Minimizing utility-scale PV power plant levelized cost of energy using high-capacity factor configurations

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ABSTRACT

Solar photovoltaic power plants have emerged in recent years as a viable means of large-scale renewable energy power generation. A critical question facing these PV plants at the utility scale remains the competitiveness of their energy generation cost with that of other sources. The relative cost of electricity from a generating source can be compared through the commonly used levelized cost of electricity (LCOE) calculation. The LCOE equation evaluates the life-cycle energy cost and production of a power plant, allowing alternative technologies – with different scales of operation, investment, or operating time periods – to be compared. This article reviews the LCOE drivers for a PV power plant and the impact of a plant's capacity factor on the system LCOE, as well as the effects of various factors such as capacity and geographical location. The economic tradeoffs between fixed and tracking systems are evaluated as well as a review of land use, plant operation and maintenance costs.

Introduction

From 2004 to 2008, the market for small (<50MW) distributed PV power plants took off around the world, particularly in Spain and Germany where more than 3GW of power plants were installed. PV power plants have also emerged in the United States where, as Table 1 shows, large installations have been built in recent years, or are under construction, including what will be one of the largest PV power plants in North America: Florida Power & Light's 25MW plant, featuring high-efficiency PV panels integrated onto tracking systems.

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Pacific Gas & Electric Co. in California has announced more than 2GW of agreements involving both solar thermal and PV power plants, including more than 750MW of photovoltaics – the largest utility-scale PV contracts in the world. As part of this program, a 210MW high-efficiency PV, central station power plant will be built in the state's California Valley and could be the first to deliver utility-scale PV power to PG&E, beginning in 2010. With LCOE falling rapidly for central station PV plants, their economic competiveness with other renewables and peaking power sources are driving adoption of the technology.

System	Company	Technology	Year	Capacity (AC)
FPL Desoto	SunPower	Tracking xSi	2009	25MW
Nellis AFB	SunPower	Tracking xSi	2007	12MW
FPL Space Coast	SunPower	Fixed xSi	2009	10MW
Sempra Energy	First Solar	Fixed CdTe	2008	10MW
Alamosa	SunEdison	Tracking xSi	2007	7MW

Table 1. PV power plants operating or under construction in the United States.

LCOE of PV power plants

A key to the continued growth of utility-scale solar is the LCOE of a PV power plant. LCOE is one analytical tool that can be used to compare alternative technologies when different scales of operation, investment, or operating time periods exist. For example, LCOE could be used to compare the cost of energy generated by a PV power plant with that of a fossil fuel-generating unit or another renewable technology [1].

The LCOE calculation is the net present value of total life cycle costs of the project divided by the quantity of energy produced over the system life, as shown in the following equation:

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

The above LCOE equation can be disaggregated for solar generation as shown in the Box 1 below.

The following sections summarize the key LCOE input parameters, including their respective sub equations.

Initial investment

The initial investment in a PV system combines the total cost of the project plus the cost of construction financing. The capital cost is driven by:

- Area-related costs that scale with the physical size of the system, namely the panel, mounting system, land, site preparation, field wiring and system protection.
- Grid interconnection costs that scale with the peak power capacity of the system, including electrical infrastructure such as inverters, switching gear, transformers, interconnection relays and transmission upgrades.
- Project-related costs, such as general overhead, sales and marketing, and site design, which are generally fixed for similarly-sized projects.

(1)

$$\text{Initial Investment} = \sum_{n=1}^{N} \frac{\text{Depreciation}^n}{(1+\text{Discount Rate})^n} \times (\text{Tax Rate}) + \sum_{n=1}^{N} \frac{\text{Annual Costs}^n}{(1+\text{Discount Rate})^n} \times (1-\text{Tax Rate}) - \frac{\text{Residual Value}}{(1+\text{Discount Rate})^n}$$

$$= \frac{}{\sum_{n=1}^{N} \frac{\text{Initial kWh/kWp} \times (1 - \text{System Degradation Rate})^n}{(1 + \text{Discount Rate})^n}}$$

Depreciation tax benefit

The depreciation tax benefit is the present value of that benefit over the financed life of the project asset. Public policy, which enables accelerated depreciation, directly benefits the system LCOE since faster depreciation translates to faster recognition of the depreciation benefit.

$$\sum_{n=1}^{N} \frac{\text{Depreciation}^n}{(1+\text{Discount Rate})^n} \times (\text{Tax Rate})$$

Annual costs

In the LCOE calculation, the present value of the annual system operating and maintenance costs is added to the total life-cycle cost. These costs include inverter maintenance, panel cleaning, site monitoring, insurance, land leases, financial reporting, general overheads and field repairs.

$$\sum_{n=1}^{N} \frac{\text{Annual Costs}^n}{(1+\text{Discount Rate})^n} \times (1-\text{Tax Rate})$$

System residual value

The present value of the end-of-life asset value is deducted from the total life cycle cost in the LCOE calculation. Silicon solar panels carry performance warranties for 25 years and have a significantly longer useful life. Therefore, if a project is financed for a 10- or 15-year term, the project residual value can be significant.

$$\frac{\text{Residual Value}}{(1+\text{Discount Rate})^n}$$

(2)

$$\sum_{n=1}^{N} \frac{\text{Initial kWh/kWp} \times (1 - \text{System Degradation Rate})^n}{(1 + \text{Discount Rate})^n}$$

System energy production

The system lifetime energy production is calculated by determining the first-year energy generation as expressed in kWh (AC)/kWp (AC), then degrading output over the system life based on an annual performance degradation rate. System degradation (largely a function of PV panel type and manufacturing quality) and its predictability are important factors in life-cycle costs since they determine the probable level of future cash flows. This stream of energy produced is then discounted to derive a present value of the energy generated to make a levelized cost calculation. The first-year kWh/kWp is a function of:

- The amount of sunshine the project site receives in a year.
- The mounting and orientation of the system (i.e., flat, fixed-tilt, tracking, etc.).
- The spacing between PV panels as expressed in terms of system ground-coverage ratio (GCR).
- The energy harvest of the PV panel (i.e., performance sensitivity to high temperatures, sensitivity to low or diffuse light, etc.).
- System losses from soiling, transformers, inverters, and wiring inefficiencies.
- System availability largely driven by inverter downtime.

Finally, the system's financing term (n) will determine the duration of cash flows and affect the assessment of the system residual value (see Box 2 above).

When evaluating LCOE and comparing other commonly known $/kWh benchmarks, it is important to remember that LCOE is an evaluation of levelized life-cycle energy costs. The price of energy established under power purchase agreements (PPAs) or by feed-in-tariffs (FITs) may differ substantially from the LCOE of a given PV technology, since PPAs and FITs may represent different

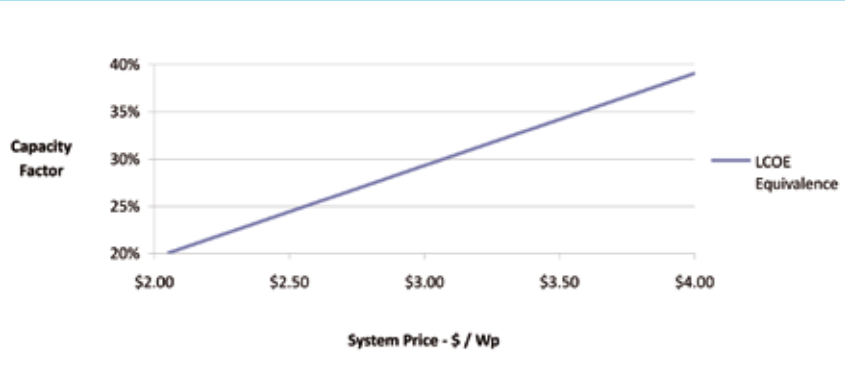

Figure 1. Associated capacity factors and system prices producing an identical LCOE.

contract or incentive durations, the inclusion of incentives such as tax benefits or accelerated depreciation, financing structures, and in some cases, the value of time-of-day production tariffs.

PV power plant capacity factor

The capacity factor, a standard methodology used in the utility industry to measure the productivity of energy-generating assets, is a key driver of a solar power plant's economics [2]. Since the majority of the expense of a PV power plant is fixed capital cost, LCOE is strongly correlated to the power plant's utilization. The net capacity factor for a PV power plant (after inverter and other plant power consumption) over a given period can be calculated (see Box 3 below).

A PV power plant's capacity factor is a function of the insolation at the project location, the performance of the PV panel (primarily as it relates to high-temperature performance), the orientation of the PV panel to the sun, the system electrical efficiencies, and the availability of the power plant to produce power.

The capacity factor's economic impact can be substantial. Figure 1 illustrates a range of identical LCOE values, expressed in $/kWh, for a given PV power plant system price as expressed in $/Wp and the associated capacity factor. (The capacity factor is generally expressed as a function of the AC rating of a plant, so the kWh/kWp calculation is based on the kWh per AC watt peak as opposed to the DC watt peak.)

(3)

$$\text{Net Capacity Factor (NCF)} = \frac{\text{Net Actual Generation}}{\text{Period Hours x Net Maximum Capacity}} \times 100\%$$

As the capacity factor declines, the required installed system price must also substantially decline to maintain system economics. For example, a $2.50/Wp system with a 24% capacity factor (such as with a fixed-tilt configuration) delivers the same LCOE as a $3.50/Wp system with a 34% capacity factor (such as with a tracker).

The highest capacity factors (CF) are generated with trackers that follow the sun throughout the day to keep the panel optimally oriented toward the sun. Tracking also has the benefit of generating more energy in the peak electricity demand periods during the afternoon. Two patented single-axis tracking systems have been developed to optimize the capacity factor of a PV power plant: the T0 tracker (Figure 2), a horizontal one-axis tracker optimized for space-constrained sites; and the T20 tracker (Figure 3), a titled one-axis tracker optimized for maximum energy production.

A tracker's benefit to a PV power plant's annual and summer capacity factors can be substantial. Figure 4 illustrates the annual and summer (June 1-Aug 31) capacity factors achievable for a power plant located in southern Nevada and built with a fixed system, horizontal one-axis tracker, or tilted one-axis tracker. It is clear that the tilted one-axis tracker can generate approximately 30% more energy than a fixed system on an annual basis. Additionally, during the summer peak season, capacity factors can exceed 38% with a horizontal one-axis unit, providing energy when the utility experiences maximum seasonal demand.

The LCOE model assigns an equal value to electricity generated throughout the year; however, electricity generated at peak periods is more valuable to the utility. The use of a solar tracking system can

Figure 2. Horizontal single-axis trackers optimized for space-constrained sites.

Figure 3. Tilted single-axis trackers optimized for maximum energy production.

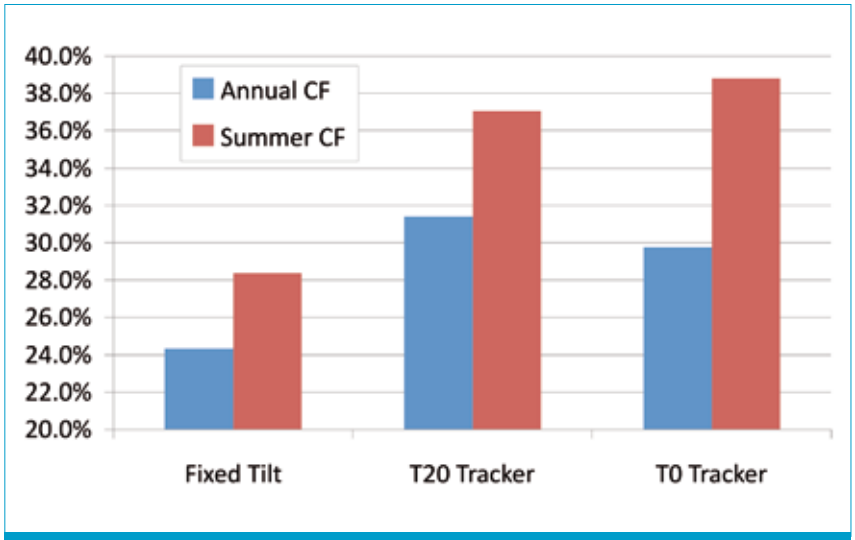

Figure 4. Annual and summer capacity factors (CF) for a southern Nevada PV power plant.

increase the output of a plant after 4 p.m. in the summer by more than 40%, which is often a peak demand period when energy is highly valued.

Figure 5 provides a comparison of the summer energy output of fixed and tracking PV power plants compared with the California ISO grid load, showing this improvement in afternoon production relative to peak demand. Figure 6 illustrates the point further, showing PV power plant capacity factors achievable during the peak 1 p.m. - 8 p.m. periods in the summer. During this peak period, capacity factors from trackers can exceed 70%, directly offsetting the need for natural gas peaking plants and other alternative peaking power resources.

Land use and capacity factor

Land for solar power plants has been readily available and inexpensive in the past, largely because it had little economic value other than in some low-yielding agricultural activities. As solar power plant developers began buying land in South Korea, southern Europe, and the southwest United States, prices for prime land conducive to a solar power plant rapidly increased in cost and general land availability became an issue. South Korea and southern Europe have seen solar-suitable land prices increase more than 300%, and southwest U.S. desert land has sold for prices as high as a reported US$23,000 per acre for flat land with high insolation located near electrical transmission lines, a roughly 15,000% increase over historical values for the same parcels [3].

There are two fundamental drivers for the land consumed by a solar power plant: solar panel efficiency and system ground-coverage ratio. System GCR represents the ratio of solar panel area to land area. Flat-mounted PV panels use the minimum land area based on system rating in MW and have the maximum GCR but have the lowest capacity factor and thus lower utilization of fixed plant costs. Conversely, a two-axis tracker has the maximum possible capacity factor but requires up to 10 times more land than flat configurations. To put it simply, the better the orientation to the sun (thus capacity factor), the longer the shadows created and therefore the further apart the panels must be placed to avoid panel-to-panel shading.

To deliver the best utility-scale PV LCOE, land use must be balanced with the system capacity factor. One way of addressing the optimization problem combines high-efficiency PV panels and tracking systems that efficiently use land while increasing energy production. A tilted single-axis tracker can maximize the capacity factor in an efficient land footprint, and a horizontal single-axis tracker helps optimize land use for constrained sites while still providing a high capacity factor.

Figure 7 illustrates the land consumption versus capacity factor for a central power plant producing 1TWh/year in a high insolation location. (Note that the listed capacity factors are based on the AC rating of the power plant at the point of grid interconnection; the DC nameplate capacity of the PV power plant will be approximately 20% higher than the AC rating, depending on the PV panel type and system configuration.) This example shows that:

- With high-efficiency PV panels, up to 75% less land is needed for a given capacity factor configuration.
- With high-efficiency PV panels mounted on trackers, up to 30% higher capacity factors can be attained while using a similar or lower amount of land than low- and medium-efficiency panels mounted on fixed-tilt systems. This means that lower LCOE, high-capacity factor configurations can be achieved without prohibitively increasing the amount of land required.

Cost effectiveness of tracking

Although the capacity factor benefit of tracking is clear, the decline in PV power plant prices raises a question about the continued cost effectiveness of tracking systems. One could argue that low-cost PV panels mounted on fixed structures would yield superior economics to a high-capacity factor tracking system during a new era of low-cost PV. This question on tracking cost effectiveness can be answered with an application of the LCOE equation. As with any change that improves the capacity factor of the system, the increase in performance must be weighed against the incremental cost, if any. In the case of tracking, the change to capital cost divided by the change in capacity factor can be seen in the following equation.

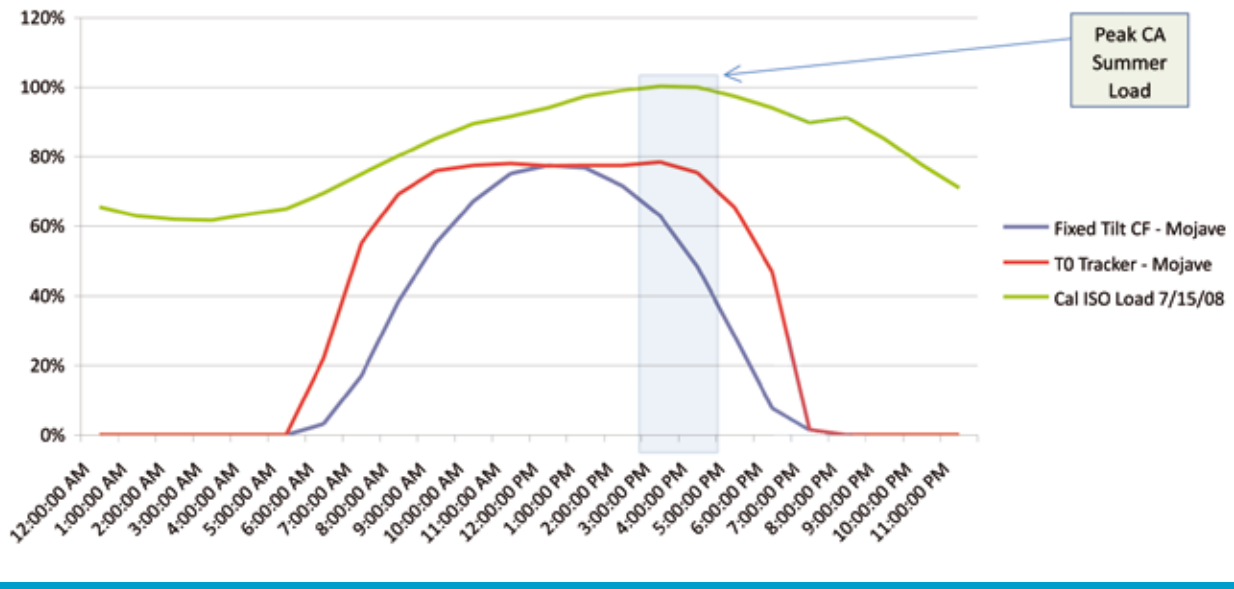

Figure 5. Comparison of California summer load requirements with fixed and tracking PV systems.

If the absolute change in capital cost is less than the absolute change in capacity factor, then economics suggest the implementation of the system that best improves the capacity factor. If this analysis is applied to a PV power plant located in the U.S. desert (southwest), even at a low system price of ~$4/Wp DC, the value of the tracker's 30% capacity factor improvement would be $1.20/Wp DC, far above the incremental capital cost of the tracker motor and control system.

Environmental conditions and capacity factor

In addition to sun tracking, local weather conditions – such as the amount of sunshine that a site receives – are the major drivers of high capacity factors. Desert sites can achieve capacity factors up to twice as high as those seen in less sunny northern states. Less obvious impacts on the capacity factor include ambient temperature, wind, solar cell technology, and soiling. Of these parameters, operating temperature and panel performance are key capacity factor drivers.

Typical solar panels experience a performance reduction of 0.5% per degree Celsius above 25°C. On a hot desert day, panel temperatures can exceed 60°C, resulting in a loss of power output of more than 15% over a panel's standard test condition rating. Some PV technologies, such as the back-contact monocrystalline silicon-cell design, perform better in high operating temperature conditions. Higher-efficiency panels can also benefit from a lower module operating temperature, owing largely to the conversion of more solar energy to electricity instead of heat.

Independent studies jointly conducted by the universities of Cyprus and Stuttgart in Nicosia, Cyprus, in 2006-07 confirmed the impact of excellent high-temperature performance on energy yield (and the resultant capacity factor). In other test comparisons of the output of high-efficiency modules with those of standard monocrystalline silicon panels, the Arizona State University Photovoltaics Testing Laboratory found that the modules demonstrated a 7.2% improvement to capacity factor during the summer test period, owing to the superior high-temperature performance of the cells (Figure 8). This extra energy provides a direct reduction in LCOE since the energy leverages all of the installed system plant costs.

Capacity factor and operations and maintenance costs

Improving the capacity factor of a system directly reduces operation and maintenance (O&M) costs through higher utilization rates of fixed assets. Table 2 shows this correlation as it relates to the inverter requirements of generating 1 TWh of annual energy in a PV power plant. In this example, 1 TWh of energy would require 335 inverters, each rated at 1 MWp, with a single-axis tilt tracker versus 442 inverters with a fixed-tilt system at the same location. The use of a tracking system would therefore significantly reduce the inverter O&M costs, the most costly portion of annual system maintenance.

Significant power-related maintenance costs also exist with respect to transformers, switching gear, and grid interconnection, and all benefit from a high capacity factor system configuration.

Module cleaning, panel repair or replacement, mounting structure and wiring maintenance and vegetation control costs also scale down with such a system.

Although tracking systems add cost in terms of motor and controller maintenance, this cost is relatively small when compared with the other O&M cost savings that trackers provide. For example, the tracker's motor requires only annual lubrication and a single motor can control more than 300kWp of PV.

Also, the tracker bearings require no lubrication and are designed for more than 25 years of use. The O&M cost of a utility-scale tracking system ends up being less than US$0.001/kWh more than a fixed configuration, a calculation which does not factor in the O&M savings from increased energy production.

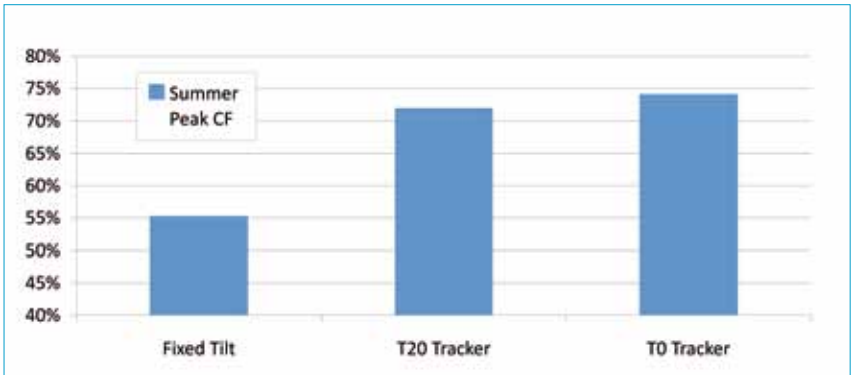

Figure 6. Summer peak period (1:00pm-8:00pm) CF for southern Nevada.

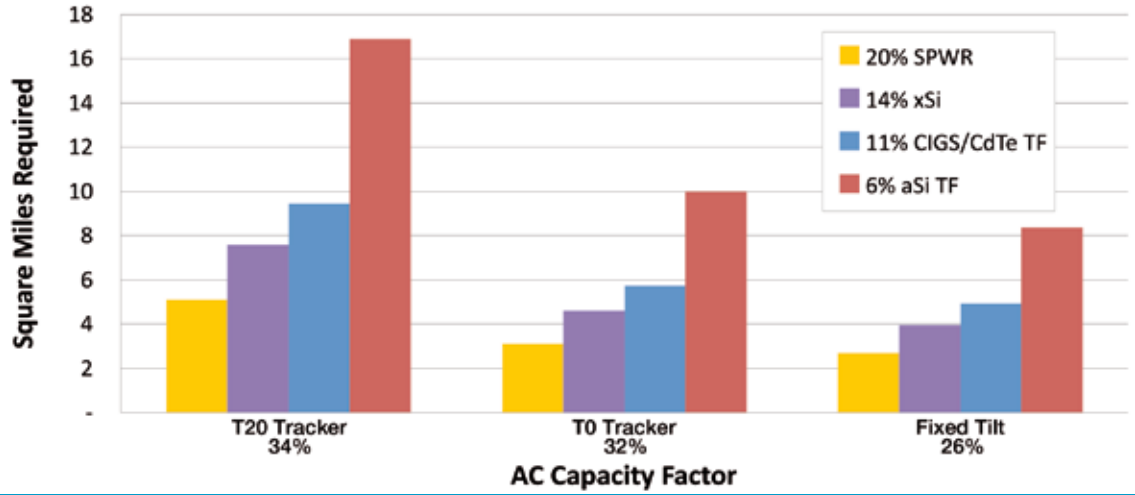

Figure 7. Land use and capacity factors for 1TWh production configurations.

Maintaining system capacity factor

Maintaining a high capacity factor throughout a system's life is critical in delivering the lowest cost of energy. PV power plant economics are maximized if the system capacity factor remains high throughout its 30- to 40-year lifetime.

A plant's capacity factor degradation largely depends on the PV panel technology and quality. Crystalline silicon has the longest operating history of any solar cell technology. Figure 9 shows a monocrystalline silicon panel that has gone through 20 years of outdoor exposure with no major visual degradation. Performance studies of silicon panels have shown only 4% total degradation after 22 years of outdoor exposure [4]. This experience provides a high level of confidence in making future performance predictions.

Most investors finance a solar system based on an assumed annual panel degradation rate of 0.5 to 1.0%, a faster rate than these historical data for silicon PV might indicate. Research on silicon PV historical performance suggests that panel life (and therefore power plant energy production) may extend much further than the 25-year design life [5]. This demonstrates that long-term performance may enable longer financeable system lives in the future.

Figure 10, which illustrates LCOE model sensitivity to financed system life based on a 7% discount rate, shows that extending the financed term of the project beyond today's 20- to 25-year values could materially impact the LCOE.

Conclusion

The levelized cost of energy is the net present value of total life cycle costs of the project divided by the quantity of energy produced over the system life. On the

	T20 Tracker	Fixed Tilt
Capacity Factor	34.1%	25.8%
1 MWp Inverters per annual TWh	335	442
Inverter O&M Cost	**100%**	**132%**

Table 2. Inverters required for 1TWh of energy production in the southwest U.S. desert.

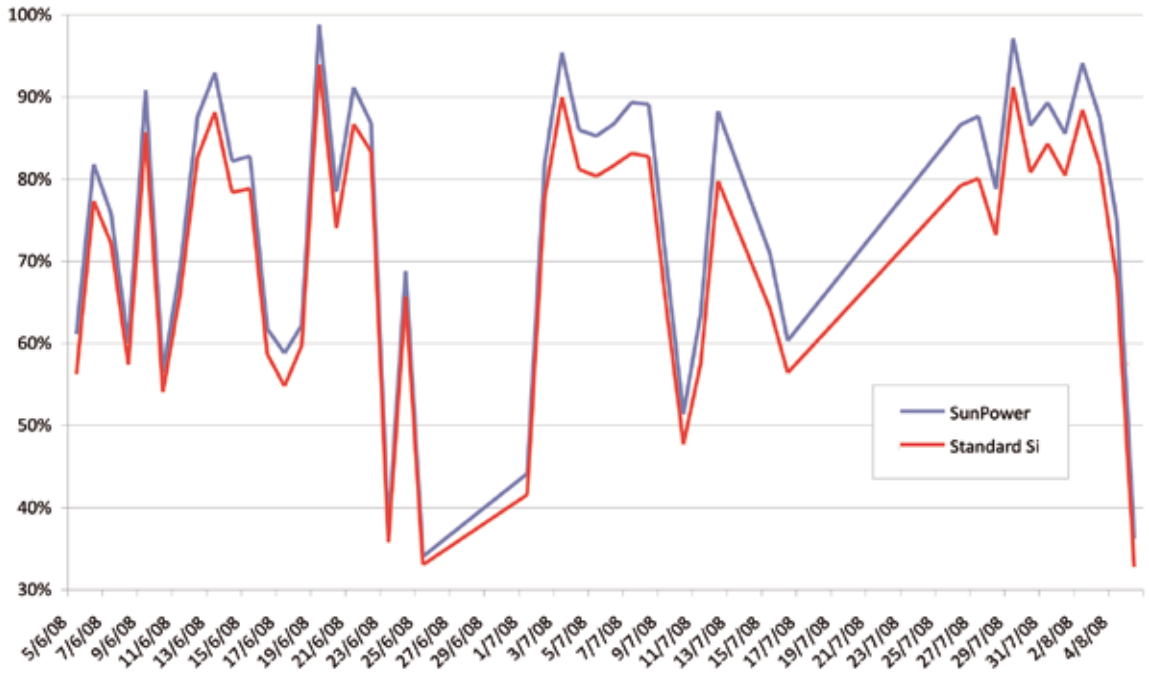

Figure 8. Performance of SunPower panels in high temperature conditions.

Figure 9. Monocrystalline silicon PV panel after 20 years of outdoor exposure.

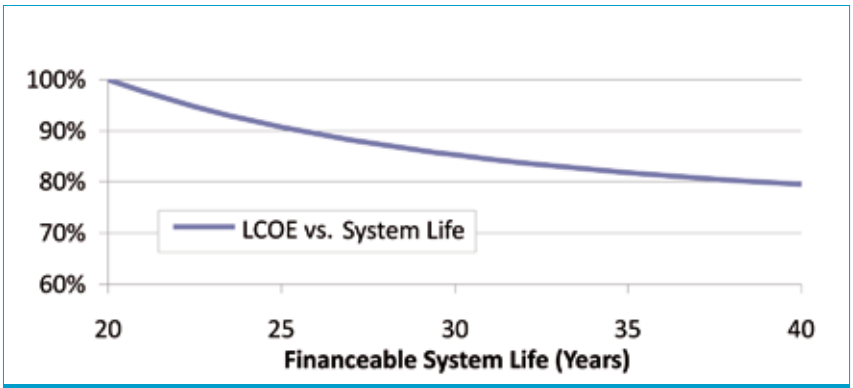

Figure 10. LCOE sensitivity to financeable system life.

many dimensions of cost and performance that underpin LCOE for a solar power plant, high-capacity factor tracking PV offers a compelling solution.

Key LCOE benefits for high-efficiency tracking PV power plants include the highest total lifetime energy production and system capacity factors; lower life-cycle operations and maintenance costs caused by up to four times the energy production per panel per year; lower power plant balance-of-system capital costs through the reduction in the number of modules and scale of the mounting system and land required to generate a given amount of energy; and the arguably the lowest long-term energy delivery risk, given that monocrystalline PV modules provide predictable capacity factor delivery, which reduces investor investment risk and enables longer financeable system lives.

The LCOE analysis detailed in this article shows how high-efficiency, monocrystalline silicon-based tracking PV power plants generate economic benefits to project investors and utilities alike. Single-axis tracking will continue to offer some of the best system economics, despite rapid reductions in panel and power plant costs.

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