash flow.** For the purposes of the LCOE calculation, the cash flow is a table showing the amount of money either spent or received each year over the life of the project. The values included in the cash flow vary depending on how the project is financed and whether you are considering tax credits or incentives.

In a simple example, the Year 0 value for a PV project cash flow would include the capital cost of installing the system and any up-front investment or capacity-based incentives. All tax credits, tax savings and performance-based incentives would begin to be recognized in Year 1. For most subsequent years, the only costs in the cash flow would be relatively small O&M expenditures. The likely exception to this would be the year when the inverter needs to be repaired or replaced. In some scenarios, the value of the equipment or material is included in the cash flow at the end of the project lifetime.

If the value of money was static over time, then the total life cycle cost of the project would be determined by simply summing each value in the cash flow. However, a dollar today is worth more than a dollar tomorrow, which leads us to the concept of present value.

**Present value.** In the context of this discussion, we want to determine how much each annual value in our project cash flow is worth in today’s dollars. To figure this out, we need to multiply each value by some factor less than 1. This factor is called the discount factor and can be represented by the following equation:

\[
\text{Discount Factor} = \frac{1}{(1 + d)}
\]

where \(d\) is the rate of return that could be expected from equivalent investment alternatives. The discount factor can be difficult to define and varies from project to project and over time.

A present value calculation allows you to account for the timing of expenditures or revenue and puts a higher value on costs and income that occur near the beginning of a project. This is important when comparing technologies because they often have different long-term cost profiles. Renewable technologies often require a large up-front investment and incur little cost over the project lifetime, whereas traditional sources of energy often have a lower up-front cost but require continuing significant investment in fuel costs.
are present-value calculations. The terms in Equation 2 may be expressed as follows, where \( N \) is the number of years in the analysis period (the project lifetime), \( C_n \) is the value of the cash flow in US dollars and \( Q_n \) is the energy generated in kWh by the system in year \( n \):

\[
\text{Total Life Cycle Cost} = \sum_{n=0}^{N} \frac{C_n}{(1 + d)^n} \tag{3}
\]

\[
\text{LCOE} \times \text{Total Lifetime Energy Production} = \sum_{n=0}^{N} \frac{\text{LCOE}}{(1 + d)^n} \times Q_n \tag{4}
\]

Substituting the expressions of Equations 3 and 4 into Equation 2 results in the following:

\[
\sum_{n=0}^{N} \frac{\text{LCOE}}{(1 + d)^n} \times Q_n = \sum_{n=0}^{N} \frac{C_n}{(1 + d)^n} \tag{5}
\]

The equation may be rearranged to solve for LCOE in $/kWh, thusly:

\[
\text{LCOE} = \frac{\sum_{n=0}^{N} C_n}{\sum_{n=0}^{N} Q_n (1 + d)^n} \tag{6}
\]

The equation in this form gives the impression that the energy generated is discounted. However, if you examine Equation 5, you can see that it is the value of the energy produced each year that is discounted rather than the energy itself. The appearance that the energy is discounted is simply a function of the algebra. For the purposes of this discussion, LCOE is assumed to have a constant value with respect to time.

The TLCC should include all costs required to operate the system over its lifetime. The most obvious of these are the construction or capital cost and the operation costs, including fuel and maintenance. Additional expenses such as, but not limited to, those related to financing the construction or insuring the system during its lifetime must also be included, as must property taxes if levied. The total energy generated by the system must incorporate variations in energy production, such as losses due to degradation.

In determining the LCOE of a PV system, the following factors should be considered:

- **Costs**
  - Initial investment or capital cost
  - O&M and operating expenses
  - Financing costs
  - Insurance costs
  - State and federal income taxes
  - Property taxes
  - Required return on investment
  - Decommissioning or removal

- **Incentives**
  - Federal tax credit
  - Accelerated depreciation (MACRS)
  - Incentive revenue

- **Energy**
  - Estimated Year 1 production
  - Annual degradation
  - System availability

Equation 6 can be expanded to show how the factors listed above can be included in the LCOE calculation. In Equation 7 (see below), \( I \) is the initial capital cost of the project, \( D \) is depreciation, \( t \) is the tax rate, \( O \) is the annual operating cost (including O&M, loan payments, finance and insurance), \( R \) is incentive revenue, \( S \) is salvage or residual value, \( Q_1 \) is the Year 1 estimate of energy production, and \( \text{deg} \) is the degradation rate.

Incentives that apply to a project—such as an investment tax credit—should be incorporated with consideration to when they appear in the project cash flow; they may not be realized at the same time as the expenditure they are based on. Finally, all of the terms shown in Equation 7 may not be applicable to every project, and there may be additional project-specific terms that should be included. **CONTINUED ON PAGE 34**
LCOE ≠ LCOE

Not all LCOEs are created equally. Making comparisons between LCOE values from different sources must be approached with caution. Various factors may be included in LCOE calculations— incentives, O&M, insurance, taxes and so forth—and a number of assumptions may be made, such as the analysis period and the discount factor. To get a true apples-to-apples comparison between projects or between technologies, the same factors must be included in each calculation. Even a small change in the assumptions that went into the calculation can drastically change the results, making comparisons unrealistic and invalid.

To add further confusion, there are two different types of LCOE that can be calculated: nominal and real. Which of these is calculated depends on whether the nominal or real discount factor is used in the energy production term of the LCOE equation (the left side of Equation 5). The nominal LCOE is higher than the real LCOE because the nominal LCOE is a current value calculation that is not adjusted for inflation, whereas the real LCOE is a constant-value, inflation-adjusted calculation. The real LCOE is generally preferred for long-term analysis.

Different Generating Technology LCOEs

One of the most widespread uses of LCOE has been in comparing the cost of energy delivered from different sources, such as conventional fossil fuel, nuclear and renewable materials. These different energy sources have very different cost structures and performance characteristics. For example, coal plants have significant capital and operating costs and a consistent generation profile, as evidenced by a high capacity factor (the ratio of a power plant’s actual output over time to its potential output based on its nameplate capacity). In contrast, PV systems are characterized by high capital costs, low operating expenses and a low capacity factor, due to the nature of the solar resource. The LCOE metric takes these differences into account and enables direct comparison.

The US Department of Energy’s Energy Information Administration regularly analyzes and publishes the LCOE of a wide range of generation technologies (see Resources). Figure 1 (p. 36) is based on data published in December 2010, which looks forward to plants coming on line in 2016. The purpose of this article is not to discuss the relative merits of the different technologies; rather, it is to explore the usage of LCOE. However, it is notable that the current low-cost electricity source is a natural gas plant, either a conventional or an advanced cycle. The assumptions made in producing this data are not presented here; however, we note that incentives were not considered in the analysis and that the LCOE of carbon-intensive technologies such as coal-fired plants is increased in an attempt to account for potential future costs of carbon emissions.

Grid Parity and the PV Market

Grid parity is a metric regularly used in evaluating the viability of renewable energy sources, which have historically been thought of as too expensive. For a retail customer, grid parity is achieved when the cost of power from an energy project is equal to or less than the retail price of power from the utility. However, it can be difficult to quantify when grid parity is reached. According to Branker, Pathak and Pearce in “A Review of Solar Photovoltaic Levelized Cost of Electricity” (see Resources), “The concept of grid parity for solar PV represents a complex relationship between local prices of electricity, solar PV system price . . . and local attributes.”
Utilities do not charge one set rate per kWh. The rate varies depending on market and by location. It can also change depending on when the power is used. In addition, the power output of many renewable energy projects is strongly dependent on the availability of local resources, such as solar insolation and wind. The result is that grid parity occurs at different project costs for different regions and at a higher rate for residential customers, followed by commercial and industrial customers, and lastly for power delivered at the utility scale.

“You cannot effectively compare LCOE to a single point value like today’s electricity price,” explains Nate Blair, manager of the data analysis and visualization group at the National Renewable Energy Laboratory (NREL). He continues, “The LCOE includes projections about future inflation and fuel cost changes, but that’s not what you see in a single point value like electricity price. To make an effective comparison, you need to take the LCOE of future projected electricity prices into account.”

The LCOE of an energy project is often compared to grid prices. This is a good first approximation because, when done correctly, an LCOE calculation accounts for regional and market variables. However, simply comparing the LCOE of a technology or project to the grid cost of electricity does a disservice to that technology or project. While LCOE captures all future anticipated costs, the current utility rate for electricity is only a snapshot.

In most cases the rate for utility power is anticipated to increase due to changes such as increased fuel costs or regulatory changes. To compare the LCOE from a new project to the cost of power from a utility, an LCOE calculation should be performed on the anticipated cost of utility power over the same lifetime as for the new project. The resulting value may be compared to the LCOE of the new project.

Here we have considered grid parity from the perspective of a retail consumer of electricity. As Nat Kreamer, CEO of Clean Power Finance, points out (see p. 48), the topic is even more complex when considering grid parity from the perspective of a utility or an independent power producer.

**Example LCOE Analyses**

While LCOE is not always the appropriate metric to use when evaluating project-specific decisions, it is an excellent tool for evaluating trends or big-picture issues. In the following examples, we explore some familiar questions in the PV industry and show how LCOE can be used to provide insight. These examples include evaluating how LCOE varies in different areas in the US, comparing single-axis tracking and fixed-tilt projects, analyzing inverter loading, analyzing module cost versus degradation rate and looking at downtime as it relates to system cost.

To provide consistency in the examples, we have defined two baselines: a fixed-tilt, ground-mounted PV system, and a single-axis tracking system. The values provided are not intended to represent the actual LCOE for a given configuration or location. Rather, they are included to show the relative values that result from varying the input assumptions. The real, rather than the nominal, LCOE is reported in each case.

**LCOE VS. LOCATION**

Site selection can have a major impact on a project’s feasibility. The weather conditions at a project site and its geographical location have implications for construction costs due to labor rates or building costs associated with land preparation or terrain, interconnection costs (these may be utility mandates, upgrade requirements due to limited utility infrastructure or distance from suitable power lines), or simply the cost of land.

It is clear that a PV system in Phoenix, Arizona, produces more power than a similar PV system in Portland, Oregon, but what does this difference mean with regard to the cost of energy from each system? What does it mean for the level of incentives that might be required to make solar financially viable in the two markets? What will PV need to cost before it makes sense in Massachusetts?
or New York without incentives? An LCOE calculation is essential to answering these questions.

While it is beyond the scope of this article to provide a comparison that would factor in all of the variables that change with location, it is a relatively straightforward task to evaluate how the LCOE of a PV system varies with the solar resources in different parts of the US. Changing the weather data used to simulate the production for the baseline fixed-tilt system from Table 1 enabled us to create the graph shown in Figure 2. (The financial assumptions we used for these analyses are detailed in Table 2.) Among other things, Figure 2 shows that, all else being equal, the LCOE for a fixed-tilt system in Portland is 56% higher than the LCOE for a fixed-tilt system in Phoenix.

SINGLE-AXIS TRACKER VS. FIXED TILT
It is well known that single-axis tracking systems are more appropriate in some locations than in others since the production gain from a single-axis tracker over a fixed-tilt system is larger for sunny locations at southern latitudes compared to the gain at northern latitudes. How much better are single-axis trackers? Are there locations in the US where a fixed-tilt system provides better results than a single-axis tracker?

To provide insight into these questions, we ran LCOE calculations for our baseline fixed and tracking systems defined in Tables 1 and 2. Note that the installation cost, O&M cost and system downtime were increased for the single-axis tracker relative to the fixed-tilt system, and the weather data was varied. The other variables were held constant for the two project types. The results are provided in Figure 3 (p. 40). This exercise did not account for changes in construction costs that may occur in different locations in the US; however, the trends observed are still relevant.

As can be seen in Figure 4 (p. 40), the decrease in the LCOE for a single-axis tracker project in locations such as Phoenix and Sacramento is more than three times greater than

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**Table 1: Baseline System**

<table>
<thead>
<tr>
<th></th>
<th>Fixed-Tilt Ground Mount</th>
<th>Single-Axis Tracker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Sacramento, CA</td>
<td>Sacramento, CA</td>
</tr>
<tr>
<td>Size (dc)</td>
<td>1.2 MW</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>Tilt</td>
<td>25°</td>
<td>0°</td>
</tr>
<tr>
<td>Azimuth</td>
<td>180° (south)</td>
<td>180° (south)</td>
</tr>
<tr>
<td>Inverter capacity</td>
<td>1 MWac</td>
<td>1 MWac</td>
</tr>
<tr>
<td>Inverter efficiency</td>
<td>96% CEC</td>
<td>96% CEC</td>
</tr>
<tr>
<td>Ground cover ratio</td>
<td>50%</td>
<td>No current function in SAM</td>
</tr>
<tr>
<td>System downtime</td>
<td>0.3% per year</td>
<td>0.5% per year</td>
</tr>
<tr>
<td>Annual degradation</td>
<td>0.5% per year</td>
<td>0.5% per year</td>
</tr>
<tr>
<td>Installed cost</td>
<td>$3.42 per Wdc</td>
<td>$3.68 per Wdc</td>
</tr>
<tr>
<td>O&amp;M cost</td>
<td>0.5% of installed cost</td>
<td>0.6% of installed cost</td>
</tr>
<tr>
<td>LCOE (real)</td>
<td>0.0901 $/kWh</td>
<td>0.0790 $/kWh</td>
</tr>
</tbody>
</table>

**Table 2: Financial Assumptions**

<table>
<thead>
<tr>
<th>Analysis Period</th>
<th>20 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflation rate</td>
<td>2.50%</td>
</tr>
<tr>
<td>Real discount rate</td>
<td>8%</td>
</tr>
<tr>
<td>Nominal discount rate</td>
<td>10.70%</td>
</tr>
<tr>
<td>Federal tax rate</td>
<td>35%</td>
</tr>
<tr>
<td>State tax</td>
<td>7%</td>
</tr>
<tr>
<td>Sales tax</td>
<td>8%</td>
</tr>
<tr>
<td>Insurance</td>
<td>0.5% of installed cost</td>
</tr>
<tr>
<td>Property tax</td>
<td>0%</td>
</tr>
<tr>
<td>Debt fraction</td>
<td>40%</td>
</tr>
<tr>
<td>Loan rate</td>
<td>7.50%</td>
</tr>
<tr>
<td>Loan term</td>
<td>15 years</td>
</tr>
<tr>
<td>Depreciation</td>
<td>5-yr MACRS federal and state</td>
</tr>
<tr>
<td>Tax credit</td>
<td>30% federal ITC</td>
</tr>
<tr>
<td>Incentives</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Figure 2** The relative LCOE in cents/kWh for 25° fixed-tilt PV systems is shown here for a variety of locations in the US.
the decrease in the LCOE seen in New York and more than two times greater than the decrease seen in Boston. Looking at these results, it is clear why single-axis trackers are a popular choice for projects in locations such as Phoenix or Sacramento. The LCOE for single-axis tracker projects is reduced by more than 12% in these locations compared to a fixed-tilt project.

It is also understandable why a fixed-tilt system might be chosen for a project constructed near Boston or New York. For these locations, the LCOE is only 5.8% and 3.5% less, respectively, with a single-axis tracker than with a fixed-tilt system. This decrease in LCOE could quickly be lost when you consider the additional weather-related issues that might occur in these locations, such as the effect of snow and ice on tracker accuracy and reliability, or the increased O&M costs that might be incurred due to snow damage.

The result for San Diego is both surprising and informative. While a single-axis tracker still provides a 7.2% lower LCOE than a fixed-tilt option, the difference is not nearly as pronounced as might be expected from the results in other locations. Without running this analysis, it would be easy to assume that the results in San Diego would be similar to those seen in Sacramento and Phoenix. However, when you compare the weather data for San Diego to the data for Sacramento or Phoenix, you see a higher percentage of diffuse irradiance in San Diego, which decreases the effectiveness of the tracker. The higher percentage of diffuse irradiance is likely due to San Diego’s proximity to the coast, and we would expect these results to change as a project site moved further inland.

Note that the production modeling portion of NREL’s System Advisor Model (SAM) tool does not currently model backtracking, which makes the production estimates for the tracker slightly higher than they should be.

INVERTER LOADING

One of the most frequently asked questions in the PV industry is how to load inverters. What should the ratio be between module capacity in dc watts and inverter capacity in ac watts? Typical answers to this question include the following:

- Use a rule of thumb (for example, size for a ratio between 0.8 and 1.2).
- It is worth paying the extra money to slightly oversize the inverter because the inverter will last longer.
- The inverter should be sized so that no power will be lost even under increased irradiance conditions, such as those caused by cloud-edge effect.
- The inverter should be overloaded as much as possible to drive down the installed cost.

Each of these answers is intended to provide the best results for the customer or investor. The goal is to pay as little as possible for the inverter without losing too much power to clipping or to long-term

CONTINUED ON PAGE 42
inverter downtime. This is precisely where an LCOE calculation can be useful. An LCOE analysis can capture all of the major variables that go into this decision: inverter cost, system production and inverter life or downtime.

As an example, we ran a parametric analysis on the fixed-tilt baseline system defined in Table 1 (p. 38). In the process, all the variables were held constant except for the size of the inverter, which was varied in 100 kW increments. The cost for the inverter was assumed to be $0.22 per ac watt. As you can see in Figure 5, the array-to-inverter ratio that results in the lowest LCOE for this example is 1.2. It also should be noted that options between ratios of 1.09 and 1.33 produce similar results.

An array-to-inverter ratio of 1.2 is within the guidelines set by most inverter manufacturers for acceptable inverter loading. For this reason, we did not consider additional downtime or decreased inverter life. However, there are cases where a similar LCOE analysis would result in a much higher ideal array-to-inverter ratio. Such cases might include arrays with low tilts (5° or lower) in hot climates, or in situations with high fixed interconnection costs where a utility or an incentive program has capped the ac system size but has not capped the dc size.

Running a similar analysis on a rooftop system with a 5° tilt in Phoenix indicates that an array-to-inverter ratio of 1.33 results in a lower LCOE ($0.0827/kWh) than a ratio of 1.2 or smaller ($0.0829/kWh). However, this ignores the possibility that this elevated inverter-loading ratio may decrease the life of the inverter. Without doing an LCOE calculation, this concern can be difficult to quantify. However, the metric lends itself to this type of analysis.

If the system with an array-to-inverter ratio of 1.33 had as little as 0.1% more downtime a year, then the LCOE of the system loaded at 1.33 would be higher than the system loaded at 1.2. Similarly, if the increased inverter loading resulted in the inverter failing 2 years earlier—assuming as a baseline that the inverter would need to be refurbished in Year 10 at 50% of the initial cost—then the LCOE would be better for the system loaded at 1.2. This type of data allows a system designer to make informed decisions.

**MODULE COST VS. DEGRADATION RATE**

Imagine that it is December 2011, and you receive an email from a distributor offering a fire sale on modules at $0.85 per watt. This is a great deal, but what if these modules are of a lower quality than the ones you would usually purchase at $1.20 per watt? At what rate of module degradation would the less expensive modules actually be a bad deal? One of the ways to answer this question is by running an LCOE calculation.

Figure 6 (p. 44) shows the results of a parametric analysis run for the baseline fixed-tilt system (see Table 1) where both the module cost and the degradation rate were varied. The lines on the chart represent a fixed LCOE value and indicate which combinations of degradation rate and module cost result in each value. This chart suggests that for this example, if all other values are held equal, a module can degrade about 0.5% more per year without having a negative impact on the LCOE if the cost is $0.10 less per watt. You could run similar analyses to look at risk factors that might be associated with less-expensive modules, such as the effects of an increased rate of module failure or a lower nameplate power tolerance.

**LCOE VS. SYSTEM AVAILABILITY**

Manufacturers and system designers always look for ways to drive down the installed cost of PV systems. Many of the methods considered involve some risk of increased system downtime due to component failure or incorrect installation. LCOE allows you to understand the tradeoffs between cost savings and potential increases in system downtime.

In this scenario, we ran a parametric analysis on the baseline fixed-tilt system (see Table 1) where the installation costs and system availability—the percentage of time that a system is fully functional—were varied. Figure 7 (p. 44) shows the somewhat surprising results. In the range shown in this example, a savings of $0.05 per watt in the installation cost can result in about 1.5% more system downtime per year without having a negative impact on LCOE. This analysis does not include the cost of any repairs that might be required to fix the cause of the system downtime. It also does not consider the negative impact that system downtime might have on the installer’s or manufacturer’s reputation.

**Figure 5** This chart shows how LCOE varies according to the array-to-inverter ratio for a 25° fixed-tilt PV system in Sacramento, CA.
LCOE Sensitivity

The PV industry’s continued growth and development depend on further reductions in PV LCOE. With this in mind, it is important to know which factors have the greatest influence on the LCOE equation. Where should energy be spent to find additional savings? What should we focus on to optimize systems for the lowest LCOE? What types of incentive or government-sponsored programs would be most effective?

Looking at the basic equation, it is clear that the two primary drivers of LCOE are energy production in kWh and system cost. However, each of those factors is determined by several subfactors, some more obvious than others. You can gain a better understanding of LCOE by running a sensitivity analysis. This analysis allows you to define a range of possible values for the inputs that determine LCOE. In a sensitivity analysis, a single input is varied within a specified range while all other inputs are held constant. The results of the analysis can be presented in a tornado chart such as the one shown in Figure 8 (p. 46). In this type of chart, the larger the bar, the greater the effect on the LCOE for that variation in the specific input.

Figure 8 shows a sensitivity analysis for the baseline 1 MW fixed-tilt system described in Table 1. What is immediately clear is that many of the inputs that have the greatest effect on LCOE are related to system financing. A change in the debt fraction or in the assumed discount rate can have nearly as large an impact on LCOE as a significant change in the module cost. In addition, the degradation rate has a significantly larger impact on LCOE than does system availability, even though these factors are comparable in magnitude. This is because the degradation rate compounds each year, resulting in relatively large losses in later years of the project. This analysis does not include a variation in irradiance that would result from constructing the system in different locations. However, a significant change in irradiance can have as large an effect on LCOE as the changes in the debt fraction and discount rate shown in this scenario.

While LCOE is very sensitive to financial inputs such as debt fraction and discount rate, those sensitivities are not always relevant. When looking at big-picture comparisons that include differing technologies and risks, it is possible that different projects may be evaluated with different financial terms. Implementing new or unproven technologies may be risky. Investors may associate greater risk with these technologies, which may impact the terms of their investment. However, when considering project-specific LCOE, those inputs are likely to either be fixed or vary so slightly that the LCOE is far less sensitive to them than to location or component selection.

LCOE as a Distribution

Any analysis that assumes the values in the LCOE equation are static gives an incomplete picture. It is important to remember that many of the inputs to the equation are assumptions, the true value of which will produce a range of possible outcomes. For example, production calculations rely on variables such as weather, system availability, module nameplate rating, soiling conditions and long-term degradation rate, just to name a few. The value chosen for each of these variables as an input to the LCOE equations may be best case, worst case or somewhere in between. CONTINUED ON PAGE 46
As Seth Darling and his colleagues at the Argonne National Laboratory note in “Assumptions and the Levelized Cost of Energy for Photovoltaics” (see Resources), “Generally, LCOE is treated as a definite number and the assumptions lying beneath that result are rarely reported or even understood.” The authors suggest that the end result of an LCOE calculation should not be a single fixed value, but rather a distribution—a range of possible outcomes with a probability of occurrence assigned to each one. This result can be achieved by running a Monte Carlo analysis. In a Monte Carlo analysis, probability distributions are defined for each of the input variables, and results are achieved by running numerous versions of the calculation, each time randomly picking a value for each input variable based on the probabilities defined in the distributions.

One interesting takeaway from the paper written by Darling and his colleagues is the idea that some projects have a tighter range of possible LCOE outcomes than others. This range could be determined by the consistency and quality of the weather data in that location, the certainty in the financing assumptions, the track record of the technology or any number of factors. An investor may choose to green-light a project with LCOE values that are centered on a higher number than another project’s, but with a tighter range of possible outcomes.

**Limitations of LCOE**

According to Chris Cameron, recently retired from Sandia National Laboratories, “A common misconception is that the project with the lower LCOE is always preferred.” LCOE is a good tool to use to study technology options and design decisions from a macro perspective. However, it is not always the most useful metric when making decisions about specific projects. Holt and his colleagues note in *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies* that LCOE is “not recommended for selecting among mutually exclusive alternatives.” Instead, one needs to determine the goals of the project and make decisions based on those factors.

Take the example of a cash purchase system built on a flat warehouse roof where you can build either a smaller system with a 20° tilt or a larger system with a 5° tilt. An LCOE calculation may indicate that the 20° tilt system has the lower LCOE. However, depending on the customer’s load and the rate that the customer is paying for power, the 5° tilt system may save more money over the long run and may be the better option. In this scenario, a net present value calculation would be the more appropriate metric for evaluating which option to choose.

While the LCOE metric is great for calculating how much each kilowatt-hour costs over an analysis period, it does not provide a method to account for how valuable the power is. For example, an LCOE calculation does not take into account time-of-use or time-of-delivery factors, which place different values on electricity. In many situations, the financial picture looks different once these factors are considered. LCOE does not account for the reliability of the power produced by a project, either. A coal-fired power plant can generally be relied on to supply a set amount of power and a natural gas “peaker” plant can be brought on line when needed; however, renewable sources of power are inherently more variable. LCOE does not capture the cost of this variability.

**LCOE Is Only One Piece of the Puzzle**

LCOE can be a valuable metric in evaluating a PV system and can help engineers, developers, policy makers and manufacturers make informed decisions. However, many other parameters influence whether to invest in a project. Those parameters are often financial but may also be qualitative or regulatory in nature.

Multiple factors may increase the LCOE on a project. For example, an architect’s aesthetic may result in a less visible, lower-tilt system, or a building owner’s energy-offset goal may push toward maximizing a...
LCOE and Technology Grid Parity

Nat Kreamer, CEO, Clean Power Finance

Power markets are complex. Measuring a generation type’s power market competitiveness using an LCOE analysis does not give a complete picture of grid parity. LCOE makes too many assumptions and leaves out too many critical market factors.

Consider the example of the 548 MW Conowingo Dam, which is one of the largest hydroelectric facilities in the PJM Interconnection power market (covering 13 states and the District of Columbia) and is the transmission organization’s black-start facility. My great-grandfather helped build the dam. LCOE can explain the discounted cash flow (DCF) value for Conowingo, provided that one assumes a constant weighted average cost of capital and a consistent water flow. Both of these assumptions, however, are erroneous. Different investors have different capital structures (debt and equity) and risk profiles (beta), which means that Conowingo’s DCF value varies among investors, even if one assumes that the Susquehanna River’s flow remains constant. Since river flow above the dam determines the potential nameplate capacity factor for Conowingo on any given day, this defines the productive capacity of the facility, effectively determining how much power can be amortized over the dam’s capital and operating costs. Water-level volatility, much like commodity price volatility for natural gas, irradiance volatility for solar, and wind-speed volatility for wind, changes the LCOE for Conowingo on a daily basis.

The value of a fuel type—determined by its power content and availability, among other factors—and the prices paid for the power it generates is described as a spark spread. A spark spread is the combination of two-option values. LCOE assumes that the value of this spark option remains constant, because LCOE does not account for the forward power prices in a market. Imagine buying Conowingo Dam today with a fixed-priced, 20-year PPA with Baltimore Gas & Electric. If power prices in PJM go up, then the value of the PPA decreases for the owner and increases for the buyer (the buyer can purchase fixed-price power from Conowingo and sell it for more in the market) and vice versa. LCOE does not account for the significant amounts of money made and lost trading spark-spread options.

Conowingo also has real-option value that LCOE does not capture. If the PJM market experiences a blackout, then Conowingo turns the grid back on. Black-start services are a valuable call option, and each US wholesale power market recognizes and pays for them, yet LCOE does not account for power-market real options like black-start services.

All power markets—wholesale grid and distributed retail—are the sum of the value of all the power plants in them, which include all generation types. Because LCOE makes broad assumptions about capital costs and fuel price value while failing to account for option value, it is very difficult to determine LCOE for grid power. Consequently, comparing LCOE for solar to LCOE for the grid tells only part of the story.

The system’s absolute energy generation (kWh) rather than specific performance (kWh/kWp). Incentive structures, such as an up-front capacity-based incentive as opposed to a performance-based incentive, may drive system size up but performance down. Utility caps on ac system size may encourage a system design that maximizes total energy generation rather than specific performance.

Other financial considerations that play into investment and design decisions span from metrics such as the simple payback period through more-sophisticated systems such as net present value or internal rate of return. Each of these may drive a project in a different direction than an LCOE metric. In addition, capital constraints may limit a project to one with a higher LCOE—for example, when a project is built with little up-front cost to the customer.

Ultimately, while LCOE is valuable in many situations, given the variability of the PV industry and the complexity of the energy industry overall, LCOE is only one of many factors that should be considered when making decisions about PV projects.

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**Resources**


System Advisor Model (SAM) / nrel.gov/analysis/sam