A new layer of efficiency for solar

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Perovskite technology could deliver a step change in solar module efficiency, cutting project costs and build times. By combining perovskite and silicon technology while using existing manufacturing infrastructure, ultra-high-efficiency modules could reach the market faster.

Solar has had an incredible global growth trajectory over the past few decades, expanding more than 1,000-fold.[1] In 2025, solar was the largest source of new power generation capacity in both Europe and the US.[2,3,4] The primary driver of this leadership position is cost, as solar is now amongst the least expensive methods to add new power generation to the grid.[5]

While silicon solar cell technology has been important in the advancement of the industry, one could argue that most of the growth has been driven by cost reductions and the expansion of manufacturing using silicon technologies developed decades ago. Consider, for example, that passivated emitter and rear cell (PERC) technology was developed in the late 1980s with a record efficiency at the time of 22.8%.[6]

This is not too far off the efficiencies we see today, nearly 40 years later. When looking at the actual technological improvements, the gains have been incremental over multiple decades, whereas cost reductions have been more dramatic in the past decade.[7]

Over the past 40 years, solar module efficiencies have improved by roughly 10 percentage points from about 15% in 1985 to 25% in 2025 for best-in-class silicon-based technology.7

A new class of technology, perovskites, has the ability to disrupt the incremental efficiency improvement curve with a step-function change in efficiency that will significantly change solar's levelized cost of electricity (LCoE).

Historical reductions in solar LCoE have been largely a result of the mass production of older solar cell technology rather than new cell technology or higher efficiency technologies that add value. This is in large part due to two reasons: high-efficiency technology has generally come with a higher price tag, relegating those technologies to niche applications, and new technology has had a hard time competing with mass-produced silicon.

This is not to say that the industry has not seen a lot of technology innovation throughout the manufacturing and solar project value chain. Still, much of the technology development has been incremental or focused on making a particular type of silicon solar cell slightly better versus coming up with an entirely new solar cell approach. Tunnel oxide passivated contact (TOPCon) technology is a good example.

For solar cell technologies that came to market with an initial higher price point, most have either failed, been relegated to niche markets over the long term or had their original patent holders exit the business (examples are SunPower and Sanyo/ Panasonic).[8,9]

When module price is the main driver, it is simply very hard to compete unless the technology can lower LCoE out of the gate or very large subsidies exist to achieve the cost reductions afforded by gigawatt-scale manufacturing. The transition from multi-crystalline cell technology to mono-crystalline cell technology is a good example.[10]

Market expansion in solar has been driven by falling costs, achieved by expanding manufacturing capacity. The industry has seen many cycles of over-expansion in manufacturing met with falling prices that have propelled the industry towards the next level of expansion.[11]





Figure 1. Caelux Energy Producing Glass in production

Perovskites offer a step change in efficiency

In 2009, a new photovoltaic technology category entered the scene: perovskites. The technology has climbed the solar efficiency learning curve[12] at a faster pace than other technologies, from about 3% in 2009 to more than 26% in 2024 on small-area research cells.[13,14] The rapid climb is largely due to the crystalline structure's ability to absorb light coupled with the vast number of researchers working globally on the promising technology.

There are multiple approaches to perovskite technology and the industry has concentrated around two main approaches that involve coupling perovskite technology with silicon technology to provide efficiencies greater than either technology can deliver on its own. This is how perovskites will help break through the theoretical single-junction silicon solar cell efficiency ceiling of 29.43%.[15] In one approach, perovskites are integrated as part of the silicon solar cell, requiring new cell designs.

In the other approach, the perovskite layer is kept completely separate from the silicon solar cell. Both offer step-function improvements in efficiency potential with early products coming to market with module efficiencies of 27% to 29% compared with today's average module efficiencies of around 23%.

This step-function improvement in efficiency is so significant because solar module efficiency is the single biggest technology lever available to drive down the cost of solar electricity, whether for a residential, commercial or massive utility-scale solar project. Efficiency improvement drives down the cost of nearly all elements of a solar project, including land, labor, balance-of-system hardware from steel to wiring, logistics and transportation costs.

Another benefit becoming more widely recognized is that higher efficiency also equates to being able to install a solar plant faster. With the rapid rise of data centers and electrification, speed-to-power is becoming an increasingly important consideration. Shaving another 20% to 30% off the timeline to build a solar plant is valuable in today's environment of increasing power demand.[16]

Competing on cost

Perovskite technology is being developed around the world and, while it is not immune to going through the process of expanding production, it has a key advantage when it comes to cost. Perovskites are an inexpensive material set[17] and therefore overcome from the start one of the biggest challenges of past technology advancements, where increased efficiency generally came with a higher material or production process cost.

Because the cost structure of perovskite-based technology can work out of the gate, the solution can compete with incumbent

silicon technologies and provide a benefit to early adopters right away.[17,18] This allows production to expand where previous, more expensive technologies have struggled to establish a sufficient market.

If a technology cannot reach high production volumes, it remains at a disadvantage. Larger production volumes help reduce production costs and can provide advantages in other areas, from logistics to financing.

Disrupting solar without disrupting the supply chain

One company bringing its perovskite technology to market is Caelux Corporation, based in California. The company has taken the approach of keeping the perovskite layer independent from the silicon solar cell and is currently producing perovskite on glass in a 2 m² format, known as Energy Producing Glass. Caelux's Energy Producing Glass is designed as a plug-and-play replacement for the standard solar top glass that is used in solar modules.

Normally only functioning as a protective shield, the top glass now also functions as a power generation layer. Caelux technology enables Hybrid-Tandem™ solar modules with two power generation layers that are expected to achieve efficiencies of up to 30% in just a few years' time. Caelux tunes its perovskite layer to absorb visible light, while the underlying silicon layer absorbs infrared light.

Further, the company voltage-matches to the silicon solar cell technology being used so that the two layers work together in parallel.

Caelux is taking the approach of disrupting solar without disrupting the billions of dollars of investment that have already been made in the solar supply chain. New technologies often attempt to completely disrupt a market but fail to reach commercial production volumes. By making the technology plug-and-play with module manufacturing lines and by partnering with existing module manufacturers, Caelux is introducing its technology using the industry's existing manufacturing capacity.

This provides a faster and more efficient path to market than rebuilding and competing with the existing solar manufacturing ecosystem, which has over 1 TW in annual module manufacturing capacity.[19]

Faster, lower-cost power and a path to 24/7 solar

At high production volumes, perovskite technology and Caelux's approach unlock a number of benefits for solar electricity generation. For solar to become an increasing portion of the power on the utility grid, 24/7 baseload solar will need to become a reality. Ultra-high-efficiency Hybrid-Tandem modules provide significant cost savings that drive LCoEs down and the savings can be combined with falling battery costs to increase the storage duration of projects. By closing the economic gap, 24/7 solar can be brought online faster, further accelerating the opportunity for solar electricity.[20,21]

In regions that rely on imported fuel, the timeline for 24/7 solar, once thought to be far off in the distance, may match closely with the rise of perovskite technology.[20]

When evaluating the benefits of high-efficiency Hybrid-Tandem solar modules, there are different ways to take advantage of efficiency gains. One is to focus on building a solar plant with the same capacity.

In a modeled 300 MW project using the first generation of Caelux technology, the land required is reduced by more than 20% while the LCoE is reduced by 7.5% and the build time is shortened by two months.[16] The same model, adjusted for technology improvements in 2029, shows a 10% lower LCoE with a 30% reduction in land and the project build time shortened by a quarter.[16]

The savings come not just from reduced costs for land, mounting hardware and labor but also from onsite rental equipment needed for less time and fewer trucks moving equipment onsite.

The other side of the equation is that if more power is needed, then a site once capable of housing 300 MW can be turned into an approximately 360 MW to 400 MW project in the same footprint. Both approaches offer significant value in a global environment demanding more abundant and affordable power.

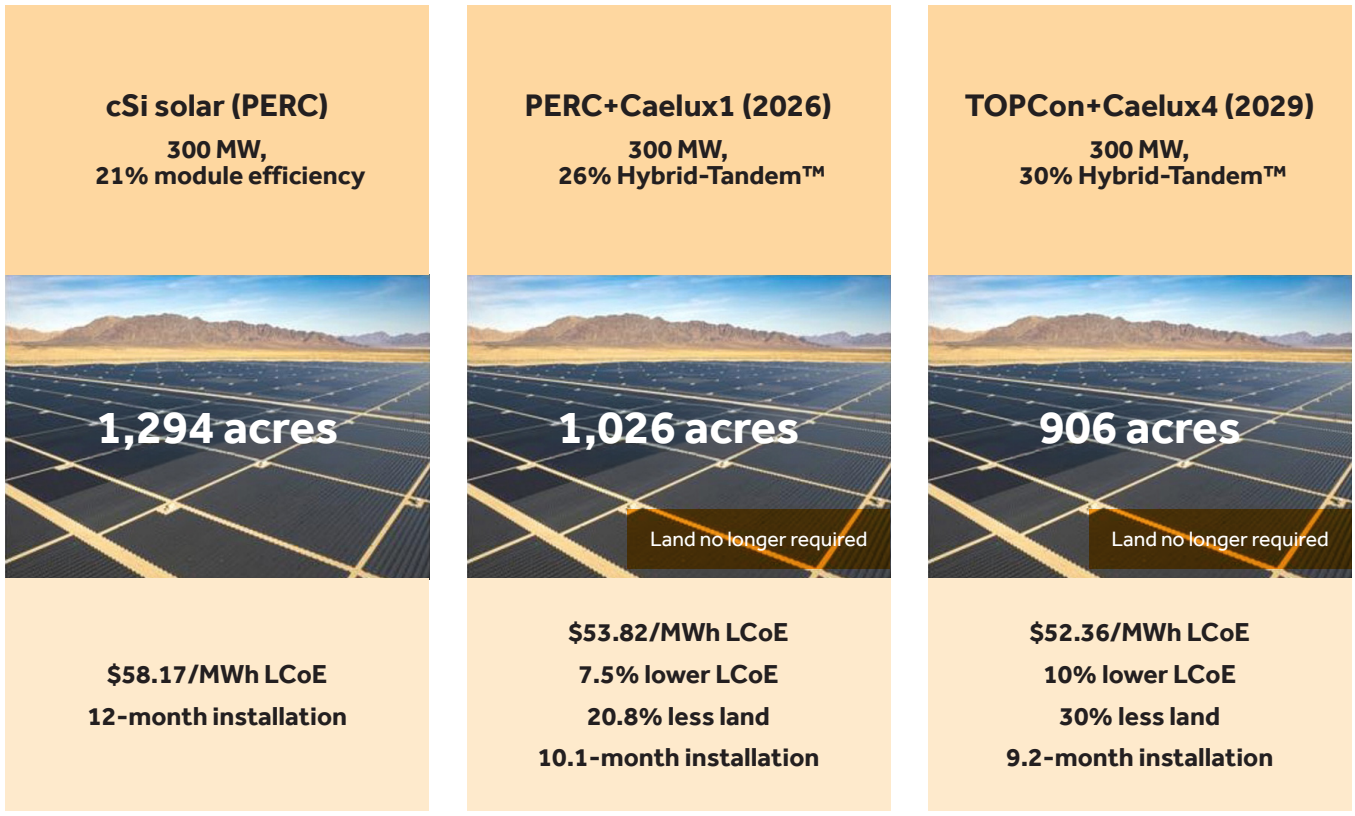


Figure 2. 300 MW modeled project example

*Illustrative examples based on Caelux modeling

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About the author

Aaron Thurlow has spent more than 25 years bringing new solar technology to market.

Early in his career, he helped launch SunPower's back-contact solar technology and was largely responsible for branding and bringing power optimizer technology to the industry during his time at National Semiconductor.

In addition, he commercialized early copper indium gallium selenide (CIGS) thin-film and TOPCon technologies in the 2010s. He is the Chief Commercial Officer at Caelux.
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About the company

Caelux is a global leader in the commercialization of perovskite solar technology with its Energy Producing Glass that enables the lowest-cost form of new energy generation.

The company's proprietary technology transforms the top glass used in solar modules into a second power generation layer, increasing energy density by up to 35% over conventional solar modules.

caelux.com

References

[1] IEA Photovoltaic Power Systems Programme (IEA PVPS), Snapshot of Global PV Markets 2026, May 2026. https://iea-pvps.org/wp-content/uploads/2026/05/Snapshot-2026-FS.pdf

[2] Solar Energy Industries Association (SEIA) and Wood Mackenzie, US Solar Market Insight: 2025 Year in Review, March 2026. https://seia.org/news/report-u-s-adds-43-gw-of-new-solar-capacity-in-2025/

[3] Solar Energy Industries Association (SEIA), 2026 Solar Data Cheat Sheet, 2026.

[4] Ember, European Electricity Review 2026, 2026. https://ember-energy.org/latest-insights/european-electricity-review-2026/

[5] Lazard, Levelized Cost of Energy+ (LCOE+), June 2025. https://www.lazard.com/news-announcements/lazard-releases-2025-levelized-cost-of-energyplus-report-pr/

[6] A. W. Blakers, A. Wang, A. M. Milne, J. Zhao and M. A. Green, '22.8% efficient silicon solar cell', Applied Physics Letters, vol. 55, no. 13, pp. 1363–1365, 1989. https://doi.org/10.1063/1.101652

[7] Fraunhofer Institute for Solar Energy Systems ISE, Photovoltaics Report, updated edition. https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report

[8] SunPower Corporation, 'SunPower Announces Voluntary Chapter 11 Filing', Form 8-K, Exhibit 99.1, U.S. Securities and Exchange Commission, 5 August 2024. https://www.sec.gov/Archives/edgar/data/867773/000086777324000086/ex991_202485pressrelease.htm

[9] pv magazine, 'Panasonic to exit solar manufacturing', pv magazine, 1 February 2021. https://www.pv-magazine.com/2021/02/01/panasonic-to-exit-solar-manufacturing/

[10] VDMA, International Technology Roadmap for Photovoltaic (ITRPV), 17th Edition, June 2026. https://vdma.eu/en/international-technology-roadmap-photovoltaic

[11] International Energy Agency (IEA), Solar PV Global Supply Chains, July 2022. https://www.iea.org/reports/solar-pv-global-supply-chains

[12] National Laboratory of the Rockies (formerly NREL), Best Research-Cell Efficiency Chart. https://www.nlr.gov/pv/cell-efficiency

[13] U.S. Department of Energy, Solar Energy Technologies Office, Perovskite Solar Cells. https://www.energy.gov/eere/solar/perovskite-solar-cells

[14] A. Kojima, K. Teshima, Y. Shirai and T. Miyasaka, 'Organometal Halide Perovskites as Visible-Light Sensitizers for Photovoltaic Cells', Journal of the American Chemical Society, vol. 131, no. 17, pp. 6050–6051, 2009. https://doi.org/10.1021/ja809598r

[15] A. Richter, M. Hermle and S. W. Glunz, 'Reassessment of the Limiting Efficiency for Crystalline Silicon Solar Cells', IEEE Journal of Photovoltaics, vol. 3, no. 4, pp. 1184–1191, 2013. https://doi.org/10.1109/JPHOTOV.2013.2270351

[16] Caelux Corporation, internal project modeling (300 MW utility-scale project, first-generation and 2029 Hybrid-Tandem™ technology), 2026.

[17] J. J. Cordell, M. Woodhouse and E. L. Warren, 'Technoeconomic analysis of perovskite/silicon tandem solar modules', Joule, 19 February 2025. https://www.sciencedirect.com/science/article/pii/S2542435124004665

[18] National Laboratory of the Rockies, 'Improving Tandem Efficiency Can Lower Solar Photovoltaic Module Cost Per Watt', News Release, 9 January 2025. https://www.nlr.gov/grid/news/press/2025/improving-tandem-efficiency-can-lower-solar-photovoltaic-module-cost-per-watt

[19] International Energy Agency (IEA), Renewables 2025, October 2025. https://www.iea.org/reports/renewables-2025

[20] Ember, Solar electricity every hour of every day is here and it changes everything, June 2025. https://ember-energy.org/latest-insights/solar-electricity-every-hour-of-every-day-is-here-and-it-changes-everything/

[21] BloombergNEF, 'Lithium-Ion Battery Pack Prices Fall to $108 per Kilowatt-Hour, Despite Rising Metal Prices', 2025 Battery Price Survey, 9 December 2025. https://about.bnef.com/insights/commodities/lithium-ion-battery-pack-prices-fall-to-108-per-kilowatt-hour-despite-rising-metal-prices/